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Submission to the UNFCCC-SBSTA Research Dialogue (RSO)

Organization: Advanced Climate Risk Education (ACRE), Germany, <https://www.acre.blue>

Contact: Dr. Manfred Mudelsee, Managing Director, mudelsee@acre.blue

Date: 13 April 2026

Contribution to SBSTA-identified research needs

This submission addresses SBSTA-identified research needs related to:

- climate data analysis and uncertainty quantification
- attribution and understanding of climate variability and change
- assessment of trends, extremes, and underlying mechanisms
- strengthening the scientific basis for climate risk assessment and adaptation

Profile and methodological focus

The work of ACRE is situated at the interface between climate science and statistical methodology. Climate data are typically non-normal, autocorrelated, and non-stationary, requiring data-analytical methods that realistically reflect these properties.

The methodological focus is on validated statistical approaches for:

- trend estimation (linear, nonlinear, nonparametric)
- analysis of climate extremes in a non-stationary framework
- correlation and lead–lag relationships
- quantitative uncertainty estimation

A key contribution is the development and application of bootstrap methods, in particular the moving block bootstrap, to obtain reliable uncertainty estimates for statements about climate variability and change. Providing realistic uncertainty estimates is considered essential for maintaining the credibility of climate science, especially in policy-relevant contexts.

Relevance for climate risk and adaptation

Climate extremes can lead to loss of human life and substantial economic damages. Their impacts underline the strong socioeconomic relevance of climate variability and change. Methodologically sound statistical analysis is required to understand these risks and their dynamics. Improved methods and careful quantitative analysis can support better-informed adaptation and risk management decisions.

Selected references

Mudelsee M (2020) Statistical Analysis of Climate Extremes. Cambridge Univ. Press, Cambridge, 200 pp. <https://doi.org/10.1017/9781139519441>

Mudelsee M (2019) Trend analysis of climate time series: A review of methods. Earth-Science Reviews 190:310–322. <https://doi.org/10.1016/j.earscirev.2018.12.005>

Mudelsee M (2014) Climate Time Series Analysis: Classical Statistical and Bootstrap Methods. Second Edition. Springer, Cham, 454 pp. <https://doi.org/10.1007/978-3-319-04450-7>

Dear RSO Team,

Following your recent request for information related to RSO research gaps, the Alliance for Global Water Adaptation (AGWA) in association with its Water Resilience Tracker partners, is pleased to share some of its most recent publications that correspond to the areas that have been identified. The most pertinent area we would like to highlight is related to work on developing resilience indicators.

Description

As the Global Goal on Adaptation Belem Indicators for the water thematic target take shape, countries face a practical question: how to determine whether their water systems are becoming more resilient using indicators they already report, without standing up a parallel monitoring framework. The Water Resilience Tracker (WRT) Technical Note on Water Resilience Indicators for National Implementation, released in April 2026 with WRT partners AGWA, Arup, Deltares, and IWMI under the Just Transitions for Water Security programme, addresses this gap. The note treats most GGA Indicators as status or action signals and shows how they can be paired and re-interpreted to produce a fuller resilience reading, drawing on data already flowing through SDG, Sendai, NAP, and NMHS reporting streams. The methodology distinguishes between status indicators that track development baselines and more sophisticated resilience indicators that capture dynamic systemic continuity under stress. Resilience Science Must-Knows (Global Resilience Partnership, 2025) are applied as prompts throughout indicator co-design and interpretation, embedding current scientific understanding of resilience in the process rather than treating it as one-off expert input. The REAL rubric (Resilience, Equity, Agency, and Lived Experience) keeps the human dimensions of resilience visible throughout interpretation, ensuring monitoring captures whose risks and recoveries are actually being measured and that disaggregation makes equity and trade-offs visible without expanding the core indicator set. This enables indicator evidence to inform decision-making on plans, budgets, and reporting, so that monitoring is consistently directed toward improving resilience outcomes rather than producing reports for their own sake. Co-design with national counterparts, supported by an institutional architecture modelled on the WMO National Framework for Climate Services, ensures the indicator set is owned and used by ministries, agencies, and statistical offices rather than imposed externally. Country applications in Brazil, Egypt, Malawi, and Nepal show that the binding constraints in adaptation tracking are rarely data volume; they are coordination across agencies, interpretation of what indicators mean for decisions, and accountability for acting on what the evidence shows.

The Technical Note is the monitoring backbone of the broader WRT methodology, which moves countries from diagnosis to decision support along a coherent pipeline. The diagnostic phase identifies leverage points and capacity gaps in national water and climate systems. System mapping defines a minimum sufficient scope for what needs to be measured. The indicator set is co-designed with national counterparts and used to inform decisions on plans, budgets, and

reporting. Vertical and horizontal linkages, supported by approaches such as the City Water Resilience Approach (CWRA), connect national signals to basin and local action.

Timeline Drafting from September 2025; major revision February 2026; publicly released April 2026. Underlying co-design and country applications conducted across the Just Transitions for Water Security programme on an ongoing basis

Geographic scope Global framework with national applications in Brazil, Egypt, Malawi, and Nepal (multi-country with a national-level implementation focus).

Cooperative effort Led by AGWA, developed jointly with WRT partners Arup, Deltares, and IWMI under the Just Transitions for Water Security programme. National counterpart engagement spans ministries, statistical offices, and sector agencies in the four pilot countries. The note draws on participatory approaches such as the City Water Resilience Approach (CWRA) and CRIDA, both developed through long-running international collaborations.

Enhancing research and institutional capacity in developing countries The methodology is explicitly designed for adoption by national agencies operating under reporting capacity constraints. Rather than introducing new data demands, it works with existing SDG, Sendai, NAP, and NMHS streams, lowering the cost of participation. The institutional architecture, modelled on the WMO National Framework for Climate Services, builds national ownership through co-design rather than external prescription. All four country applications sit in the global south.

Relevant links

Blog posts:

- <https://www.alliance4water.org/blog-posts/water-resilience-indicators-for-national-implementation>
- <https://www.alliance4water.org/blog-posts/the-nature-of-reality>

Technical Note (PDF):

- <https://www.waterresiliencetracker.cc/resources/water-resilience-indicators-for-national-implementation>

WRT programme page:

- <https://www.waterresiliencetracker.cc>

Suggested mapping to the gap categories

- 2025: assessing the impact of adaptation action on reducing risk, particularly in developing countries (primary fit).
- 2025: assessing progress in adaptation in a consistent and robust manner (primary fit).
- 2023: synergies and trade-offs between mitigation, adaptation, and the SDGs (the note avoids a parallel framework and works with existing reporting).
- 2023: consideration of equity (REAL rubric and GEDSI integration).

In addition, we would like to flag two Policy Briefs that we have published in recent months under the Water Resilience Tracker collaborative.

- **Scaling Water and Climate Resilience: Tools to link national Strategies to Local Realities (January 2026):** <https://static1.squarespace.com/static/685c9977ddd8f91ecc2313da/t/6997d04aba2281757db67cce/1771556938121/Water+Resilience+from+National+to+Local+-+26-02-07.pdf>
- This Knowledge Brief highlights the available tools and approaches available to bridge the gap from national policy to local action, linking them in a five-step process that can be flexibly applied to different contexts. Drawing from the experience of the Water Resilience Tracker and other approaches, it provides real-world success stories to illustrate how meaningful action on climate-water resilience can be achieved.

and

- **Inclusion as Resilience: Operationalizing Equitable Water and Climate Governance (March 2026):** <https://static1.squarespace.com/static/685c9977ddd8f91ecc2313da/t/69bd50f5e4c9ed0b18a50d2a/1774014709845/WRT+2026+Inclusion+and+Climate+Resilience.pdf>
- This Knowledge Brief examines how inclusion is reflected across global climate and environmental governance frameworks, identifies persistent gaps between rhetoric and implementation, and explores how initiatives such as the Water Resilience Tracker (WRT) can operationalize GEDSI principles at national and sub-national levels for better outcomes. It argues that moving from procedural participation toward substantive power-sharing and equitable financing is essential to achieving resilient water systems that truly leave no one behind.

These publications, which are both global in scope, support knowledge and shared learning related to adaptation action, especially in developing countries, and also address climate risks for vulnerable groups and equity issues.

Please don't hesitate to reach out should you have any questions or thoughts on any of these materials.

With my best regards,

Australian Academy of Science

Research Sub-themes: Near term climate change and its prediction

A Brief Summary of the Research: The Earth System Science Decadal Plan (2024–2033) outlines a coordinated national research agenda to advance understanding of the Earth system through integrated observations, data systems, and modelling. It focuses on improving climate prediction capability, enhancing monitoring of atmosphere–ocean–land interactions, and strengthening data infrastructure to support climate scenarios and decision-making. The plan brings together multidisciplinary research to address key knowledge gaps in climate processes and future projections and recommends establishing a national institute to coordinate research, strengthen data systems, and support decision-making for climate risk, adaptation, and sustainability.

Timeline of the research, if applicable: 2024–33

Geographic Scope (Pick from List): National

Please provide details of cooperative efforts (if any) undertaken in conducting the research: The Earth System Science Decadal Plan (2024–2033) was developed through extensive national collaboration across the Australian research community. It brings together universities, national research agencies, government departments, and research infrastructure providers to identify shared priorities and coordinate future investment in Earth system science. The plan builds on existing partnerships between key organisations, such as the Australian Academy of Science, CSIRO, the Bureau of Meteorology, and leading universities, as well as national facilities such as the Integrated Marine Observing System (IMOS) and the National Computational Infrastructure (NCI). These collaborations support integrated observations, data sharing, and advanced modelling capabilities across the atmosphere, oceans, and land systems. The plan also highlights the importance of international collaboration, recognising that Earth system science is essentially global. Australian researchers contribute to and benefit from international scientific programs, including those coordinated through the World Climate Research Programme (WCRP) and other multilateral efforts. In addition, the plan emphasises cross-sector engagement, including partnerships with government, industry, and Indigenous communities, to ensure that research is aligned with national priorities and supports evidence-based decision-making. These cooperative efforts aim to strengthen Australia’s contribution to global climate science while addressing national challenges related to climate variability, extreme events, and long-term environmental change.

Please Provide Details of efforts related to enhancing research and institutional capacity, particularly of developing countries: The strategic plan recognises the importance of strengthening research and institutional capacity through collaboration and knowledge sharing. While the plan is focused on national priorities, it acknowledges that Earth system science is global and that partnerships with developing countries, particularly in the Indo-Pacific region, are important. The plan supports engagement through international programs, shared data systems, and collaborative research efforts. It also highlights the need for open access to data, tools, and knowledge to support broader participation in Earth system science. These efforts

contribute to capacity building by supporting collaboration, improving access to information, and supporting the development of skills and understanding needed to address climate-related challenges.

Links to Research Page: <https://science.org.au/our-work/resources-reports/reports-publications/decadal-plan-australian-earth-system-science-2024-2033>

Links to Publications (If Available): <https://science.org.au/sites/default/files/Publication/document/decadal-plan-earth-system-science-2024-33.pdf>

Research Sub-themes: Implications of different emission metric choices towards climate change policies

A Brief Summary of the Research: This report looks at ways Australia can remove carbon dioxide from the atmosphere to help reduce climate change. It brings together experts to explore different approaches, including new technologies and natural methods. The report discusses what is already possible, what still needs development, and the challenges involved, such as cost, scale, and policy support. It also highlights the need for careful planning to ensure these methods are safe, effective, and suitable for Australia's conditions.

Timeline of the research, if applicable: 1/3/2023

Geographic Scope (Pick from List): National

Please provide details of cooperative efforts (if any) undertaken in conducting the research: This report was developed through a collaborative roundtable involving experts from academia, government, and industry across Australia. It brought together a range of perspectives to share knowledge, identify key challenges, and explore practical approaches to greenhouse gas removal. The roundtable discussions encouraged dialogue between different sectors and helped build a shared understanding of priorities and opportunities.

Please Provide Details of efforts related to enhancing research and institutional capacity, particularly of developing countries: This report is primarily focused on the Australian context and does not directly involve capacity building in developing countries. However, the findings contribute to the broader global knowledge base on greenhouse gas removal and may inform future research, collaboration, and capacity development efforts in other countries.

Links to Publications (If Available): [Greenhouse gas removal in Australia: A report on the novel negative emissions approaches for Australia roundtable | Australian Academy of Science](#)

Links to any outputs (and/or upload further information):

[Greenhouse gas removal in Australia: A report on the novel negative emissions approaches for Australia roundtable](#)

Scientific Committee on Antarctic Research (SCAR)

Research Sub-themes: Synergies and trade-offs between mitigation, adaptation and Sustainable Development Goals and the consideration of equity.

A Brief Summary of the Research: Scientific evidence shows human greenhouse gas emissions are driving ongoing warming, ocean acidification, ice loss, altered circulation, and rising sea levels. These changes are unequivocally linked to human activity and already causing widespread, sometimes irreversible, harm to ecosystems and people. Impacts will intensify without rapid emissions reductions. Antarctic changes, especially ice loss, will significantly affect global sea levels and extreme events. Current efforts are insufficient to match the pace of change. Urgent, coordinated global action, stronger policies, and increased scientific investment are essential to support adaptation, resilience, and a sustainable future.

Timeline of the research, if applicable: 1/5/2022

Geographic Scope (Pick from List): Global

Please provide details of cooperative efforts (if any) undertaken in conducting the research: The research underpinning the ACCE decadal synopsis was developed through extensive international cooperation and synthesis. The report was compiled by SCAR through its Secretariat, then circulated for independent review, with comments incorporated before finalization by SCAR's Standing Committee on the Antarctic Treaty System. It draws heavily on the consensus findings of the IPCC and IPBES, and it was reviewed in the context of work across the Antarctic Treaty System, including input from Antarctic Treaty Consultative Parties, the Committee for Environmental Protection, and relevant national programs. The report also notes the contribution of SCAR's Horizon Scan and Scientific Research Programs, as well as annual SCAR synopses prepared for the Antarctic Treaty Consultative Meetings. In addition, the report emphasizes that the research priorities it identifies require "cooperative and coordinated international responses" and "coordinated, international and transdisciplinary research efforts across Antarctica and the Southern Ocean."

Please Provide Details of efforts related to enhancing research and institutional capacity, particularly of developing countries: The report does not describe a dedicated capacity-building programme for developing countries in operational terms, but it does set out several measures that strengthen research and institutional capacity more broadly. These include support for integrated, international, long-term monitoring programs and observatories; investment in new science and technology; and the development of an appropriately resourced scientific workforce for the future. The report also stresses the importance of science communication and education, collaboration with SCAR and other researchers, and improved diagnostic and monitoring services, all of which can help institutions build technical capability and participate more effectively in international research networks. Because the report is built on international synthesis and coordination, its recommendations are designed to support wider access to shared knowledge, methods, and monitoring systems across countries and institutions.

Links to Publications (If Available): [Documents | SCAR](#)

Links to any outputs (and/or upload further information):

<https://scar.org/~documents/scar-publications/antarctic-climate-change-and-the-environment/acce-decadal-synopsis>

Links to any outputs (and/or upload further information)

<https://www.youtube.com/watch?v=P07sDH-kmw0>

Submission by CDRterra to the UNFCCC-SB64 mapping progress in filling climate change research gaps

Please select a research theme category:

- A. Understanding climate change, related climate data and scenarios development
- B. Adaptation, loss and damage and extreme weather events
- C. Ecosystems and nature-based solutions
- D. Mitigation & related technologies, greenhouse gas (GHG) emissions and reporting
- E. Cross-cutting issues

Please provide the following information: A brief summary of the research.

This submission presents selected research findings from the CDRterra research programme (2021-2028), with a particular focus on addressing research gaps and needs identified under SBSTA and the Research Dialogue. The contribution draws primarily on the programme's synthesis factsheet (<https://zenodo.org/records/17277506>), which is submitted alongside this document. It aims to provide targeted, policy-relevant insights on carbon dioxide removal (CDR) and negative emissions, aligned with the research priorities highlighted in recent SBSTA conclusions and Research Dialogue outcomes. We welcome the opportunity to contribute to this process and to support the ongoing exchange between the scientific community and Parties.

SBSTA 56, 2022; FCCC/SBSTA/2022/6; 62(e)

Identified research gap: *"The potential opportunities, risks and costs of carbon dioxide removal technologies and options;"*

The CDRterra research programme directly addresses this gap by providing a comprehensive assessment of both novel and conventional land-based CDR approaches, including their opportunities, risks, and implementation challenges.

On the opportunity side, the programme demonstrates that a portfolio of biological and (geo-)chemical CDR methods is essential to achieve greenhouse gas neutrality, as no single method fits all heterogeneous local implementation- and deployment conditions (e.g. due to regional differences in available resources, local actors as well as local public) and if one method fails, the failure could be potentially offset by the other methods of the portfolio. Novel approaches such as combined enhanced weathering-biochar mixtures, CO₂-binding building materials, DACCS with improved adsorption efficiency, and artificial photosynthesis expand the (geo-)chemical CDR portfolio and offer new pathways for scaling up removals. These findings highlight the innovation potential and diversification benefits of CDR measures.

At the same time, CDRterra provides analyses of risks and limitations. These include technical uncertainties, environmental effects, and socio-economic risks, as well as the fundamental limitation that CDR cannot substitute for emission reductions. The

research also identifies trade-offs and constraints of nature-based solutions, such as land-use conflicts, resource competition, and ecological impacts.

Regarding costs and feasibility, the research of the programme shows that the primary implementation barriers are not technological but rather structural, including legal uncertainties, lack of infrastructure, limited expertise, and insufficient societal acceptance. For example, BECCS deployment is constrained by missing CO₂ transport and storage infrastructure, while land-based approaches face regulatory and knowledge gaps in agricultural practice.

SBSTA 58, 2023: FCCC/SBSTA/2023/4; 50

Identified Research gaps: *“Scientific advances, knowledge gaps and research needs related to scenario development and use; [...]; risks and opportunities related to upscaling carbon dioxide removal; [...]; enabling environments, including technologies and support; synergies and trade-offs between mitigation, adaptation and the Sustainable Development Goals; and the consideration of equity.”*

CDRterra provides empirical and analytical insights into the conditions for scaling up CDR and the associated systemic challenges. Regarding upscaling opportunities, the research shows that additional CO₂ removal can be achieved by combining approaches. For instance, for Germany, the use of biogenic residues in existing bioenergy systems could remove 28 to 39 Mt CO₂ per year without additional land demand, illustrating the importance of system integration and resource efficiency. Land-based CDR options can conflict with existing land uses and may face resistance due to visible landscape changes or unclear benefit-sharing mechanisms. In terms of enabling environments, next to infrastructure development, especially for CO₂ transport and storage, CDRterra highlights the need for clear regulatory frameworks and targeted political funding mechanisms.

With regard to synergies and trade-offs with sustainable development, CDRterra shows that well-designed CDR portfolios can generate co-benefits for biodiversity, soil health, and agricultural resilience, for example through agroforestry or paludiculture combined with BECCS. At the same time, it stresses the need to minimize trade-offs, particularly regarding land and resource use.

CDRterra addresses equity considerations by emphasizing that the distribution of costs and benefits must be fair, and that regions and the public who provide land, infrastructure, or resources should also benefit economically and socially. It also highlights the importance of a dialogue between all affected parties by stakeholder participation, including farmers, local communities, and businesses, throughout planning and implementation processes.

SBSTA 62, 2025: FCCC/SBSTA/2025/L.5; 7 and 9(c), (f)

Identified Research Gaps: *“7. The SBSTA noted the needs and gaps, including in research, and welcomed advances in the understanding of [...] the synergies and trade-offs between climate actions and sustainable development. It noted the importance of urgently aligning adaptation and mitigation actions with sustainable development, including poverty eradication, noting that mitigation and adaptation actions have synergies with many*

Sustainable Development Goals, although some actions also have trade-offs that need to be addressed, and that the actions vary depending on context and scale of implementation across different countries and regions.

9. The SBSTA noted the information, including the scientific findings, presented by representatives of research programmes and organizations during the meeting of the dialogue, including in relation to:

(c) Research needs and gaps in the modelling of sustainable development in mitigation pathways, including the consideration of equity and justice, while recognizing ongoing and encouraging further efforts to address these;

(f) Scientific findings, advances and gaps in relation to the deployment of carbon dioxide removal technologies and approaches, the importance of their role in meeting the long-term goals of the Paris Agreement and linkages with sustainable development;”

The CDRterra programme contributes directly to these gaps by demonstrating how CDR deployment can be integrated into sustainable development pathways, while also identifying the conditions under which this integration is successful.

The research shows that CDR must be combined with emission reductions to achieve climate neutrality, reinforcing its role within broader mitigation pathways rather than as a standalone solution. Therefore integrated modelling of mitigation and sustainable development is needed.

CDRterra provides insights into the linkages between CDR deployment and sustainable development goals. It finds that CDR can support multiple objectives simultaneously, including climate mitigation, biodiversity protection, soil improvement, and economic opportunities in rural areas, if implemented strategically. For example, combining biomass use with cascading utilization enhances efficiency while reducing environmental pressure.

At the same time, the programme identifies the need to address trade-offs and context-specific impacts, which vary across regions and scales which is well in line with SBSTA’s recognition that climate actions can generate both synergies and trade-offs depending on implementation context.

Importantly, CDRterra highlights the necessity of robust Monitoring, Reporting, and Verification (MRV) systems. Current approaches are fragmented and lack standardized definitions and criteria. The programme recommends the development of science-based best-practice frameworks ensuring quality, permanence, and transparency of CO₂ removal.

The research emphasizes equity and justice considerations, showing that successful CDR deployment requires inclusive governance, fair distribution of benefits, and early stakeholder engagement. This addresses SBSTA’s call to integrate equity into sustainable development modelling and implementation.

Complementary Research Findings to SBSTA 62 and Research Dialogue 17 (2025), Key Message 6

“6. CDR can support in achieving net-zero and net-negative emissions in the long term, and further research is required to understand its feasibility and related risks and in supporting its

upscaling. Scaling-up CDR could be more effective through a diversified CDR portfolio that adopts a holistic and integrated approach.”

Building on the presentation by our colleague Shraddha Gupta (LMU Munich) at SBSTA 62, which drew on findings from the RESCUE research project and CDRterra research programme, the CDRterra research programme provides additional insights that directly respond to Key Message 6 of the 17th meeting of the Research Dialogue, particularly regarding the need for comprehensive assessments of CDR feasibility and desirability, scenario building process, risks, and scaling pathways.

CDRterra advances the development of comprehensive assessment frameworks for both land-based and ocean-based CDR methods, explicitly distinguishing between feasibility and desirability. While feasibility includes technological viability, resource availability, legal and political conditions, desirability captures broader societal dimensions such as fairness, inclusiveness, environmental integrity, and alignment with policy goals. The CDRterra Assessment Framework integrates around 120 variables into 90 indicators, evaluated against 18 criteria rooted in societal norms and ethical considerations. Applied to single CDR methods of a future CDR scenario, the CDRterra assessment framework enables transparent evaluation of both, the implementation process of CDR measures and the effects of a CDR measure, identifying risks, co-benefits, barriers, and leverage points across CDR methods. This responds directly to the need for holistic, transparent, and decision-relevant assessments of CDR highlighted in the Research Dialogue.

CDRterra highlights that assessments additionally need to go beyond individual methods in order to evaluate entire CDR portfolios within coherent scenarios. Since large-scale climate neutrality requires combinations of methods, portfolio-level assessment frameworks are necessary to capture interactions, trade-offs, and system-wide effects. The development of such frameworks is currently being advanced within CDRterra and its partner programme CDRmare.

The programme demonstrates the importance of translating global CDR insights into regional and national contexts. While global scenarios by the IPCC ARs and the State of CDR reports provide essential benchmarks, they must be complemented by regionally specific scenarios and assessments that reflect national resource constraints, governance structures, and societal conditions. The future German CDRterra scenario, for example, illustrates how a consistent deployment pathway can be derived at national level, including estimates of removal potentials across methods. Therefore, future CDR scenarios must integrate multiple modelling approaches. Reliance on a limited set of integrated assessment models is insufficient, as many CDR methods are not yet fully represented. Instead, robust scenario development requires combining e.g., Earth system models, integrated assessment models and other cost-optimization models, ex-post assumptions, and bottom-up calculations. This methodological integration enables a more complete and realistic representation of the full CDR portfolio currently discussed in the scientific literature.

Timeline of the research, if applicable:

10-21 to 10-28

Geographic scope:

- Global
- regional
- multi-country
- National
- sub-national

Please provide details of cooperative efforts (if any) undertaken in conducting the research:

The CDRterra research programme is funded by the German Federal Ministry of Research, Technology and Space and consists of ten research projects during its first phase (2021 to 2025) and 17 research projects during its second phase (2025-2028) with around 120 interdisciplinary researchers.

URL to the research page, if available:

www.cdrterra.de/en

Links to publications, if available:

<https://cdrterra.de/publikationen/?cid=24>

Links to any outputs (and/or upload further information to the box below):

<https://zenodo.org/communities/cdrterra/>

Inova-e Platform: Mapping Investments and Patents in Clean Energy Technologies for Climate Mitigation

The importance of structuring databases to guide policies aimed at developing technologies appropriate to the energy transition contexts in countries has been widely highlighted in international forums, such as Mission Innovation. Since 2018, Brazil has participated in the Mission Innovation Ministerial Meetings, and it became clear that, despite the country's significant investments in energy research, development, and demonstration (RD&D), it still lacked an integrated, comprehensive, and structured database to consolidate the available information. The absence of such a database made it difficult to formulate more effective public policies, attract partnerships between the public and private sectors, and promote Brazilian solutions and innovations internationally, many of which have high potential to contribute to the energy transition. In response to this challenge, the CGEE, in collaboration with the Energy Research Office (EPE) and strategic partners, developed Inova-e, which has played an important role in generating transparency and strategic insights in the energy sector. It provides visibility into the volume and distribution of RD&D investments in various energy technologies, facilitates international comparability, and allows for classification by energy category.

The [inova-e platform](#) is an innovative tool with a concrete impact that systematizes, updates, and disseminates data and information on public and private investments in energy innovation throughout Brazil. Data used pertain to public and publicly funded investments in R&D. Although these data are scattered and organized in different formats, they are available and open. The inova-e statistics considered investments made under the responsibility of the following institutions: ANEEL, ANP, BNDES, CNEN, CNPq, FAPESP, FINEP, and FNDCT. For the purposes of this project, these institutions are referred to as funding institutions. The data were organized according to the International Energy Agency's (IEA) classification of technology categories, as detailed in the IEA Guide (2011). As a result of this initiative's work, Brazil is the first country outside OECD to have its data published by the International Energy Agency (IEA). The construction and improvement of inova-e platform exemplify how the Center can be a fundamental think tank, developing and updating methodologies, building databases, and promoting more effective work and solutions. The institution also promotes and disseminates the platform at events and publications, such as strategic factsheets. The most recent factsheet of the platform is attached. CGEE's work translates problems into effective solutions, generates investment strategies, and produces measurable impacts on national and international policies.

Further information on the platform, including studies and analyses of results and impacts, is available at the links below on the [CGEE](#) and [EPE](#) websites, as well as in the report [Overview of Energy Innovation Investments in Brazil: Data for an Energy Big Push](#).

Annex 1: Inova-e Factsheet

WHAT IS INOVA-E?



A digital platform designed to make data on Brazilian investments in energy Research, Development and Demonstration (RD&D) accessible to the most diverse audiences.



It allows for a deeper understanding of investment trends in energy RD&D and to support the formulation and promotion of public policies, research and new investments in the field of energy innovation.



Under the coordination of EPE, the platform is the result of extensive collaboration between the MME and the MCTI, as well as other organizations of the Brazilian government, the private sector and civil society.



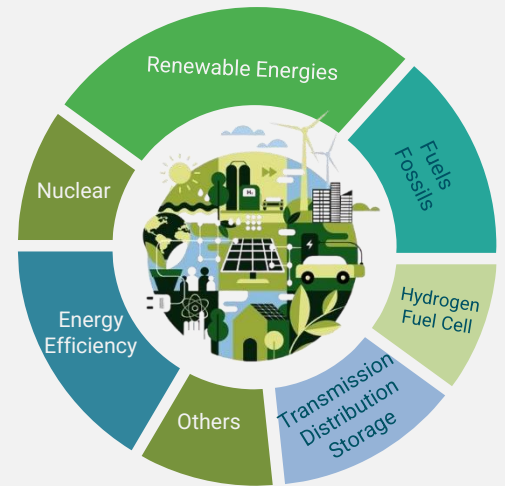
The strategic information made available in inova-e was organized in a single database, providing an unprecedented overview of innovation efforts in the energy sector in Brazil.

FUNDING INSTITUTIONS AND CLASSIFICATION

Created in 2021, inova-e is already in its 4th annual update. Every year, the platform's database is updated with information provided by the funding institutions, such as ANP and ANEEL, with data from investments in RD&D.

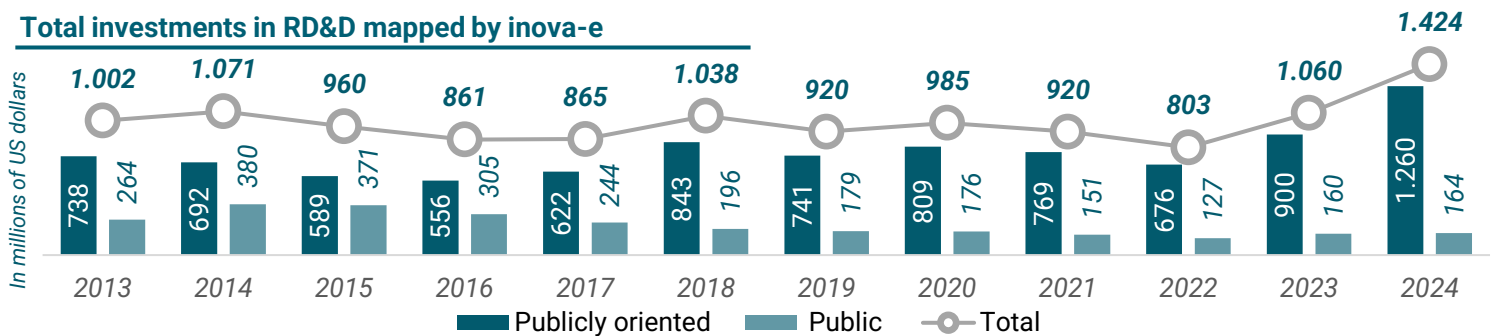
In the current version, projects are also categorized into two maturity levels: R&D and Demonstration.

The data are grouped according to the methodology for categorizing investments in RD&D of the International Energy Agency (IEA).



2025 UPDATE HIGHLIGHTS

Total investments in RD&D mapped by inova-e



CCUS, Hydrogen and Biofuels in the hype



Investments in **CCUS** sharply increased in the last 2 years, reaching US\$ 39 million.

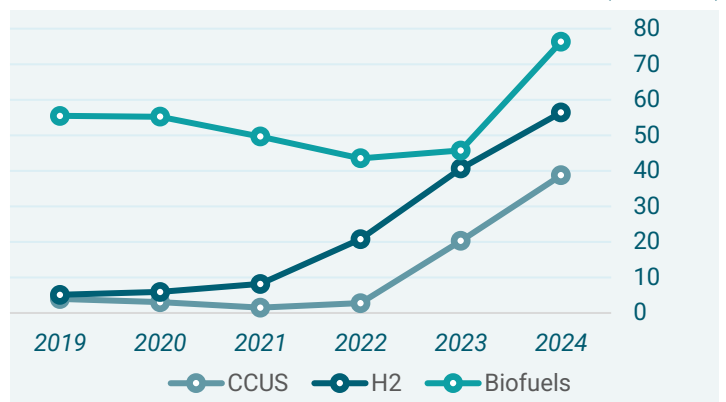


Hydrogen has been on an upward trajectory since 2019, surpassing the US\$ 50 million mark last year.



In 2024, **biofuels** led the growth among renewable technologies, reaching US\$ 76 million invested.

Variation in investments between 2019 and 2024 (MM US\$)

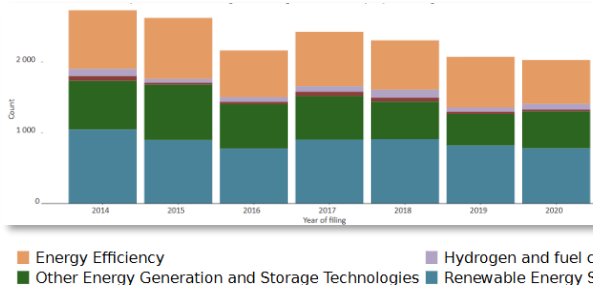


Source: Energy Research Office (EPE, 2025)

Patent mapping



Inova-e also includes a module dedicated to data on green patents and utility models filed in the country, covering technologies related to the energy transition.

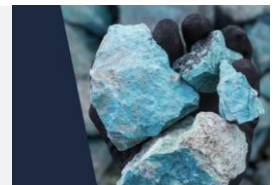


This mapping and data collection are essential for assessing the outcomes of innovation policies.

Stay tuned...

Spotlight on minerals

Given the growing importance of critical and strategic minerals in the global energy transition, we will launch a factsheet dedicated to the sector, focusing on the analysis of investments in RD&D aimed at this topic.



Explore the Inova-e platform at <https://dashboard.epe.gov.br/apps/inova-e-eng/>



IMPLEMENTING PARTNERS



PARTNERS



The **Climate Adaptation and Resilience (CLARE)** research framework is pleased to offer this submission to UNFCCC Secretariat as an input ahead of the 18th Research Dialogue. The submission highlights CLARE research responding to Party-identified needs on adaptation, loss and damage, and extreme events. It is structured to present first an overview of CLARE as a programme, followed by more detailed submissions on three selected CLARE projects. Additional inputs from other projects can be prepared if needed.

CLARE is a UK-Canada framework research programme on climate adaptation and resilience, aiming to enable socially inclusive and sustainable action to build resilience to climate change and natural hazards in Africa and Asia-Pacific. Through partnerships and needs-driven, action-focused research, CLARE has bridged critical gaps between science and action: developing new tools and supporting partner governments, communities, and the private sector to use evidence and innovation to drive effective solutions to the climate challenge, whilst building the capacity of both those carrying out the research and those using the resulting evidence.

Research need(s) addressed: CLARE research addresses needs identified under ‘*B. Adaptation, loss and damage and extreme events*’, with a specific focus on: early warning systems and climate services; assessing adaptation progress and the effects of adaptation action on risk reduction; complex, cascading and transboundary risks; and climate risks for vulnerable groups.

Timeline: 2023 - 2026

Geographic scope: Multi-country and regional across Africa and Asia-Pacific.

Relevant links: [About CLARE](#); [CLARE stories of change](#)

During [2025](#), CLARE was one of the most prominent climate adaptation research programmes globally. This community includes over 170 partners in 36 countries, who have already supported 51 solutions in 20 countries — 17 of which have already been adopted. Together we have influenced 20 plans, policies and strategies, provided capacity strengthening for 11,000 individuals in 45 countries, and published 35 peer-reviewed papers.

A distinguishing feature of CLARE is its emphasis on co-production, Southern leadership, and research for impact. The programme is not only generating climate risk evidence, but also testing how that evidence can be translated into practical decisions by communities, local governments, and other institutions. Recent CLARE stories of change demonstrate how this is happening in practice: localized surge forecasting helped communities in coastal Bangladesh reinforce weak embankments before Cyclone Remal; community-driven anticipatory action processes in the Horn of Africa changed who was identified as most at risk and what early actions were prioritized; and community hydrologists in Tanzania are feeding locally generated water data into formal water management decisions. A number of insights are publicly available through open access briefs. Those most relevant to RD18 include:

- **How adaptation drives [development and growth](#)** - climate adaptation is more than a protective measure – it is a catalyst for inclusive and resilient growth. Nature-based activities tailored to how informal economies in Kenya function can strengthen productivity and reduce exposure to climate risks. Remittance incomes are used by communities in South Asia in ways that drive economic development, job creation, and national prosperity. Adaptation measures have co-benefits for fiscal stability and human capital in Rwanda, with reduced strain on public budgets and a stronger workforce. Measures which strengthen the climate resilience of pastoralist communities ensure that productivity is sustained despite

changes in climate. Fishing communities can protect resources vital for their livelihoods and ensure sustainable economic growth in Indonesia and the Philippines.

- **Behavioural research for adaptation action** - Combining behavioural research with systems thinking helps to identify root causes, leverage points and potential intervention outcomes. Integrating behavioural research with human-centred design emphasizes a thorough diagnosis of problems, co-creation with affected communities and context-specific adaptable solutions. Applying behavioural research both as a tool for intervention design and an analytical lens, and moving beyond nudging, opens up space for integration with critical social sciences. This integration can enhance the effectiveness and fairness of interventions for more inclusive water outcomes.

The three examples below are selected programmes from the wider CLARE portfolio.

1. SURF-IT: impact-based forecasting for early action against storm surges

Research need(s) addressed: Extreme events, early warning systems and climate services; adaptation action to reduce risk; climate risks for women and other vulnerable groups.

Timeline: 2023-2026

Geographic scope: Bangladesh

SURF-IT develops impact-based forecasts of storm surge levels for inland tidal estuaries in coastal Bangladesh and links those forecasts to inclusive early action protocols. The research combines artificial intelligence, hydrological data and dynamic embankment mapping with community knowledge so that warnings are grounded in the places and populations most at risk. The project is focused on making early action protocols operational for women and other vulnerable groups rather than treating forecasting as a technical exercise.

During Cyclone Remal in May 2024, the project team identified two weak embankment points in advance of landfall and worked with communities to take protective action. Those communities reinforced the vulnerable sections before the cyclone struck, directly benefiting around 200 households and reducing the likelihood of substantial losses to lives and property. This research demonstrates how localized climate services can become more actionable when they are co-produced with exposed communities and embedded in decision systems that support anticipatory action.

Relevant links: [SURF-IT project page](#); [Story of Change: Using impact-based forecasting for community-led protective action in the face of Cyclone Remal](#); [Community-Led Embankment Management in Coastal Bangladesh](#)

2. PASSAGE: locally led anticipatory action for drought and transboundary risk

Research need(s) addressed: Extreme events, early warning systems and climate services; complex, cascading and transboundary risks; climate risks for vulnerable groups; locally grounded anticipatory action.

Timeline: 2023-2026

Geographic scope: Greater Horn of Africa - Ethiopia, Kenya, Somalia, South Sudan and Uganda

PASSAGE seeks to improve forecasting, anticipatory action planning and local government preparedness for drought in pastoralist livelihood systems across the Greater Horn of Africa. The project addresses the gap that warnings often exist, but they do not trigger timely, context-appropriate action. PASSAGE responds by combining climate and socio-economic modelling with participatory methods that co-produce risk narratives, thresholds and targeted actions for different groups within pastoralist communities, including in transboundary areas where vulnerability is especially acute.

The project's Forecast to Local Action (FOLA) process blends scientific outlooks with indigenous indicators through learning hubs where communities, scientists and local organizations jointly interpret risk and agree triggers for action. In Moyale on the Kenya-Ethiopia border, the process showed that lactating mothers and infants were consistently at highest risk even under moderate drought conditions, leading to agreed triggers for mobile nutrition teams, cash top-ups and borehole repairs. In Karamoja/West Pokot-Amudat, the analysis highlighted children under five and persons with disabilities as most at risk, which informed actions such as pre-positioned nutrition supplies, accessible alerts and inclusive referral systems. The research provides a practical model for connecting climate services, local knowledge, vulnerability analysis and anticipatory finance and action.

Relevant links: [PASSAGE project page](#); [From Early Warning to Anticipatory Action: Lessons from Horn of Africa's Drylands](#)

3. CLARITY: community hydrology and adaptation-relevant water governance

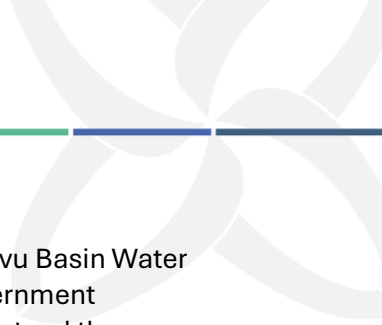

Research need(s) addressed: Assessing adaptation progress and the effects of adaptation action on risk reduction; climate risks in vulnerable dryland settings; strengthening locally relevant knowledge for adaptation planning and action.

Timeline: 2023-2026

Geographic scope: India, Niger, Nigeria, Tanzania

CLARITY focuses on equitable, sustainable and climate-resilient development pathways in tropical drylands, especially around water resilience in rapidly changing rural-urban systems. Through transformational labs, the project works with communities and institutions to assess water management practices, build plausible pathways, and embed research into wider policy and practice. Its approach combines modelling with participatory methods, including video diaries, interviews and the training of community or para-hydrologists who help generate locally useful evidence.

One of the project case studies is examining the effects of climate change on transboundary water availability in Niger's Maradi region, which also affects northern Nigeria via transboundary flows. Early career researchers at Abdou Moumouni University (Niger) and Maiduguri University (Nigeria) leveraged training provided through the CLARITY project to develop hydrological models in DRYP – a modelling tool developed for water-scarce dryland environments- to test the climate resilience, renewability and equity of water development pathways in the two countries. Collaborations and technical support for DRYP modelling in these contexts also led to sharing and integration of datasets across national boundaries and has led to the first transboundary maps of groundwater-level contours in the central Sahel. CLARITY research is also already informing adaptation-relevant decision-making in other case study areas. Officials and community members trained by the project mapped borehole



locations and collected water level data that are now being used by the Wami Ruvu Basin Water Board in Tanzania to inform a more sustainable regime for water extraction. Government employees and students are applying the techniques in their own work, helping extend the reach of the initiative.

Relevant links: [CLARITY project page](#); [Story of change: Community hydrologists support water monitoring for climate resilience in Tanzania](#); [Bridging Knowledge and Action: The Community Hydrology Approach](#); [Getting better at mapping the story of water in Tropical Drylands](#)

Research and Systematic Observations (RSO)

Thanks for this. At Climate Interactive we haven't engaged around the SB meetings recently but your list of research gaps sparks my interest that perhaps there is something for us to offer or at least to get highlighted. With MIT we have developed the [En-ROADS](#) Climate Solutions simulator, maybe you have seen it. We have lots of functionality in the tool to explore some of the research gaps that are identified. I've copied the most relevant three with some notes. Is that what is needed? If you or the RSO secretariat see opportunities to engage further, I appreciate you flagging them.

- Research needs and gaps in the modelling of sustainable development in mitigation pathways, including the consideration of equity and justice, while recognizing ongoing and encouraging further efforts to address these;

- En-ROADS (en-roads.org) is an accessible integrated assessment model for anyone to create custom global mitigation pathways by testing a mix of energy, land, econ policies and then examine their impact on climate risks (sea level rise, wildfire danger, labor losses from extreme heat, etc. etc.) and economic factors (cost of electricity, oil, etc.)

- Scientific findings, advances and gaps in relation to the deployment of carbon dioxide removal technologies and approaches, the importance of their role in meeting the long-term goals of the Paris Agreement and linkages with sustainable development;

- En-ROADS (en-roads.org) enables people to test a variety of carbon dioxide approaches at the global level and look at many of the subsequent costs, land use needs, and energy requirements for each. CDR approaches include: afforestation, biochar, agricultural soil carbon, direct air capture, and enhanced mineralization (with active work on ocean alkalinity modeling to be added to the simulator later this year).

- scenario development and use;

- En-ROADS is aligned with the scenarios used by NGFS and IPCC but is distinct in how the model is free to use, available in 20+ languages, and operates via a straightforward online interface. It is also not based solely around optimal scenarios, En-ROADS enables people to test what-if scenarios for pathways that have uncertain costs, for example.

- En-ROADS Climate Solutions simulator <https://www.climateinteractive.org/en-roads/>
- Comparison of En-ROADS to historical trends: https://docs.climateinteractive.org/projects/en-roads-reference-guide/en/latest/pages/comparison_history.html

- Comparison of En-ROADS to other future model scenarios: https://docs.climateinteractive.org/projects/en-roads-reference-guide/en/latest/pages/comparison_future.html
- General En-ROADS support resource library: <https://www.climateinteractive.org/resource-library/>

1. We have several projects underway in our SPARCLE and integrated spatial planning workstreams that directly address planning for climate, biodiversity and land alongside productive land uses under various sustainable development pathways.

As an example, we just had this paper come out earlier this week in Nature Communications:
<https://www.nature.com/articles/s41467-026-69952-6>;

CI write-up here: <https://www.conservation.org/press/research-highlights-trade-offs-and-opportunities-for-climate-food-and-nature-in-land-planning>

Project website here: <https://www.conservation-sparcle.org/> --

We are also engaging in several national/sub-national efforts along those same lines and are actively developing proposals to enhance/extend the work.

2. *"Islands are unique hotspots of biodiversity, endemism, and cultural value. In many ways, they are microcosms of Earth's most important and vulnerable ecosystems – and yet, they are vulnerable to irreversible change and ecosystem collapse. Despite their global ecological and cultural importance, island ecosystems remain among the least understood in terms of how coupled water and nutrient cycles govern stability and collapse. This research aims to model these ecosystem dynamics to promote island resilience in the face of development pressures and climate change. The goal of the Irreversible Islands research*

study is to assess the minimum vegetation cover needed on islands to maintain freshwater and nutrient cycles. By illustrating the delicate relationship between standing carbon stock and freshwater and nutrient cycling, we can identify 'tipping points' which may drive investment in small island developing states that are often overlooked. Research around the urgency of tipping points has been key in motivating attention to places such as the Amazon rainforest; however, similar work has not been done to highlight the importance of island ecosystems. The model will be designed to be transferable across island geomorphic types and usable in data-limited contexts, which is common for many remote island nations. The intended audiences are 1) government entities involved in land use planning, 2) freshwater utility and private bottling companies, and 3) sustainable development NGOs with a focus on nutrition outcomes."

This project is new and will be ongoing for a while before we have concrete results to show, so I think this blurb can be used primarily to highlight current gaps in the literature that we are trying to address.

Next generation Earth System Models to support political decisions related to climate change

The aim of this research activity within the framework of CAP7 (Contribution to the Coupled Model Intercomparison Project) is to further develop global Earth system models as a contribution to CMIP7 (<https://wcrp-cmip.org/cmip7/>). CAP7, which is funded by the German Ministry of Research, Technology and Space ([BMFTR](#)), focuses specifically on the climate configuration of ICON (ICON-XPP) and the models of the Alfred Wegener Institute (AWI) (AWI-CM & AWI-ESM). These data serve as a basis for policy consultancy, for example within the UNFCCC process. The global climate projections are also used as lateral boundary conditions for regional climate projections, which form the basis for national adaptation strategies in many countries. Stakeholders can use these projections to assess potential impacts on ecosystems, the economy, human health and infrastructure, enabling the development of robust strategies for climate adaptation and risk management. The new model versions will be able to simulate the nitrogen cycle and the interactive carbon cycle so that emission-driven climate projections can be performed. This is recommended for CMIP7. Furthermore, a first prototype of a hybrid ICON-XPP-ML model is being developed, in which some parameterizations are replaced by machine learning-based parameterisations. The aim is to demonstrate the potential of this new approach for climate modelling. The advanced Earth System Model Evaluation Tool (ESMValTool) is used to evaluate the model simulations. The simulation data generated in the project will be processed according to the standards of CMIP7 and published for further use in science and policy for planning adaptation measures to climate change.

Concentration-driven simulations

ICON-XPP, AWI-CM and AWI-ESM are being prepared for the production of concentration-driven simulations for the CMIP7 cycle. This includes a further development of the models. A key objective is to reduce the remaining discrepancies from reference datasets in historical simulations, to perform the requested simulations, to carry out the scientific evaluation and analysis of the model results and to standardise and publish the data.

Emission-driven simulations

After implementing and testing the carbon cycle in ICON-XPP, reference experiments will be carried out with an interactive carbon cycle, which will then be required for the tuning under pre-industrial conditions. The aim is to achieve a stable model climate and reasonable values for key characteristics of the climate system with the new configuration. This also includes tests of equilibrium climate sensitivity and transient climate response. We will then carry out the required simulations, conduct a scientific evaluation and analysis of the model results, and standardise and publish the data.

Data driven climate simulations

Furthermore, the team will develop a hybrid ICON-XPP-ML model. In this model some of the physically based formulations will be replaced by machine-learning based ones. The aim of this endeavour is to produce simulations using this prototype.

The collaborative research project *Integrated Greenhouse Gas Monitoring System for Germany (ITMS)* combines research concerning greenhouse gas observation, process modelling, atmospheric transport and inversion modelling to supplement national inventories and to yield useful and actionable climate information.

The Integrated Greenhouse Gas Monitoring System – or in German: Integriertes Treibhausgas- Monitoringsystem (ITMS) – is a research and development endeavour funded by the German Federal Ministry of Research, Technology and Space (BMFTR). ITMS will enable Germany to operationally monitor the sources and sinks of the three most important anthropogenic long-lived greenhouse gases (GHG) CO₂, CH₄, N₂O with the help of atmospheric measurements and innovative modelling approaches.

Monitoring of greenhouse gas emissions for climate protection was put into force at the political level with the Paris Agreement from 2015. Both, the Intergovernmental Panel on Climate Change (IPCC), and the United Nations Framework Convention on Climate Change (UNFCCC) recommend supplementing the national inventory reports with an observation-based monitoring of greenhouse gas emissions. The World Meteorological Organisation (WMO) Framework Integrated Global Greenhouse Gas Information System (IG3IS) develops recommendations for national contributions. The Integrated Greenhouse Gas Monitoring System (ITMS) implements the German contribution to the IG3IS.

With the establishment of the operational ITMS service, the scientific measurement and modelling communities of Germany will be integrated, utilizing the Copernicus Services, the European Research Infrastructure projects ICOS and IAGOS, as well as satellite data in a continuous manner. The ITMS is planned to be developed through three phases, with evaluations in between, and to finally put it into operation at the Deutscher Wetterdienst (DWD). The Phase 1, aiming for a ITMS Demonstrator spanned 2021-mid 2026, the Phase 2 is planned mid 2026-2030 aiming for a First Generation ITMS and a subsequent Phase 3 is envisaged for transfer to operations. The long-term implementation of the ITMS research results at the operational authorities DWD, UBA and Thünen Institute make the project efficient and sustainable.

ITMS results benefit from contributions from the German research community covering the greenhouse gas (GHG) observing system, sources and sink processes of GHG, and modelling and inversion methods (see <https://www.itms-germany.de/en>) for scientific details and current results. International collaboration and knowledge exchange is organized through WMO IG3IS.

ITMS contributes to addressing following identified SBSTA aims:

- To strengthen systematic observation and research relevant to the climate system
- to provide information on greenhouse gas emission sources and sinks
- to identify and quantify the impact of human activities
- to promote usable and accessible scientific information for the science-policy interface, including in support of implementation of the Convention and the Paris Agreement
- to inform regional and national decision making

Submission: Downscaling global emission pathways for subnational climate action

By: Data-Driven EnviroLab, University of North Carolina at Chapel Hill

Contact: Angel Hsu (angel.hsu@unc.edu), Diego Manyá (diego.manya@unc.edu)

Supporting: RSO – Advancing high-resolution local and regional climate information and the development of downscaled sub-regional climate models to better understand climate risks and support effective climate action

Understanding how city and subnational climate mitigation efforts contribute to global pathways towards meeting the Paris Agreement goals is a persistent challenge. Most global mitigation scenarios are generated by integrated assessment models (IAMs)¹⁻³ at large scales such as world regions or at best countries. As a result, these scenarios are limited for cities and subnational governments which have assumed a more central role in climate governance, and are often expected to align their emission reduction targets and climate plans with global temperature goals.

To address this gap, a novel framework that integrates downscaled global mitigation pathways from the IMAGE IAM (Current Policies and 2 °C scenarios) under SSP2 with a dynamic administrative-boundary approach to derive urban policy-compatible future mitigation pathways was developed. This process included the implementation of a Kaya-based statistical downscaling approach for every decade from 2020 to 2100, the identification of the urban administrative entities based on their socioeconomic and physical characteristics by 2100, and the comparison of country-specific urban pathways between the projected scenarios and their current climate mitigation pledges for G20 countries based on of 3,526 subnational climate mitigation targets.

Results show that global mitigation is dominantly urban, and that this urban concentration remains consistent across regions and scenarios using a dynamic administrative-boundary approach. Urbanization trends towards 2100 emphasize this even more, as urban areas become more prevalent worldwide, particularly in Africa. We also find that the need to increase the ambition of existing city-scale and subnational mitigation pledges to align urban pledges to the ambition required by both Current Policies and 2°C scenarios.

Specific findings include:

- Urban emissions trajectories closely resemble global pathways under both Current Policies and 2°C scenarios, indicating that the long-term dynamics of climate mitigation are concentrated overwhelmingly in urban areas including non-AFOLU negative emissions (Figure 1).
- Urban share of global emissions is estimated as 81.8% (78.8% - 83.6%) in 2020, rising to 88.2% (82.4% - 90.3%) by 2100 under the Current Policies Scenario and to 87.7% (81.9% - 89.9%) in 2100 for the 2 °C Scenario,
- Country-level urban emissions per capita aggregated for G20 countries start at 12.7 tCO₂ per capita in 2020 and decrease to 5.0 tCO₂ per capita by 2050. By 2050, the

collective urban-pledge trajectory for the G20, as well as for the European Union, Indonesia and Japan are less ambitious compared to both 2 °C and the Current Policies scenarios. In Argentina, Australia, China, and Turkey, the collective urban-pledge pathway is more ambitious than the Current Policies scenario but less than the 2 °C scenario. The urban pledges in Brasil, Canada, Korea, India, Mexico, the United States and South Africa are more ambitious compared to both 2 °C and the Current Policies scenarios. These results underscore the need to raise ambition in many contexts and the substantial contributions that highly ambitious urban action can make to achieving global climate goals.

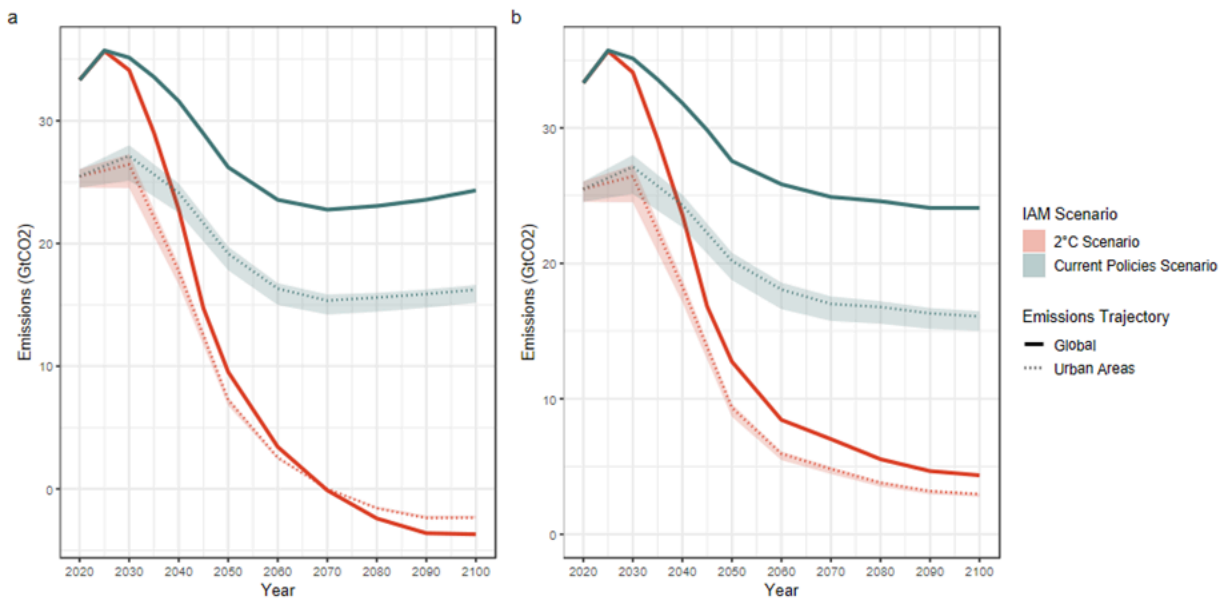


Figure 1. Comparison of Global and Downscaled urban pathways for a) net CO₂ emissions and b) gross CO₂ emissions for Current Policies and 2 °C pathways.

Geographic Scope: Global

Relevant Links:

- Preprint: <https://doi.org/10.15139/S3/THMDLV>
- Github code: https://github.com/imagepbl/downscaling/tree/main/Kaya_downscaling
- ClimActor 2.0: <https://eartharxiv.org/repository/view/10382/>



In response to the request for information on research addressing gaps identified in paragraph 32 of FCCC/SBSTA/2025/4, the Environmental Defense Fund wishes to highlight the latest research addressing the following party-identified gap: “Gaps and research needs in regard to science-based GHG reporting methodologies”.

“Warming induced emissions” are defined as greenhouse gas (GHG) emissions from intensifying wildfires, thawing permafrost, warming wetlands and other natural processes related to climate change. These emissions continue to increase as a result of ongoing warming driven by direct anthropogenic emissions, triggering positive feedback loops that are currently poorly reflected in national GHG inventories and not explicitly managed. They impact health, safety and infrastructure, and ultimately reduce the time to Paris Agreement’s temperature limits by multiple years - thus highly relevant for the climate and for policymaking.

Recent scientific literature has better ascertained the global magnitude and potential growth of these emissions, and highlighted gaps in observations and estimates at high spatial and temporal magnitudes. It recognizes a need for better quantifying this emerging and globally relevant emissions source and highlighting impacts, and mitigation opportunities, with relevance for climate plans, the Global Stocktake, and global levels of ambition.

Relevant research papers with key findings in italics:

Buma et al. 2026. Policy solutions to better assess progress toward Paris goals given warming-induced ecosystem emissions, which shorten timelines by 2–5 years. *One Earth*. (<https://doi.org/10.1016/j.oneear.2025.101571>)

Thawing permafrost, increasing circumboreal fires, and warming tropical wetlands increase CO₂ emissions by ~15 to ~300 Tg C year⁻¹ and CH₄ by ~17 to ~50 Tg C year⁻¹ above 2020 levels by 2050, lessening time to the 1.5°C and 2.0°C Paris thresholds by ~21%–25%. Policy frameworks and tools for quantifying/reporting indirect emissions from managed and unmanaged lands should be developed.

Jones et al. 2024 Global rise in forest fire emissions linked to climate change in the extratropics. *Science*. (DOI:[10.1126/science.adl5889](https://doi.org/10.1126/science.adl5889))

Overall, forest fire C emissions increased by 60% globally during the study period, with the most substantial contributions coming from extratropical regions.

Zhen et al. 2023. Recent intensification of the wetland methane feedback. *Nature Climate Change*. (<https://doi.org/10.1038/s41558-023-01629-0>)

Here, using a wetland model, we report intensified wetland CH₄ emissions during 2000–2021, corresponding with 2020 and 2021 being exceptional years of growth. The estimated increase is higher than the ensemble average under the high warming climate scenario RCP8.5. This indicates that global wetlands in high-latitude and tropical regions are experiencing stronger impacts of climate change than predicted in the most intensive climate warming in the CMIP5 models.

Ury et al. 2025 Addressing methane emission feedbacks from global wetlands. *Nature Sustainability*. (<https://doi.org/10.1038/s41893-025-01625-6>)

Earth-system feedback loops that exacerbate climate warming cause concern for both climate accounting and progress towards meeting international climate agreements. Methane emissions from wetlands are on the rise owing to climate change—a large and difficult-to-abate source of greenhouse gas that may be considered indirectly anthropogenic.

Li et al. 2026. Amplified Arctic-boreal fire regimes from permafrost thaw feedbacks. *Nature Geoscience*. (<https://doi.org/10.1038/s41561-025-01894-y>)

These cascading feedbacks may create a positive fire–climate feedback loop, whereby more burning accelerates carbon release from vegetation and soil, further destabilizing northern ecosystems. Our findings highlight the potential escalating fire and climate risks initiated by permafrost thaw, emphasizing the urgent need for immediate climatic action to mitigate climate change and the compounding impacts of wildfires and permafrost degradation.

Schadel et al. 2026. Permafrost and wildfire carbon emissions indicate need for additional action to keep Paris Agreement temperature goals within reach. *Communications Earth and Environment*. (<https://doi.org/10.1038/s43247-026-03189-5>)

Our model suggests that including permafrost thaw and fire-related carbon emissions reduces the remaining allowable carbon budgets from 2025 onward by 25 % ± 12 % for avoiding 1.5 °C and 17 % ± 7 % for avoiding 2.0 °C, relative to simulations without these processes. Accounting for these additional emissions is critical for setting emissions reduction targets aligned with the Paris Agreement.

Lamb et al. 2026. Differences in anthropogenic greenhouse gas emissions estimates explained. *Earth System Science Data*. (<https://doi.org/10.5194/essd-18-2549-2026>)

Paris Agreement doesn't cover all relevant sources of emissions. Fires and other disturbances occur on land, including the managed lands covered by national GHG inventories, and can generate significant emissions of CO₂, CH₄ and N₂O. To illustrate, an estimated 8.8 GtCO₂ was released in March 2023–February 2024 fire season, including extreme wildfires in Canada that were around 3 times more likely due to anthropogenic climate change. The key problem with fires is that although they can occur naturally, they are now more likely than in the pre-industrial period due to anthropogenic climate change [leading to imbalance between recovery and non-recovery]. This leads to major definitional obstacles to separating “anthropogenic” from “natural” fire emissions.

UN Emissions Gap Report, 2025. (<https://doi.org/10.59117/20.500.11822/48854>)

On the other hand, because many Earth system feedbacks scale with either CO₂ concentrations or global warming, exceeding 1.5°C can also result in stronger amplifying feedbacks being triggered. For global warming between 1.5°C and 2°C, one such feedback would be the accelerated thawing of permafrost that would amplify global warming as a result of the CH₄ and CO₂ emissions that are being released in the process.

...

However, an increase in frequency and intensity of droughts and heatwaves associated with human-induced climate change has contributed to an increase in the likelihood of large-scale wildfires in some parts of the world (Copernicus 2024).

UN Emissions Gap Report, 2024. (<https://wedocs.unep.org/handle/20.500.11822/46404>)

Climate change can itself drive changes in anthropogenic emissions as well as natural emissions and uptakes. Examples include the effect of warming on increases in wildfire events, the amount of carbon intake by vegetation, or on energy supply and demand patterns. Increased emissions from these sources could in turn further exacerbate climate change.

Submission of input to the UNFCCC SBSTA/RSO

Eighteenth meeting of the research dialogue, to be held in conjunction with the SBSTA 64 (June 2026).

This submission was prepared¹ in response to the invitation received by Future Earth to provide information on relevant research efforts undertaken to date in response to the identified needs and gaps during SBSTA 22 (June 2005) under the agenda item on ‘Research and Systematic Observation (RSO)’. We present a selection of outcomes from the last six editions of the *10 New Insights in Climate Science* series (2020-2025), relevant to the categories of research needs provided in the invitation.

Description: The [10 New Insights in Climate Science](#) series is a yearly selection of key advances in climate change research, across the natural and social sciences. Every year, ten key advances are prioritised and synthesised, and delivered as two self-standing products: 1) A peer-reviewed article targeted to an academic audience. This paper underpins the scientific messages of 2) a science-policy report targeted to policymakers, government officials, and other stakeholders. In particular, the report is aimed at the UNFCCC COP participants, including the press covering the event, providing them with a trust-worthy selection of very up-to-date, scientifically grounded, and policy-relevant insights in climate change, its causes, consequences, and available solutions.

Timeline of the research: Annual editions

Geographic scope: Global

¹ Prepared by: Daniel Ospina. Senior Science Officer, Future Earth secretariat, Global Hub Sweden.
daniel.ospina@futureearth.org

Ten New Insights in Climate Science (Editions: 2000- 2025)

- Bustamante, M., Roy, J., Ospina, D., Achakulwisut, P., Aggarwal, A., Bastos, A., ... & Zickfeld, K. (2023). Ten new insights in climate science 2023. *Global Sustainability*, 7, e19, 1–30. <https://doi.org/10.1017/sus.2023.25>
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A. Understanding climate change, related climate data, and scenarios development and use:

a. Near term climate change and its prediction

Ospina et al., (2026) and Schaeffer et al. (2025):

- Record global surface temperatures in 2023/24 shattered previous marks, representing a **significant surge rather than a gradual step in the long-term trend** (Forster et al., 2025). These anomalies **challenge near-term prediction models**, which face difficulties reconciling the surge due to limitations in representing aerosol–cloud interactions and the extreme statistical rarity of the observed warmth (Rantanen & Laaksonen, 2024).
These dynamics are consistent with a continued **acceleration of global warming**, making the exceedance of the 1.5° C warming threshold all but inevitable (Forster et al., 2025). Indeed, 2024 was confirmed as the warmest year on record at 1.55°C above pre-industrial levels (WMO, 2025). This period revealed an **elevated Earth’s energy imbalance (EEI)** that reached more than double the 2006–2020 average, driven by a record-low planetary albedo and reductions in sulfate aerosol pollution (Hodnebrog et al., 2024; Merchant et al., 2025).
- **Aerosol emissions and atmospheric loadings have been declining globally** over the past two decades, influencing observed climate change via pathways distinct from greenhouse gases (Persad et al., 2023; Quaas et al., 2022). **This cleanup of air pollution has de-masked the true level of warming caused by accumulated greenhouse gas emissions**, contributing to recent record-breaking global temperatures (Hodnebrog et al., 2024; Forster et al., 2021; Persad et al., 2023).
Martin et al. (2021): A critical challenge for future carbon management is that decarbonization will eliminate the cooling effect of co-emitted aerosols, which currently offset 20–50% of anthropogenic warming, potentially leading to a sharp increase in net non-CO2 forcing (Bellouin et al., 2020; Mengis & Matthews, 2020).

Bustamante et al. (2023):

- An **overshoot of the 1.5°C warming limit is now considered nearly inevitable**, as current emission trends are projected to exhaust the remaining carbon budget in approximately 6 to 7 years (Forster et al., 2023). Analysis indicates that emissions from already-planned and existing fossil fuel projects would produce up to twice the carbon budget for 1.5°C, creating a substantial "production gap" (Kühne et al., 2022).
Furthermore, there is a 42% probability that past emissions alone have already committed the Earth system to a peak warming of at least 1.5°C (Dvorak et al., 2022).

Pihl et al. (2021):

- **The likely range of equilibrium climate sensitivity has been narrowed to 2.3–4.5° C** following a comprehensive WCRP analysis that integrated evidence from feedback processes, historical data, and the palaeoclimate record (Sherwood et al., 2020). **This refinement helps constrain future climate risks**, particularly as decadal predictions of atmospheric circulation and regional temperatures (especially around the Atlantic Basin) now demonstrate encouraging levels of skill (Smith et al., 2020).
- Near-term climate understanding is further enhanced by the **improved ability of models to simulate hydrological extremes and drought frequency** (Ukkola et al., 2020). However, predictive precision is complicated by the fact that many high-sensitivity models, which estimate climate sensitivity up to 5.6° C, frequently overestimate recent warming trends (Zelinka et al., 2020; Tokarska et al., 2020). Additionally, current models face a signal-to-noise paradox, where predictable signals are weak compared to internal variability, requiring the use of large ensembles to realize prediction skill (Smith et al., 2020).

*b. Overall advances in **scenario development and use**, including scenarios that limit warming in 2100 to **below 1.5 °C**, relative to pre-industrial times*

Martin et al. (2021):

- **Demand-side measures:** To achieve '**1.5°C lifestyles' compatible with the Paris Agreement**, global per capita emissions need to halve by 2030, with remaining emissions eliminated in the following decade (Ivanova & Wood, 2020). This transition is framed within a '**consumption corridor**' that seeks to balance minimum consumption for human well-being with a maximum limit defined by the available carbon budget (Fuchs et al., 2021).
Research highlights the **deep inequality in responsibility**, indicating that the richest 1% would have to reduce their footprints by a factor of 30 to reach these targets, while the poorest 50% could potentially increase their per capita emissions to meet development needs (Gore, 2020; Oswald et al., 2020). The implementation of such demand-side measures is described as requiring **redistributive mechanisms**, such as equal per capita revenue sharing, to **prevent regressive impacts on low-income groups and to facilitate poverty eradication** while pursuing ambitious climate goals (Soergel et al., 2021).
- Refined uncertainty analyses indicate that the **remaining carbon budget for 1.5° C is smaller than previously estimated**, largely because improved interpretation of historical data has increased the estimate of early-industrial warming by approximately 0.1°C (Morice et al., 2021; Vose et al., 2021; Matthews et al., 2021). Atmospheric carbon uptake must be capped at 440 GtCO₂ from 2020 onwards to maintain even odds of success of **limiting peak warming to 1.5° C requires sustaining annual emission reductions of approximately 5% to reach net-zero by 2040, alongside unprecedented**

cuts in non-CO₂ greenhouse gases and the simultaneous deployment of all mitigation levers at their most ambitious scales (Matthews et al., 2021; Warszawski et al., 2021).

However, these predictions face high uncertainty due to fluctuating non-CO₂ factors (such as the rapid growth of methane and nitrous oxide emissions) and the risk that an individual year could statistically exceed the 1.5° C threshold by 2025 (WMO, 2021; Matthews et al., 2021; Mengis & Matthews, 2020).

*c. Advances in **climate model simulations**, particularly by combining multiple lines of evidence and on a wider range of climate variables to improve parameterization of the physical climate system and understanding of scenarios*

Ospina et al., (2026) and Schaffer et al. (2025):

- **Aerosol-cloud interactions (ACIs) remain the leading source of model uncertainty and transient climate sensitivity**, which is central to reconciling observed and modelled warming (Chen et al., 2024; Forster et al., 2021). Advances in climate simulations require regional models to better differentiate aerosol types and incorporate more accurate sea-surface temperature records to close the gap between models and observations, thereby addressing biases that currently lead to the underestimation of future warming risks (Armour et al., 2024; Quaas et al., 2022).
- To address challenges in climate model simulations, such as those related to representing **aerosol-cloud interactions and cloud feedbacks** (Rantanen & Laaksonen, 2024), advanced modeling protocols like CERESMIP are integrating multiple lines of evidence (specifically observed Earth Energy Imbalance trends) to improve parameterization and reduce the range in climate sensitivity estimates (Myhre et al., 2025; Schmidt et al., 2023). These developments indicate that low climate sensitivity models are unable to reproduce observed EEI trends, and further scrutiny is required of coarse-resolution models that currently cannot adequately represent sub-grid effects such as ship tracks and high-latitude wildfire disturbances (Myhre et al., 2025).

Schaffer et al. (2025):

- Atmospheric methane has exhibited unprecedented high growth rates within the last five years, driven primarily by anthropogenic activities and modified by natural fluxes such as those from tropical wetlands (Jackson et al., 2024; Feng et al., 2023). **These observations are forcing improvements in methane cycle representation**, though current models still face significant challenges in constraining the feedbacks between climate change and natural methane emissions, which risks an underestimation of future biogenic contributions (Shindell et al., 2024). **To address these uncertainties, recent advances combine satellite remote sensing, ground networks, and isotopic analysis with atmospheric modeling to better characterize sources and sinks** (Worden et al., 2023; Saunio et al., 2024). This integration of multiple lines of evidence is critical for closing the gap between models and observations, thereby improving the parameterization of the physical climate system and ensuring that mitigation strategies remain consistent with the 1.5°C Paris Agreement target (Shindell et al., 2024).

*d. Addressing **sensitivities of climate simulations to varying scenarios and parameterizations***

Schaeffer et al., (2025):

- **Global declines in aerosol emissions and atmospheric loadings constitute a critical factor in modern climate simulations**, with the corresponding increase in effective radiative forcing estimated at 0.1 to 0.3 W m⁻² over the 2000–2019 period (Quaas et al., 2022; Schaeffer et al., 2025). Yet **aerosol-cloud interactions (ACIs) remain the dominant source of model uncertainty, complicating efforts to reconcile observed and modeled temperature trends** (Forster et al., 2021).
 - Sensitivities in climate simulations are further affected by biases in sea-surface temperature patterns, which can lead to an underestimation of future warming risks (Armour et al., 2024).

- However, the thermal inertia of the climate system may delay the full warming impact of these air-pollution reductions by two to three decades (Persad et al., 2023; Quaas et al., 2022).

Pihl et al. (2021):

- **The likely range of equilibrium climate sensitivity (ECS) has been narrowed to 2.3–4.5°C** through a comprehensive WCRP analysis that integrated multiple lines of evidence, including process understanding of cloud feedbacks, historical warming records, and paleoclimate data (Sherwood et al., 2020). This represents a step-change in climate model evaluation, particularly as many recent CMIP6 models exhibit a broader range of 1.8 to 5.6°C due to strengthened amplifying feedbacks from low clouds (Zelinka et al., 2020). Because high-sensitivity models (above 4.5°C) often overestimate recent warming trends, they are currently treated with caution (Tokarska et al., 2020).

e. Addressing uncertainties identified in the Intergovernmental Panel on Climate Change (IPCC) Reports (from the Fourth Assessment Report to date)

Martin et al. (2021):

- **Non-CO₂ factors**, including greenhouse gases such as methane and warming aerosols like black carbon, account for approximately 46% of current climate warming (IPCC, 2021). While anthropogenic aerosols provide a significant cooling effect estimated at 0.6–1.6 W/m², **the interaction between aerosols and clouds remains the largest source of uncertainty in current climate forcing assessments** (Bellouin et al., 2020). Refining these uncertainties is essential for determining the remaining carbon budget, particularly as updated historical data reveals that global warming is already 0.1° C higher than previously estimated, and nitrous oxide levels are rising faster than all current IPCC scenarios (Morice et al., 2021; Tian et al., 2020; Matthews et al., 2021).
- See also: ***Abrupt permafrost thaw processes*** (in section C.c)

f. High resolution local and regional climate information, as well as improving the development and application of downscaled regional and sub regional climate models, for understanding risks and implementing climate actions

Martin et al. (2022):

- **Vulnerability hotspots**: Approximately 1.6 billion people reside in regions classified within the highest category of climate vulnerability—areas where populations are projected to double by 2050 (Birkmann et al., 2021). The identification of these regional hotspots relies on data that integrates socioeconomic sensitivity and adaptive capacity with exposure to climate hazards. This regional-scale understanding is enhanced by accounting for local topographic heterogeneity, which influences local climate variability and can alter the timing of climate-induced impacts on biodiversity and human systems (Trew & Maclean, 2021).

g. Advances and gaps in attribution science, including at regional and national scale, as well as attribution of monsoon pattern changes

Schaeffer et al., (2025):

- **Attribution science** has confirmed that anthropogenic drivers, such as aerosol forcing, are significantly altering large-scale systems like the Australian summer monsoon (Fahrenbach et al., 2024). While satellite-based monitoring now allows for the attribution of individual emission sources, substantial research gaps remain regarding aerosol-cloud-precipitation interactions and the feedbacks between

warming and natural methane releases, both of which influence the accuracy of regional risk assessments.

Bustamante et al. (2023):

- **Advances in extreme event attribution have allowed to established links between compound events**, demonstrating that the impacts of these events are more likely to exacerbate one another than singular hazards, largely due to extended recovery timescales (Zscheischler & Lehner, 2022; de Ruiter et al., 2020), expanding scientific understanding of these risks across the ocean and terrestrial ecosystems, identifying how simultaneous stressors can trigger cascading socioeconomic impacts on food security and public services (de Ruiter et al., 2020).

B. Adaptation, loss and damage and extreme events:

a. The evolution and dynamics of extreme events, and early warning systems and climate services

Ospina et al. (2026):

- Record global surface temperatures in 2023/24 and unprecedented global mean sea surface temperatures, reaching 0.6°C above the 1981–2019 baseline (Cheng et al., 2025). This signals a qualitative and potentially accelerating shift in the climate system (Merchant et al., 2025; Rantanen & Laaksonen, 2024). This surge has intensified extreme weather events, including record-breaking heatwaves and the rapid intensification of hurricanes (Choi et al., 2024; Terhaar et al., 2025). As marine heatwaves become more intense and persistent across 65% of the ocean (Capotondi et al., 2024).
- See: **Marine heatwaves (MHW)** (in section C.b)

Schaffer et al. (2025):

- See: **Maternal and reproductive health (MRH)** (section B.e.)

Bustamante et al. (2023):

- **Mountain glacier loss** is accelerating at a rate of 267 ± 16 Gt/year, accounting for nearly one-quarter of observed sea-level rise (Hugonnet et al., 2021). This deglaciation contributes to heightened **water stress for 2 billion people** and **increases the risk of moraine-dammed glacial lake outburst floods (GLOFs)**, which currently threaten approximately 15 million people globally (Taylor et al., 2023; Zheng et al., 2021). While moraine-dammed risks are projected to triple, ice-dammed lake outbursts are showing a decrease in frequency and intensity (Veh et al., 2023). Factual analysis indicates that addressing these impacts on mountain biodiversity and ecosystem functioning requires a shift toward community-driven adaptation and high-resolution climate services that integrate atmospheric and hydrological modeling to support international loss and damage frameworks.
- See also: **Compound extreme events** (in section B.d)

Pihl et al., (2021):

- **Changes in extreme precipitation** are likely to be stronger than changes in mean precipitation, with extreme events increasing in intensity and frequency across all climate regions (Myhre et al., 2019). These shifts heighten water crisis risks by driving scarcity through physical shortages and institutional

supply failures. Evidence indicates that **water stress is amplifying, with aridity projected to increase over 72% of the land area**, particularly affecting the Middle East, North Africa, southern Europe, and Australia (Tabari et al., 2019).

*b. Assessing **adaptation progress**, and the impact of adaptation actions on reducing risks, to inform adaptation planning and action*

Bustamante et al., (2023):

- New approaches for **enhancing justice in adaptation action**, have emerged supported by empirical work on the adaptation justice index and **locally led adaptation (LLA)** (Juhola et al., 2022; Rahman et al., 2023). Justice in adaptation action has emerged as a fundamental condition for effective results. To inform more effective planning, there is a need to address current monitoring gaps and the frequent exclusion of vulnerable populations from policy tools (Ulibarri et al., 2022). The use of '**adaptation rationales**', i.e. impact pathways that link priorities to specific outcome, serves as a foundation for understanding avoiding the worsening of inequalities (Carr & Nalau, 2023) Continuous assessment and intersectional analysis are necessary to shift priorities and prevent maladaptive outcomes in a warming world (Juhola et al., 2022).

Martin et al. (2022):

- By 2020, climate change was already responsible for 37% of **heat-related deaths, and increased heat-related mortality** is observed across every inhabited continent (Vicedo-Cabrera et al., 2021).
- A systematic global stocktake indicates that **existing adaptation efforts are insufficient to adequately reduce risks, as actions remain largely fragmented and incremental** (Berrang-Ford et al., 2021).
- **Limits to adaptation:** Adaptation limits are formally defined as thresholds beyond which adaptive action can no longer secure people or systems from intolerable risks, and evidence indicates that these limits are already being reached in specific vulnerable places (IDow et al. 2013; Thomas et al., 2021).

*c. **Climate impacts across 1.5 °C warming scenarios at local and regional levels***

Ospina et al., (2026):

- Regional disparities in the economic impacts of further global warming are stark: at 3°C of warming, effective labor in high-exposure sectors is projected to decline by 33% in Africa and 25% in Asia (Dasgupta et al., 2024). Further warming of just 1°C is expected to expose over 800 million people in tropical regions to unsafe heat stress, potentially reducing working hours by 50% (Masuda et al., 2024)
- Under a high-emissions scenario, labor productivity losses from heat could result in annual global GDP reductions of 1.4–2.6%, with indirect losses from global supply chain disruptions accounting for 12–43% of total economic losses (Sun et al., 2024). Beyond economic productivity, the climate crisis is driving unprecedented health and water risks, including a surge in dengue fever responsible for up to 40% of cases in some countries in the Americas (Childs et al., 2025) and acceleration in groundwater depletion in critical agricultural zones like northwestern India and the USA due to rising irrigation demands and disrupted aquifer recharge (Jasechko et al., 2024).

Schaffer et al. (2025):

- At a warming level of just 1°C, an estimated >600 million people already live outside the “human climate niche”, a trend accompanied by expanding heat and humid-heat extremes across tropical regions (Lenton et al., 2023). Recent empirical findings indicate that **human thermoregulatory limits**

are reached at wet-bulb temperatures of ~31°C, which is significantly lower than previously theorised (Vecellio et al., 2023).

Bustamante et al. (2023):

- In the context of an impending overshoot of the 1.5°C warming limit, it is important to note that while global temperatures may eventually return to target levels through net-negative emissions, **differentiated impacts emerge under overshoot scenarios, including spatially heterogeneous and potentially irreversible regional changes to ecosystems and biodiversity** (Meinshausen et al., 2022).

d. Understanding of **complex, cascading and transboundary risks**

Ospina et al., (2026) and Bustamante et al. (2023):

- **Climate change and biodiversity loss reinforce one another in a destabilising feedback loop that directly impacts global climate stability** (Pörtner et al., 2023). Current projections indicate that 3–6 million species are threatened even under intermediate warming scenarios (Wiens & Zelinka, 2024), a loss that erodes the carbon storage capacity and ecosystem services required to buffer societies from climate impacts (Weiskopf et al., 2024). These reinforcing feedback loops that undermine both ecosystems and societies, yet these intertwined crises continue to be addressed by separate political, economic, social, and legal institutions (Pörtner et al., 2021).
- These processes contribute to cascading transboundary risks, such as the accelerated depletion of groundwater (Kuang et al., 2024) and the spread of infectious diseases like dengue into temperate and high-altitude regions (Childs et al., 2025). These phenomena result in **cascading impacts that move through interconnected systems**, such as when agricultural failures disrupt energy security, public health, and general social well-being (de Ruiter et al., 2020; Pörtner et al., 2021). Because these **risks are interdependent and transboundary**, effective risk management requires institutional cooperation at scales that reflect the shared nature of the impacts rather than traditional, singular decision-making frameworks (de Ruiter et al., 2020; Pörtner et al., 2021).

Schaffer et al. (2025):

- **Critical infrastructure is increasingly exposed to cascading climate hazards**, where interdependencies between systems like energy distribution, healthcare, and water supply can intensify risks, triggering a domino effect of service failures (Barquet et al., 2024). These vulnerabilities are illustrated by energy system disruptions that progress from isolated local asset damage to widespread, multi-dimensional impacts across interconnected networks, often leading to billion-dollar damages and severe public health repercussions, such as waterborne disease outbreaks (Nyangon & Byrne, 2023). The integration of AI and machine learning into smart grids offers a technological pathway to fundamentally upgrade real-time monitoring and response to these climate-induced disruptions (Nyangon, 2024).

Bustamante et al. (2023):

- **Compound extreme events**, due to their associated longer recovery timescales, are more likely to exacerbate one another compared to singular hazards (Zscheischler et al., 2018), triggering cascading disruptions across socioeconomic systems and critical infrastructure (de Ruiter et al., 2020). To address these intensifying risks, **current climate services are integrating "compound event thinking" to enhance early warning systems and emergency response** (van den Hurk et al., 2023). Robust adaptation requires accounting for these multi-hazard dynamics rather than relying on univariate hazard planning (Schlumberger et al., 2022).
- See also: ***Overshooting +1.5°C and the risk of triggering multiple climate tipping points*** (in section C.d)

Martin et al. (2022):

- **Climate security and conflict risks** constitute a cross-cutting governance challenge, as human security and climate change interact in insidious 'vicious circles' where climate-driven resource scarcity can contribute to violent tensions generate displacement, and result in further cascading social risks such as large-scale infectious disease outbreaks (Adams et al., 2022; Semenza et al., 2022; Buhaug & von Uexkull, 2021; von Uexkull & Buhaug, 2021). Global governance institutions, including the United Nations Security Council, recognise these complex links, noting that the distribution of impacts is heavily influenced by structural inequalities and governance frameworks (Maertens, 2021; Daoudy, 2021; Busby, 2021).

Martin et al. (2021):

- *See also: Interactions among tipping elements can produce cascading non-linear transitions (in section C.d)*

e. Climate risks for vulnerable groups such as Indigenous Peoples, local communities, children and youth, people with disabilities and women

Schaffer et al. (2025):

- **Maternal and reproductive health (MRH):** Excess heat exposure and extreme weather events are directly and indirectly linked to hypertensive complications of pregnancy, increased pregnancy loss, and preterm births (He et al., 2024; Rekha et al., 2024). Impacts of climate change disproportionately affect women, particularly those of colour, low income, and low education, whose challenges are amplified by existing gender and racial discrimination (Jiao et al., 2023; Rekha et al., 2024). These vulnerabilities manifest through direct pathways, such as increased pregnancy loss from floods and doubled miscarriage risks from occupational heat stress, as well as indirect pathways including surges in intimate partner violence (He et al., 2024; Rekha et al., 2024; Zhu et al., 2023).

Bustamante et al. (2023) and Martin et al. (2022):

- **Climate-driven mobility:** There is now "high confidence" and unambiguous evidence that climate impacts are already altering global human mobility patterns (IPCC AR6 WGII, 2022). Without effective intervention, internal migration is projected to accelerate by 2050, particularly in vulnerable regions like sub-Saharan Africa (Clement et al., 2021), with displacement risks potentially increasing by ~50% for every degree of warming (Kam et al., 2021). Climate-driven mobility manifests through various pathways: slow-onset events like desertification often drive rural-to-urban migration (Šedová et al., 2021), while sudden-onset disasters frequently cause temporary internal displacement (Foresight Project, 2011).
- **Involuntary immobility:** Significantly, adverse impacts can also trap the most socio-economically vulnerable populations in place by depleting the resources required to move (Ludolph & Šedová, 2021; Koubi et al., 2022). Involuntary immobility disproportionately affects the poorest populations as climate-driven economic degradation erodes the resources necessary for migration. Analysis indicates that climate change could decrease emigration rates by over 10% among the lowest-income groups by 2100 under medium development and climate scenarios, with potential decreases of up to 35% in pessimistic cases (Benveniste et al., 2022).

Pihl et al. (2021):

- **Water crises disproportionately affect vulnerable populations**, as the impacts of inadequate supply are highly unequal and dictated by pre-existing social inequalities (Craig et al., 2019; Roshan & Kumar, 2020). Within these vulnerable groups, women and girls are particularly affected via negative health outcomes (Pouramin et al., 2020).

See also: **Changes in extreme precipitation** (in section B.a)

C. Ecosystems and nature-based solutions:

a. Opportunities and challenges of implementing **nature-based solutions** in land and ocean systems in support of climate adaptation and mitigation

Ospina et al. (2026):

- Conserving plant and tree diversity functions can enhance ecosystem carbon storage through complementarity and insurance effects, with a potential to reduce emissions by 2–3 Gt C per year (Mori et al., 2021).
 - In land systems, the projected loss of global plant species could lead to the emission of 7–145 PgC in the coming decades, a risk compounded by defaunation which disrupts the growth of high-carbon biomass (Brodie et al., 2025; Weiskopf et al., 2024).
 - In ocean systems, the recovery of baleen whale populations promotes carbon sequestration through biomass and essential nutrient recycling services (Pearson et al., 2024; Savoca et al., 2021).

Implementing these solutions effectively requires a shift in governance; current initiatives often emphasize ecosystem extent over quality and composition, which can lower their effectiveness as carbon sinks (Mori, 2020; Seddon et al., 2019). To optimize results, nature-based solutions should emphasise the protection of entire species interaction networks and biocultural diversity to foster climate-resilient development (Bello et al., 2024; Domeignoz-Horta et al., 2024).

- See also: **Climate change and biodiversity loss reinforce one another** (in section B.d)

Martin et al. (2022):

- See also: **Sustainable land management (SLM)** (in section E.a)

b. Climate change impacts and risks for the **ocean and cryosphere** and related ecosystems

Ospina et al. (2026):

- **Marine heatwaves:** The global mean sea surface temperature for 2024 was 0.6°C warmer than the 1981–2019 baseline (Cheng et al., 2025), reflecting an acceleration in the underlying warming trend detectable over the last decade (Merchant et al., 2025). Marine heatwaves have reached unprecedented intensity and spatial extent, affecting 65% of the global ocean and increasingly occurring in the sub-surface where they intensify more rapidly than surface layers (Capotondi et al., 2024; Guo et al., 2024). These **ocean extremes** have **profound impacts on marine ecosystems**, including the onset of the fourth global coral bleaching event in 2024 and an 8% reduction in global net CO₂ uptake during heatwave periods (Li, Burger, et al., 2024; Reimer et al., 2024). These conditions contribute to the **rapid intensification of hurricanes and record-breaking storms** (Choi et al., 2024).

The **Atlantic Meridional Overturning Circulation (AMOC)** have been discussed in various editions:

- Schaffer et al. (2025): New research indicates that the **AMOC is exhibiting behavior that suggests a potential slowdown or collapse at lower global-warming thresholds than predicted by earlier**

assessments, with evidence suggesting the system is on a tipping course that could reach a tipping point within this century (Ditlevsen & Ditlevsen, 2023; van Westen et al., 2024).

- Martin et al. (2021): **The AMOC has significantly weakened in recent decades** and is currently at its weakest in at least a millennium, with observational evidence indicating an ongoing loss of stability (Boers, 2021; Caesar et al., 2021). Disruption of this circulation constitutes a critical tipping risk because interactions among Earth system elements, such as the Greenland and Antarctic Ice Sheets, can produce cascading non-linear transitions (Wunderling et al., 2021).
- Beyond circulation shifts, the ocean faces a fourfold increase in oxygen loss that expands hypoxia zones and accelerates the emission of potent non-CO₂ greenhouse gases (Oschlies, 2021). Simultaneously, the cryosphere is responding to warming with **accelerating mass loss**, where meltwater from the Northern Hemisphere can raise global sea levels and directly influence the retreat of the Antarctic Ice Sheet (Garbe et al., 2020; Gomez et al., 2020).

Schaffer et al. (2025):

- **El Niño events persistently reduce country-level economic performance**, with historical costs actually estimated much greater than previously understood (Callahan & Mankin, 2023; Liu et al., 2023), as the economic impacts of El Niño persist for at least six years after the initial event, contributing to a projected median loss of USD 33 trillion to the global economy by 2100 under current emissions trajectories (Callahan & Mankin, 2023; Liu et al., 2023);

Bustamante et al. (2023):

- **Mountain glacier loss** is accelerating at a rate of 267 ± 16 Gt/year, accounting for nearly one-quarter of observed sea-level rise (Hugonnet et al., 2021). Globally, glaciers are projected to lose between 26% (+1.5°C) to 41% (+4°C) of their current volume by 2100 (Rounce et al. 2023). Mountain glaciers will continue to be one of the primary contributors to **sea-level rise** throughout the 21st century. Insight 7: Glaciers are losing 267 ± 16 Gt/year with clear acceleration; under +4°C, glaciers could lose 41% of their current volume by 2100.

c. Emissions and removals from terrestrial ecosystems, and information on ecosystems with high-carbon reservoirs

Terrestrial carbon sinks have been discussed in various editions:

- Ospina et al., (2026): The **northern permafrost region has shifted to a net carbon source** of 0.14 GtC/yr over decadal time scales (2000–2020), while the record temperatures and extreme events of 2023 caused the global natural land carbon sink to decline sharply from 3.9 GtC/yr in 2022 to 2.3 GtC/yr (Friedlingstein et al., 2025; Hugelius et al., 2024). High-carbon reservoirs like boreal forests are showing significant strain, with carbon uptake declining by 36% in recent decades due to intensifying disturbances such as insect outbreaks and record-breaking wildfire emissions, which alone reached 0.65 GtC in the Canadian boreal in 2023 (Byrne et al., 2024; Pan et al., 2024). Now, 30% of the Arctic-boreal zone is now a net CO₂ source, and northern extra-tropical ecosystems are seeing a transition from biomass growth to decline (Virkkala et al., 2025). As a weakening land sink implies that a larger fraction of human emissions will remain in the atmosphere, current trajectories lead to higher warming than previously estimated (Burton et al., 2024).
- Bustamante et al. (2023): Evidence is mounting that the **rate of increase in the land carbon sink has slowed**, with sparse but strong data indicating that terrestrial ecosystems are changing more rapidly than anticipated (Chandra et al., 2022; Friedlingstein et al., 2022). This trend is driven by destabilising climate stressors, including concurrent hot-dry extremes and human disturbances that threaten to

transition key reservoirs, such as the tropics and Canadian boreal forests, from carbon sinks into net sources (Gatti et al., 2021; Hubau et al., 2020; Liu et al., 2023b). Ultimately, the **risk that current models overestimate future sink capacity**, and hence also the remaining carbon budgets.

- Martin et al. (2021): Parts of the Amazon rainforest have already transitioned into a net carbon source (Ciemer et al., 2021; Gatti et al., 2021; Gomez et al., 2020).
- Pihl et al., (2021): Land ecosystems remove approximately 30% of anthropogenic CO₂ emissions, providing a critical natural sink that has more than doubled since 1960 (Friedlingstein et al., 2019). However, evidence indicates that tropical forest sinks are reaching saturation, largely due to land-use change and the physiological limits of CO₂ fertilization in nutrient-constrained environments (Hubau et al., 2020). High-carbon reservoirs are facing additional risks: abrupt permafrost thaw is projected to release twice as much carbon as gradual thaw models suggest, potentially shifting vast peatland regions into net methane sources (Hugelius et al., 2020; Turetsky et al., 2020). Furthermore, soil carbon loss is being amplified by rhizosphere priming, a root-driven feedback that could lead to an additional 40 PgC emission this century (Keuper et al., 2020).

Pihl et al. (2021):

- **Abrupt permafrost thaw processes** are projected to approximately double cumulative carbon emissions compared to estimates of gradual thaw alone, representing a major uncertainty as these thermokarst-inducing processes are largely excluded from current global climate models (Turetsky et al., 2020; Gasser et al., 2018). This carbon release is further amplified by rhizosphere priming effects, which may add an estimated 40 PgC of soil carbon loss by 2100, a biological feedback that remains omitted from standard climate simulations (Keuper et al., 2020). Such findings, alongside these revised data points on permafrost stability imply tighter restrictions on the remaining anthropogenic carbon emission budgets required to limit warming (Nitzbon et al., 2020). This, along with the narrowing of the Equilibrium Climate Sensitivity (ECS) range to 2.3–4.5°C (described before), indicate that moderate emission scenarios are less likely to meet Paris Agreement targets than previously assumed (Sherwood et al., 2020).

d. The vulnerability of natural and human ecosystems (including their interactions and associated tipping points), and strengthening their resilience, particularly for the most vulnerable systems

Schaffer et al. (2024):

- The Amazon hosts ~10% of Earth's terrestrial biodiversity, yet climate change and the deforestation of 18% of its cover are synergistically pushing the system toward a systemic tipping point. Growing concern centers on a potential systematic collapse triggered by self-reinforcing feedback loops, with 40% of the remaining forest already degraded and some regions transitioning from carbon sinks to net sources (Flores et al., 2024; Gatti et al., 2023). Resilience in the face of these disturbances is strengthened by maintaining rich functional diversity and integrating Indigenous and traditional knowledge into adaptation strategies, including the restoration of nutrient-rich soils (Levis et al., 2024; Sakschewski et al., 2016; Doughty et al., 2023).
- See also: **Atlantic Meridional Overturning Circulation (AMOC)** (in section: C.b)

Bustamante et al. (2023):

- **Overshooting the 1.5°C global warming limit severely increases the risk of triggering multiple climate tipping points**, which would cause irreversible impacts on life on Earth (Armstrong McKay et

al., 2022; Meyer et al., 2022). The probability of triggering devastating "tipping cascades" increases severely with each fraction of a degree of overshoot, necessitating integrated international policy and anticipatory action (Wunderling et al., 2023).

Martin et al. (2022):

- See: **Vulnerability hotspots** (in section A.f)
- See: **Limits to adaptation** (in section B.b)

Martin et al. (2021):

- **2021: Interactions among tipping elements can produce cascading non-linear transitions**, effectively creating "climate domino effects" where one tipping event triggers the next (Wunderling et al., 2021). The probability of triggering these cascades increases strongly between 1°C and 3°C of global warming, making every fraction of a degree vital for preventing systemic Earth system instability that threatens human societies and biosphere integrity (Wunderling et al., 2021). These cascades link geographically distant systems; for example, Greenland meltwater can weaken the Atlantic Meridional Overturning Circulation (AMOC), further resulting in inter-hemispheric heat redistribution which may alter precipitation over the Amazon rainforest (Caesar et al., 2021; Ciemer et al., 2021; Gomez et al., 2020).

D. Mitigation and related technologies, and greenhouse gas (GHG) emissions and reporting:

a. GHG emissions by sources, removals by source and all reservoirs

Schaffer et al. (2024):

- **Atmospheric methane levels have surged since 2006**, with concentrations currently tracking warming scenarios of 3°C or more (Rogelj & Lamboll, 2024). Anthropogenic sources, primarily from agriculture, waste, and fossil fuel use, account for 63–68% of total methane emissions, yet only about 13% of these emissions are currently covered by mitigation policies (Jackson et al., 2024; Saunio et al., 2024). Without rapid reductions in methane emissions, the remaining carbon budget to meet the Paris Agreement temperature limits will be finished (Rogelj & Lamboll, 2024).

Bustamante et al. (2023):

- **Fossil fuels** account for close to 90% of global CO₂ emissions, yet government subsidies for their production and use reached an all-time high of 1 trillion USD in 2022 (Friedlingstein et al., 2022; IEA, 2023). This financial support persists despite evidence that emissions from already-existing infrastructure exceed the remaining carbon budget for 1.5°C, creating a "production gap" that threatens climate targets (Tong et al., 2019; Trout et al., 2022). A managed and equitable **fossil fuel phase-out** is necessary to address "**carbon lock-in**" and prevent trillions of dollars in stranded assets. To meet the Paris Agreement, **global food systems**, responsible for ~31% of global emissions, must also be transformed, alongside a massive scale-up of carbon dioxide removal (CDR).

Martin et al. (2021):

- About 46% of current climate warming (representing 21% of net warming) is caused by factors other than carbon dioxide, including greenhouse gases such as methane and nitrous oxide, their precursors, and warming aerosols like black carbon. These **non-CO₂ factors** represent the largest source of

uncertainty in the remaining carbon budget, making updated and comprehensive emission inventories essential, particularly as nitrous oxide is accumulating faster than all current IPCC scenarios due to agricultural fertilizer use (Tian et al., 2020).

b. Opportunities, risks and costs associated with the deployment and upscaling of carbon dioxide removal (CDR) technologies and options

Ospina et al. (2026) and Bustamante et al. (2023):

- Current carbon dioxide removal (CDR) deployment is approximately 2 Gt CO₂/yr, consisting primarily of conventional methods such as afforestation and reforestation (Smith et al., 2024; Forster et al., 2024). Due to **severe sustainability constraints**, including competition for land use, food production, and high energy and material demands, **achievable CDR capacity** is estimated to be sufficient only to compensate for residual emissions from truly hard-to-abate sectors serving critical needs, such as livestock and international aviation (Gidden et al., 2024; Shindell & Rogelj, 2025; Edelenbosch et al., 2024).
- A significant '**CDR gap**' exists between current national plans, which propose only 0.05 to 0.53 Gt CO₂/yr in additions by 2030, and the significantly higher deployment levels required by Paris-consistent scenarios (Lamb, Schleussner et al., 2024; Lamb, Gasser et al., 2024). While conventional land-based CDR is widely practiced, 'novel' CDR methods (such as BECCS and DACCS) currently contribute only 0.1% of removals and face major challenges in up-scaling, accounting, and potential trade-offs with sustainable development goals (Fuss et al., 2018; Smith et al., 2023).
- Furthermore, the **reliability of carbon removals** is also challenged by the fact that global emissions from deforestation and peat fires (~4.4 Gt CO₂/yr) still significantly outweigh current carbon removal in the land sector (Forster et al., 2024; Friedlingstein et al., 2025). While nature-based removal approaches are subject to **reversal risks** from intensifying disturbances such as wildfires and have been shown in some instances to overestimate actual carbon sequestration (Smith et al., 2024).
- Beyond these residual needs, a '**preventive CDR capacity**', which could require as much as 400 Gt CO₂ by 2100, is identified as necessary to address overshoot and hedge against physical climate uncertainties and stronger-than-expected Earth system feedbacks (Schleussner et al., 2024; Lamb, Schleussner et al., 2024).

c. Role of CDR in meeting Paris Agreement goals and linkage with attaining sustainable development

Ospina et al., (2026):

- Current national plans reveal a significant '**CDR gap**,' as countries propose only 0.05 to 0.53 Gt CO₂/yr in CDR additions by 2030 in their NDCs and 1.5 to 1.9 Gt CO₂/yr by 2050 in long-term strategies, both of which fall short of the levels required by **Paris-compatible 1.5° C pathways** (Lamb, Gasser et al., 2024; Lamb, Schleussner et al., 2024).
- While CDR is essential to balance residual emissions from hard-to-abate sectors like aviation and livestock (Edelenbosch et al., 2024; Shindell & Rogelj, 2025), its deployment is limited by **sustainability constraints** related to land use, food security, and energy demands (Gidden et al., 2024; Deprez et al., 2024).

- **These findings indicate that achieving climate goals depends on stringent near-term emissions reductions to minimize CDR dependence while ensuring removals are reserved for the most critical societal needs** (Shindell & Rogelj, 2025)

Bustamante et al. (2023)

- Returning to 1.5°C after overshooting will require unprecedented levels of Carbon Dioxide Removal (CDR). But a significant "**CDR gap**" exists between current national plans and the gigaton-scale deployment required by Paris-compliant scenarios (Smith et al., 2023). Ambitious pledges and early policy support that prioritizes a "**like-for-like**" **approach**: ensuring fossil emissions are countered by durable storage while maintaining a primary focus on the rapid phase-out of fossil fuels (Allen et al., 2022).

*e. Implications of different **emission metric choices** towards climate change policies*

- See: **Atmospheric methane** (in section D.a)
- See: **Non-CO2 factors** (in section A.e)

E. Cross cutting

a. Synergies and trade-offs between mitigation, adaptation and Sustainable Development Goals and the consideration of equity

Schaffer et al. (2024):

- **Climate-resilient development in cities** requires a Social-Ecological-Technological Systems (SETS) approach to simultaneously identify and integrate co-benefits across urban adaptation and mitigation while addressing developmental and sustainability concerns (Chester et al., 2023; McPhearson et al., 2022; Sharifi, 2023). By moving beyond one-dimensional technological solutions, which can create maladaptive feedback loops and exacerbate social injustices, cities can utilize integrated approaches (e.g., green and blue infrastructure, Sharifi, 2023; Sharifi, 2021). Integrating SETS allows planners to minimize trade-offs, such as "green gentrification" or the exclusion of vulnerable residents in informal settlements, thereby fostering synergies between mitigation, adaptation, and Sustainable Development Goal (SDG) equity (Aboagye & Sharifi, 2024; McPhearson et al., 2022; Sharifi, 2023)
- **Public acceptance of climate policy depends critically on perceived fairness**, and a successful climate transition cannot be achieved through top-down implementation (Bergquist et al., 2022; Schaeffer et al., 2025). Acceptability is driven by both distributive fairness, i.e., the equitable sharing of economic costs, and procedural fairness, which requires that citizens are not excluded from the decision-making process (Maestre-Andrés et al., 2019; Schaeffer et al., 2025). Resistance often stems from job insecurity, social justice concerns, and a lack of trust in the state, yet it can also serve as a vital form of political participation that highlights the overlooked needs of marginalized and vulnerable groups (Brink et al., 2023; Vargas Falla et al., 2024). To foster popular acceptance, policies must be tailored to local cultural and economic conditions and utilize mechanisms like revenue recycling to offset unfair impacts through social programs (Harring et al., 2023; Jones & Cardinale, 2023). Ultimately, overcoming resistance requires inclusive approaches to

governance to ensure the transition is both sustainable and socially just (Biresselioglu et al., 2024).

Bustamante et al. (2023):

- **Adaptation justice** is a foundational requirement for effective climate action, as current opportunities are unevenly distributed and frequently fail to consider the most vulnerable and marginalized populations (Araos et al., 2021). To avoid maladaptation, climate strategies must integrate a **multidimensional justice lens**, i.e. addressing distributive, restorative, and epistemic concerns, while prioritizing locally led adaptation that empowers local communities (Juhola et al., 2022; Orlove et al., 2023).
- **Just transitions in the food sector:** In the same way as the notion of just transitions has emerged to enable the transformation of energy systems, it is also increasingly understood as central for the transformation of food systems (Tribaldos & Kortetmäki, 2022) **Justice-centred approaches for food system transformations** (Woodhill et al., 2022) imply balancing urgent mitigation and adaptation needs with the Sustainable Development Goals (SDGs), as high ambition in one area can inadvertently harm food security, biodiversity, or human rights (Seddon et al., 2021) Because "moderate ambition across all targets may achieve balance, but high ambition for just one results in lower achievement of others" (Arneeth et al., 2023), policy must prioritize synergistic approaches that minimize negative trade-offs. Realizing the full mitigation potential of food systems is only possible if governance processes are reformed to address power asymmetries, curb corporate influence, and implement inclusive, participatory decision-making that empowers smallholders and Indigenous communities (McGreevy et al., 2022).

Martin et al. (2022):

- **Inclusive and empowering decision-making is essential for just and effective climate policy**, as it serves as a critical enabler for climate-resilient development—the integration of mitigation and adaptation actions to advance sustainable development (Bussu et al., 2022; Falzon, 2021). Because high ambition in one sector can inadvertently harm others, meaningful involvement that addresses power asymmetries and historical injustices is vital (Sultana, 2022). Integrating diverse knowledge systems, such as Indigenous and local knowledge, helps prevent "one-size-fits-all" solutions and allows for the identification of synergistic opportunities, such as climate-resilient soil management that provides both mitigation and adaptation benefits (Rarai et al., 2022).
- **Sustainable land management (SLM)** as the land system currently accounts for approximately 22% of global GHG emissions; consequently, a radical transformation of these systems is required to meet 2050 net-zero goals. Well-executed SLM offers synergistic benefits, including such as climate-resilient soils and enhanced biodiversity—poorly planned initiatives, particularly in reforestation, risk increasing CO₂ emissions and marginalizing local communities (Di Sacco et al., 2021; Lal et al., 2021a).

Pihl et al., (2021):

- **Climate mitigation provides immediate health co-benefits** and support adaptation efforts (Karlsson et al., 2020). For instance, reducing local air pollution through strategies like urban electrification delivers direct gains for human health and quality of life (Rauner et al., 2020; Romero-Lankao et al., 2019). These integrated approaches act as "win-win" policies, concurrently tackling the causes of

climate change while helping to align mitigation and adaptation with the Sustainable Development Goals (SDGs) (Nagabhatla et al., 2020). Fostering healthy, sustainable lifestyles and protecting blue and green spaces can improve mental health and emotional resilience, forming a core component of equitable climate-resilient development.

- There is growing evidence that changing climatic conditions are adversely affecting **mental health**, including states of emotional resilience and psychosocial well-being (Basu et al., 2018; Hayes, Berry & Ebi, 2019). Impacts from these shifting conditions are expanding across clinical disorders like anxiety, depression, and post-traumatic stress disorder (PTSD), as well as emerging phenomena such as eco-anxiety and solastalgia (Cianconi et al., 2020; Clayton, 2020; Wu et al., 2020).

*b. Contribution of **Indigenous and traditional knowledge** towards understanding climate change and its consequences*

Schaffer et al. (2024):

- The Amazon is a complex system hosting more than 400 ethnicities of Indigenous peoples and local communities whose traditional ecological practices, such as creating nutrient-rich soils and food forests, demonstrably enhance functional diversity and improve forest resilience (Science Panel for the Amazon, 2021; Levis et al., 2024). This **biocultural and ecological diversity** serves as a vital safeguard that can bolster the Amazon against climate change and mitigate the risk of a systemic tipping point (Flores et al., 2024). Current evidence indicates that the long-term resilience of these ecosystems depends on the integration of **Indigenous and traditional knowledge** alongside technical conservation efforts, particularly through "social-ecological hotspots" and community-based conservation initiatives where local populations are empowered with autonomous decision-making (Levis et al., 2024; Science Panel for the Amazon, 2021).

Indigenous territories act as buffers against deforestation and are central to a new socio-bioeconomy that values biodiversity while supporting local livelihoods and human rights (Almada et al., 2024; Flores et al., 2024). Ultimately, the presence of rich functional diversity, stabilized by traditional governance and ways of life, is essential for maintaining forest productivity and Earth system stability (Sakschewski et al., 2016; Levis et al., 2024).

*c. **Other research activities** relevant for and aimed at supporting work under the Convention and Paris Agreement such as the Nairobi Work Programme*

Ospina et al. (2026):

- **Carbon credit markets face persistent integrity challenges** that act as a cross-cutting concern for the effectiveness of climate action. A systematic analysis of nearly one billion tons of carbon credits revealed that less than 16% represented actual emission reductions, highlighting systemic flaws where many projects achieve lower reductions than claimed or provide no statistically significant climate benefits (Probst et al., 2024; Gill-Wiehl et al., 2024). These integrity issues undermine market credibility and risk delaying direct decarbonization, as many corporate buyers rely on low-quality avoidance credits without transparently disclosing their role in GHG accounting (Trencher et al., 2024; Green et al., 2024). Developing MRV protocols via SBSTA and SBI and establishing quality benchmarks for Article 6 international standards to ensure that nature-based removals do not serve as a substitute for fossil-fuel cuts (Allen et al., 2025).

- A global, systematic evaluation of 1,500 climate policy measures in 41 countries identifies 63 successful cases of large emissions reductions averaging a 19% cut, demonstrating that **reductions matching zero-emissions targets are possible if effectively scaled** (Stechemesser et al., 2024). Empirical evidence indicates that **carefully designed policy mixes frequently outperform standalone instruments** by addressing multiple market failures and maximizing credibility to shape investor and consumer expectations (Blanchard et al., 2023; Dolphin et al., 2023; Stechemesser et al., 2024). For instance, integrating pricing instruments (such as carbon taxes or reduced fossil fuel subsidies) often serves as the essential complement that enables significant reductions when paired with regulatory measures like performance standards, bans, or building codes (Dimanchev & Knittel, 2023; Stechemesser et al., 2024). While the most effective mixes vary significantly by sector, country context, and stage of economic development, they are **typically designed to balance emissions cuts with broader objectives, including distributional equity, energy security, and innovation** (Blanchard et al., 2023; Edmondson et al., 2025; Stechemesser et al., 2024).

Schaffer et al. (2025):

- Recent research indicates that 54% of ETM projects are located on or near Indigenous lands, and global mining waste from these minerals is projected to reach 2,000 Gt by 2050 (Owen et al., 2022; Valenta et al., 2023). **Governance of energy-transition minerals (ETMs)** functions as a cross-cutting issue that connects decarbonisation targets with geopolitics, Indigenous rights, and environmental stewardship (IRENA, 2023).

Martin et al. (2022):

- Finance flows function as a critical cross-cutting enabler for deep mitigation, with climate finance growing to an average of US\$632 billion in 2019–2020 (Buchner et al., 2021). However, evidence indicates that **private sector sustainable finance practices** are currently not influencing the real economy to the degree required to catalyse rapid transitional changes (Ahlström & Monciardini, 2022; de Cunha et al., 2021). This lack of impact is exacerbated by **data gaps in climate disclosure** and a 'greenwashing endemic' that masks actual environmental performance (Kölbel et al., 2020).

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SBSTA Call*: Research and Systematic Observation

Research theme as per FCCC/SBSTA/2025/L.5	Pertinent IDOS research (title)	Year	Publication details	Keywords	IDOS authors and contacts
(a) Global warming leading to multiple hazards, including on the land and in the hydrosphere (including oceans) and cryosphere; this can increase compounding climate risks related to sea level rise, declining inland water levels, biodiversity and ecosystems, water security, food security, floods, drought and desertification, and health, reinforcing the importance of enhancing adaptation and adaptive capacities, mitigation, climate resilience, and averting, minimizing and addressing loss and damage	Empowering global water governance: taking the 2023 UN Water Conference outcomes forward to address the current water crises	2025	<i>Water International</i> 50 (1), 4-10 https://www.tandfonline.com/doi/full/10.1080/02508060.2025.2452108	WEFE-Nexus, multilevel governance, climate change, adaptation, water governance	Ines Dombrowsky, Ines.Dombrowsky@idos-research.de Elke Herrfahrtd-Pähle, Elke.Herrfahrtd@idos-research.de Annabelle Houdret, annabelle.houdret@idos-research.de
	Time in and for nature-based solutions: no quick fix solutions for complex ecological and social processes	2025	<i>Nature-Based Solutions</i> 7, article 100219; https://doi.org/10.1016/j.nbsj.2025.100219	Biodiversity and ecosystems, enhancing adaptation and adaptive capacities, mitigation, climate resilience, governance	Steffen Bauer steffen.bauer@idos-research.de Jean Carlo Rodriguez jean.rodriguez@idos-research.de Jonas Hein jonas.hein@idos-research.de
	Impacts and synergies of weather index insurance and microcredit in rural areas: a systematic review	2022	<i>Environmental Research Letters</i> 17 (10), article 103002; https://doi.org/10.1088/1748-9326/ac9244	Climate risks, floods, drought, enhancing adaptation and adaptive capacities, climate resilience, loss and damage	Mariya Aleksandrova mariya.aleksandrova@idos-research.de
	Reaching the poorest and most vulnerable: addressing loss and damage through social protection	2021	<i>Current Opinion in Environmental Sustainability</i> 50, 121-128; https://doi.org/10.1016/j.cosust.2021.03.010	Climate risks, averting, minimizing and addressing loss and damage, social protection	Mariya Aleksandrova mariya.aleksandrova@idos-research.de

*„Research and scientific organizations are invited to submit information on how their research is addressing research needs and gaps identified under the SBSTA since June 2005, by 15 April 2026“; c.f. [Research and Systematic Observation | UNFCCC](#), last accessed 14 April 2026.

	Working together to achieve the Paris climate goals and sustainable development: international climate cooperation and the role of developing countries and emerging economies	2021	Report, German Development Institute, Bonn; https://doi.org/10.23661/r1.2021	Sustainable development, climate policy, international cooperation, mitigation, climate resilience	Steffen Bauer steffen.bauer@idos-research.de Clara Brandi clara.brandi@idos-research.de Jean Carlo Rodriguez jean.rodriguez@idos-research.de Srinivasa Srigiri srinivasa.srigiri@idos-research.de
	Household Vulnerability to Climate Change and Identification of Target Beneficiaries to Implement Household-Specific Adaptation Strategies: A Quantitative Assessment	2021	<i>Asian Journal of Agriculture and Development</i> , 18(1362-2022-003), 17-34 https://doi.org/10.37801/ajad2021.18.2.p2	Climate change, household vulnerability, semi-arid tropics, cluster analysis, adaptation strategies	Srinivasa Srigiri srinivasa.srigiri@idos-research.de
	Principles and considerations for mainstreaming climate change risk into national social protection frameworks in developing countries	2019	<i>Climate and Development</i> 12 (6), 511-520; https://doi.org/10.1080/17565529.2019.1642180	Climate risks, enhancing adaptation and adaptive capacities, climate resilience, social protection	Mariya Aleksandrova mariya.aleksandrova@idos-research.de
	Social protection as a tool to address slow onset climate events: emerging issues for research and policy	2019	Discussion Paper 16/2019, German Development Institute, Bonn; https://doi.org/10.23661/dp16.2019	Climate risks, sea level rise, drought, enhancing adaptation and adaptive capacities, climate resilience, social protection	Mariya Aleksandrova mariya.aleksandrova@idos-research.de

	Non-economic losses from climate change: opportunities for policy-oriented research	2017	<i>Climate and Development</i> 10 (2), 97-101; https://doi.org/10.1080/17565529.2017.1372268	Climate risks, climate resilience, averting, minimizing and addressing loss and damage, research gaps	Steffen Bauer steffen.bauer@idos-research.de
	Aligning climate change mitigation and sustainable development under the UNFCCC: a critical assessment of the Clean Development Mechanism, the Green Climate Fund and REDD+	2017	Report, German Development Institute, Bonn; https://www.idos-research.de/fileadmin/migratedNewsAssets/Files/Study__96.pdf	Mitigation, adaptation, resilience, sustainable development	Jonas Hein jonas.hein@idos-research.de
(b) Advances and gaps in attribution science, and particularly the need to improve climate attribution at the national and regional level, such as monsoon pattern changes	--	--	--	--	--
(c) Research needs and gaps in the modelling of sustainable development in mitigation pathways, including the consideration of equity and justice, while recognizing ongoing and encouraging further efforts to address these	Climate futures require politics	2026	<i>Nature Communications</i> (accepted, forthcoming)	Scenario development; climate scenarios	Julia Leininger Julia.Leininger@idos-research.de
	Political inequality and impacts on climate mitigation: the case of Germany's energy sector	2025	<i>Applied Energy</i> 393, article 125928 https://doi.org/10.1016/j.apenergy.2025.125928	Mitigation pathways, energy transition, inequality	Ines Dombrowsky ines.dombrowsky@idos-research.de

In the name of justice: the case of riverine dwellers and the restoration of the Matanza Riachuelo River, Argentina	2025	<i>Journal of Latin American Geography</i> 24 (2), 102-129 https://doi.org/10.1353/lag.2025.a971717	Restoration, adaptation, justice, rivers	Jean Carlo Rodriguez jean.rodriguez@idos-research.de
Unlearning modernity? A critical examination of the Intergovernmental Panel on Climate Change (IPCC)	2025	<i>Climatic Change</i> , 178(2), 32. https://doi.org/10.1007/s10584-025-03866-y	Research institutions, equity, justice, climate policy	Anna-Katharina Hornidge Anna-katharina.hornidge@idos-research.de Niklas Wagner Niklas.wagner@idos-research.de
Policy mixes for sustainable development pathways: representation in integrated assessment models	2024	<i>Environmental Research Letters</i> 20, article 014030 https://doi.org/10.1088/1748-9326/ad993a	Sustainable development pathways, mitigation pathways, policy mixes, integrated assessment modelling	Ines Dombrowsky ines.dombrowsky@idos-research.de
Multiple pathways towards sustainable development goals and climate targets	2024	<i>Environmental Research Letters</i> 19, article 124009 https://doi.org/10.1088/1748-9326/ad80af	Sustainable development pathways, mitigation pathways, integrated assessment modelling	Ines Dombrowsky ines.dombrowsky@idos-research.de
Three foci at the science-policy interface for systemic Sustainable Development Goal acceleration	2024	<i>Nature Communications</i> 15, article 8600, https://doi.org/10.1038/s41467-024-52926-x	SDG interactions, SDG modeling, SDG tools, science-policy interface	Julia Leininger Julia.Leininger@idos-research.de Christopher Wingens Christopher.Wingens@idos-research.de
Climate Futures are Political Futures: Integrating Political	2024	<i>Preprint Version. Zenodo.</i> https://doi.org/10.5281/zenodo.14387075	Scenario analysis; SSPs; political development	Julia Leininger Julia.Leininger@idos-research.de

	Development Into the Shared Socioeconomic Pathways (SSPs)				Christopher Wingens Christopher.Wingens@idos-research.de
	<i>More than policy neutral: Justifying the power of science-policy interfaces through legitimacy.</i>	2024	<i>Earth System Governance</i> , 21, 100219. https://doi.org/10.1016/j.esg.2024.100219	Legitimacy, procedural justice and equity, research needs	Niklas Wagner Niklas.wagner@idos-research.de
	<i>Effectiveness factors and impacts on policymaking of science-policy interfaces in the environmental sustainability context.</i>	2023	<i>Environmental Science & Policy</i> , 140, 56–67. https://doi.org/10.1016/j.envsci.2022.11.008	Research institutions, sustainable development equity, justice, climate policy	Niklas Wagner Niklas.wagner@idos-research.de
	Defining a sustainable development target space for 2030 and 2050	2022	<i>One Earth</i> 5 (2), 142-156 https://doi.org/10.1016/j.oneear.2022.01.003	Scenario analysis, sustainable development goals, indicators	Julia Leininger Julia.Leininger@idos-research.de Armin von Schiller Armin.Schiller@idos-research.de
	Introduction to the special issue “Climate and marine justice – debates and critical perspectives”	2021	<i>Geographica Helvetica</i> 76, 305–314; https://doi.org/10.5194/gh-76-305-2021	Equity, justice, mitigation, adaptation	Jonas Hein jonas.hein@idos-research.de
	Post-conflict transition and REDD+ in Colombia: Challenges to reducing deforestation in the Amazon	2021	<i>Forest Policy and Economics</i> 127, article 102450; https://doi.org/10.1016/j.forpol.2021.102450	Mitigation, equity, justice	Jean Carlo Rodriguez jean.rodriguez@idos-research.de Jonas Hein jonas.hein@idos-research.de
	A sustainable development pathway for climate action within the UN 2030 Agenda	2021	<i>Nature Climate Change</i> 11 (8), 656–664 : https://doi.org/10.1038/s41558-021-01098-3	Sustainable development pathway; integrated assessment modelling; climate mitigation; scenario analysis	Julia Leininger Julia.Leininger@idos-research.de Christopher Wingens Christopher.Wingens@idos-research.de

Achievements and needs for the climate change scenario framework	2020	<i>Nature Climate Change</i> 10, 1074–1084 https://doi.org/10.1038/s41558-020-00952-0	Scenario analysis, integrated assessment modelling	Julia Leininger Julia.Leininger@idos-research.de
Innovations for sustainability: pathways to an efficient and sufficient post-pandemic future	2020	3 rd report prepared by <i>The World in 2050 Initiative</i> (TWI2050), Laxenburg: International Institute for Applied Systems Analysis https://doi.org/10.22022/TNT/07-2020.16533	Pathways, sustainable development, governance	Anita Breuer Anita.Breuer@idos-research.de Julia Leininger Julia.Leininger@idos-research.de Christopher Wingens Christopher.Wingens@idos-research.de
The transnationalisation of competing state projects: carbon offsetting and development in Sumatra's coastal peat swamps	2018	<i>Antipode</i> 50(4), 953-975; https://doi.org/10.1111/anti.12381	Mitigation, equity, justice	Jonas Hein jonas.hein@idos-research.de
Deforestation and the Paris climate agreement: an assessment of REDD+ in the national climate action plans	2018	<i>Forest Policy and Economics</i> 90, 7-11; https://doi.org/10.1016/j.forpol.2018.01.005	Mitigation, equity, justice	Jonas Hein jonas.hein@idos-research.de
Political ecology of REDD+ in Indonesia agrarian conflicts and forest carbon	2018	Abingdon, New York: Routledge; https://doi.org/10.4324/9781351066020	Mitigation, equity, justice	Jonas Hein Jonas.hein@idos-research.de
Why equity is fundamental in climate change policy research	2017	<i>Global Environmental Change</i> 44, 170-173; https://doi.org/10.1016/j.gloenvcha.2016.08.002	Research needs, climate policy, governance, institutions, equity and justice	Steffen Bauer steffen.bauer@idos-research.de

(d) Advances and research needs and gaps in knowledge and methodologies related to assessing the impact of adaptation action on reducing risk, to inform adaptation planning and action, particularly in developing countries	A theory of change approach to enhance the post-2030 sustainable development agenda	2026	<i>Science</i> 391 (6782), 241-244; https://doi.org/10.1126/science.adz5704	Methodology to measure impact of SDGs, including SDG 13	Julia Leininger Julia.Leininger@idos-research.de
	Adapting to Uncertainty: Knowing Shifting Sands and Blue Infrastructure in Unpredictable Seas	2025	<i>Geo: Geography and Environment</i> 12, no. 2: e70041. https://doi.org/10.1002/geo2.70041	Adaptation, reducing risk, adaptation planning	Jonas Hein Jonas.hein@idos-research.de
	Unlocking climate finance for social protection: an analysis of the Green Climate Fund	2024	<i>Climate Policy</i> 24 (7), 878-893; https://doi.org/10.1080/14693062.2024.2338817	Climate risk management, social protection, adaptation action, adaptation planning	Mariya Aleksandrova mariya.aleksandrova@idos-research.de Daniele Malerba daniele.malerba@idos-research.de
	Impacts and synergies of weather index insurance and microcredit in rural areas: a systematic review	2022	<i>Environmental Research Letters</i> 17 (10), article 103002; https://doi.org/10.1088/1748-9326/ac9244	Climate risks, floods, drought, enhancing adaptation action, adaptation planning, climate resilience	Mariya Aleksandrova mariya.aleksandrova@idos-research.de
	Groundwater governance through institutional bricolage? Participation in Morocco's Chtouka aquifer contract	2022	<i>Water International</i> 47 (4), 565-582 https://www.tandfonline.com/doi/full/10.1080/02508060.2022.2049545	Groundwater management, adaptation governance, participation, MENA region, critical institutionalism	Annabelle Houdret Annabelle.houdret@idos-research.de
	Reaching the poorest and most vulnerable: addressing loss and damage through social protection	2021	<i>Current Opinion in Environmental Sustainability</i> 50, 121-128; https://doi.org/10.1016/j.cosust.2021.03.010	Climate risks, adaptation planning & action, social protection	Mariya Aleksandrova mariya.aleksandrova@idos-research.de

	Working together to achieve the Paris climate goals and sustainable development: international climate cooperation and the role of developing countries and emerging economies	2021	Report, German Development Institute, Bonn; https://doi.org/10.23661/r1.2021	Sustainable development, climate policy, international cooperation, adaptation action, climate resilience	Steffen Bauer steffen.bauer@idos-research.de Clara Brandi clara.brandi@idos-research.de Jean Carlo Rodriguez jean.rodriguez@idos-research.de Srinivasa Srigiri srinivasa.srigiri@idos-research.de
	Principles and considerations for mainstreaming climate change risk into national social protection frameworks in developing countries	2019	<i>Climate and Development</i> 12 (6), 511-520; https://doi.org/10.1080/17565529.2019.1642180	Climate risks, adaptation planning, adaptation action, climate resilience, social protection	Mariya Aleksandrova mariya.aleksandrova@idos-research.de
	Social protection as a tool to address slow onset climate events: emerging issues for research and policy	2019	Discussion Paper 16/2019, German Development Institute, Bonn; https://doi.org/10.23661/dp16.2019	Climate risks, adaptation planning, adaptation action, climate resilience, social protection	Mariya Aleksandrova mariya.aleksandrova@idos-research.de
	Ecosystem-based adaptation projects: more than just adaptation: analysis of social benefits and costs in Colombia	2019	<i>International Journal of Environmental Research and Public Health</i> 16 (21), 4248 https://doi.org/10.3390/ijerph16214248	ecosystem-based adaptation; social benefits; climate change; water; mangroves	Jean Carlo Rodriguez jean.rodriguez@idos-research.de
	Tracing sustainability transformations and drivers of green economy approaches in the global south	2018	<i>Journal of Environment and Development</i> 27 (1), 3-25; https://doi.org/10.1177/1070496517747661	Green economy, sustainable development, sustainability transformations, developing countries	Steffen Bauer steffen.bauer@idos-research.de

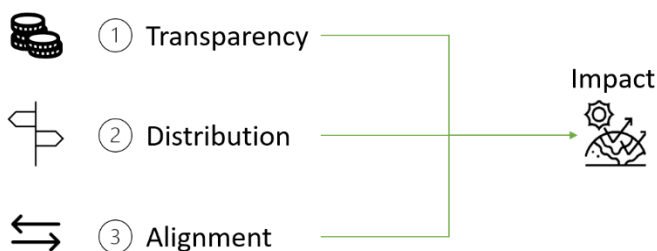
	Adapting in a carbon pool? Politicising climate change at Sumatra's palm oil frontier	2018	<i>A critical approach to climate change adaptation: discourses, policies, and practices</i> , London, New York: Routledge, 151-167	Climate risk management, social protection, adaptation action, adaptation planning	Jonas Hein Jonas.hein@idos-research.de
	Assessing agricultural systems vulnerability to climate change to inform adaptation planning: an application in Khorezm, Uzbekistan	2016	<i>Mitigation and Adaptation Strategies for Global Change</i> 21 (8), 1263–87; https://doi.org/10.1007/s11027-015-9655-y	Climate risks, agriculture, vulnerability, adaptation planning	Mariya Aleksandrova mariya.aleksandrova@idos-research.de
	Modelling the potential impacts of climate change and adaptation strategies on groundnut production in India	2021	<i>Science of the Total Environment</i> 776 (145996) https://doi.org/10.1016/j.scitotenv.2021.145996	Climate change impacts, adaptation strategies, spatial modelling, semi-arid tropics	Srinivasa Srigiri srinivasa.srigiri@idos-research.de
	Regional Integrated Assessment of Climate Change Impacts on the Rainfed Farming System in Kurnool District, Andhra Pradesh, India	2021	<i>Handbook of Climate Change and Agroecosystems: Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research Part 2</i> , eds. C. Rosenzweig, C.Z. Mutter & E.M. Contreras. Singapore: World Scientific, 395-445; https://www.worldscientific.com/doi/abs/10.1142/9781786348814_0009	Climate Change impacts, Adaptation strategies, Integrated assessments, Semi-Arid Tropics	Srinivasa Srigiri srinivasa.srigiri@idos-research.de
(e) The role and importance of traditional, Indigenous and local knowledge in relation to climate change, recognizing the gaps and barriers related	WaterS beyond SDG 6: unveiling the multiple dimensions of water	2026	<i>Water International</i> 51 (2), 120-131 https://www.tandfonline.com/doi/full/10.1080/02508060.2026.2617120	SDG6, post 2030, local, traditional and indigenous water knowledge, progress report, indicators	Annabelle Houdret Annabelle.houdret@idos-research.de Jean Carlo Rodriguez jean.rodriquez@idos-research.de

to accessing, assessing and communicating that knowledge	What is at stake: the ontological dimension of environmental conflicts	2024	<i>Society and Natural Resources</i> , 37 (5), 608-622; https://doi.org/10.1080/08941920.2024.2329888	Indigenous knowledge	Jonas Hein Jonas.hein@idos-research.de
	Seven strategies to leverage water for peace and foster sustainable and just water management for all	2024	<i>Nature Water</i> 2, 1134-1138 https://doi.org/10.1038/s44221-024-00353-z	Participatory adaptation, local knowledge, transboundary water governance, gender, local resilience	Annabelle Houdret, Annabelle.houdret@idos-research.de
(f) Scientific findings, advances and gaps in relation to the deployment of carbon dioxide removal technologies and approaches, the importance of their role in meeting the long-term goals of the Paris Agreement and linkages with sustainable development	--	--	--	--	--
(g) Gaps and research needs in relation to science-based greenhouse gas reporting methodologies used, inter alia, for carbon accounting frameworks	Spaceborne height models reveal above ground biomass changes in tropical landscapes	2021	<i>Forest ecology and management</i> , 497, 119497 https://doi.org/10.1016/j.foreco.2021.119497	Aboveground biomass change, height models, Interferometric synthetic aperture radar (InSAR) data, TanDEM-X, tropical rainforest	Jonas Hein jonas.hein@idos-research.de

EVALUATION RESULTS TO INFORM SBSTA

In this document, the German Institute for Development Evaluation submits evidence addressing research needs and gaps identified under the SBSTA since June 2005.

Evidence on **climate change mitigation** relates to the transparency, distribution, alignment, and impact of mitigation ODA. Evidence related to **adaptation** relates to the transparency, distribution, alignment, and impact of mitigation ODA.



Overall, the evaluation recommends that mitigation ODA should be orientated towards **partner priorities** in order to increase effectiveness through ownership.

As the funds made available will probably not be sufficient, further distribution criteria are necessary. **Mitigation potential** could play a greater role here. This applies especially to interventions with the **primary objective of climate change mitigation, as such interventions effectively mitigate GHG emissions**. More democratic and better governed development partners are particularly suitable. In non-democratic countries or where there are restrictions on good governance, promoting the state and civil society can also help to achieve climate targets, although short-term success is not so likely here.

Where the mitigation of GHG emissions is only a secondary objective, distribution can continue to be primarily based on need. In this case, the primary aim is to take account of **negative externalities** for climate change mitigation in order to counter the immense dangers of further global warming for development goals.

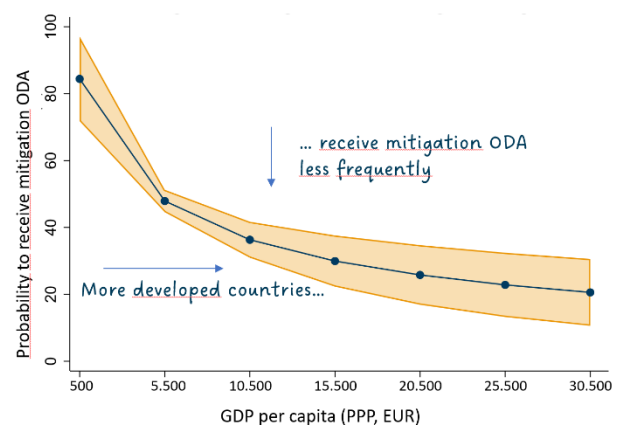
SBSTA 58 §50 Synergies and Trade-offs

The aim of international and German development cooperation is a holistic approach to sustainable development that encompasses both **climate change mitigation and socio-economic development**. This gives rise to the challenge of distributing scarce funds in a balanced manner.

A DEval evaluation finds that, when distributing mitigation-relevant development finance, the Federal Ministry for Economic Cooperation and Development **focuses more on countries' socio-economic need than on their mitigation potential**. This means that poorer countries receive more frequent and higher commitments. However, there is hardly any evidence to suggest a focus on mitigation potential, e.g. a lack of efficiency in energy supply or high per capita emissions.

In addition to synergies between mitigation and socio-economic development, there are also **conflicts of objectives relating to inequality**. Climate change mitigation can increase consumption and production costs in the short term, disproportionately penalising poorer population groups. The just transition approach can offset negative social consequences of climate change mitigation and thus reduce potential conflicts of objectives.

When distributing mitigation relevant ODA, contributors should **deal more systematically with conflicts of objectives and focus mitigation-relevant development more strongly on mitigation potential**.



SBSTA §75(d) Nature-based Solutions

DEval's modular evaluation of climate change adaptation finds that **nature-based solutions and infrastructure interventions are the most effective approaches for adaptation**, ideally combined with informational and educational measures. Restoration of mangrove forests, wetlands, and construction of dams or irrigation systems are largely successful in dealing with climate risks. This offers clear evidence for prioritising these intervention types in adaptation portfolios.

DEval's systematic review lends further support to this result. **Nature-based solutions, infrastructure interventions, and informational/educational interventions prove to be particularly effective** in the adaptation-relevant sectors of agriculture and water. Nature-based solutions and associated agroecological practices can enhance land ecosystem services and ensure sustainable land use systems. This counters overly pessimistic narratives and shows that evidence-based adaptation is achievable in LMIC.

DEval 2023, Adaptation Synthesis Report; DEval 2023, Adaptation Module 2; Villamayor-Tomas et al. 2024, Communications Earth & Environment

SBSTA §62 Strengthening Resilience

A DEval-funded geospatial impact evaluation of nearly 1,000 irrigation sites in Mali found that the **introduction of irrigation led to substantial increases in agricultural production, with gains persisting even a decade later**. Children in nearby communities are less likely to be stunted or severely underweight, and conflict risks decrease in the closest communities.

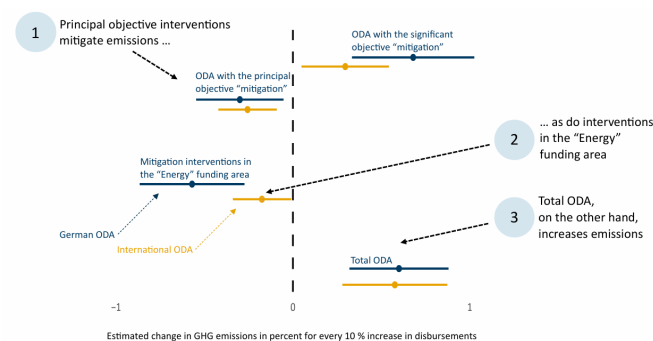
This demonstrates that **well-targeted adaptation investments can simultaneously build climate resilience, improve nutrition, and contribute to stability in fragile contexts**.

DEval Discussion Paper 1/2023, PNAS Nexus 2024

SBSTA 57-52 §75(a) Science-Policy Interface

To understand the effects and impacts of mitigation ODA, a sound scientific documentation of the effectiveness and impact of ODA interventions is necessary. An evidence synthesis sums this up **for seven groups of interventions**.

The results show that **two forms of mitigation ODA contribute to reducing emissions**: ODA that primarily aims to mitigate GHG emissions and ODA that concerns energy generation, distribution and efficiency.

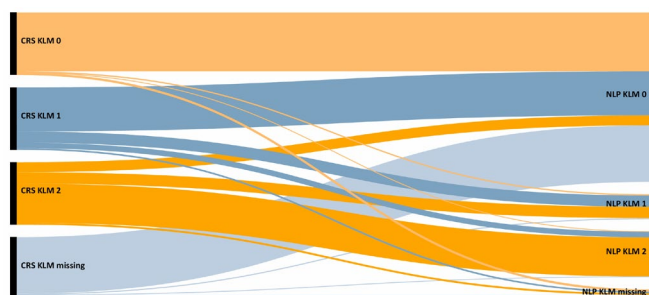


There is evidence of a favourable effect for **technological and infrastructural interventions**. Specifically, disbursements of mitigation ODA are linked to a growing share of renewable energies in electricity generation in partner countries.

DEval 2024, Climate Change Mitigation Through Development Cooperation. Evaluation Report and Policy Brief

SBSTA 42 §31-33 Data and information gaps

A DEval evaluation uses machine classification (natural language processing) of interventions based on their descriptions in OECD-DAC CRS in combination with a qualitative analysis. The evaluation shows that climate finance is lower than official reporting suggests.



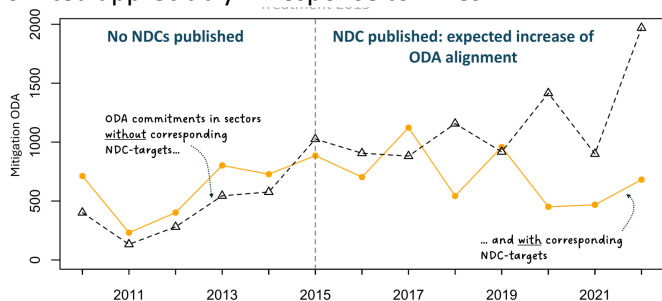
The findings indicate that the **Rio markers for climate change adaptation and mitigation are assigned too frequently and sometimes too high**. This demonstrates that the climate relevance of significant objective interventions is not always clear. Quantifying climate finance ODA using the Rio markers thus remains challenging affecting transparency and accountability.

DEval 2024, Climate Change Mitigation Through Development Cooperation. Evaluation Report and Policy Brief,

SBSTA 57-52 §75 Usable information at science-policy interface for implementation

A DEval Policy Brief provides empirical evidence on an implementation gap under the Paris Framework. The Paris Agreement underlines the importance of providing support to developing country Parties for ambitious emissions reduction, while also recognizing their "specific needs and special circumstances." However, we know very little about the degree to which alignment has been achieved. The Policy Brief fills this gap, examining the extent to which mitigation-related official development assistance (ODA) aligns with priorities expressed in recipients' nationally determined contributions (NDCs).

The Policy Brief shows that conditional targets in NDCs do not, by themselves, drive sectoral allocation of mitigation ODA. Thus, there is no evidence that allocation has shifted appreciably in response to NDCs.



The Policy Brief identifies a need for more transparent reporting. A potential entry point is the "enhanced transparency framework," agreed at COP24: guidelines for reporting climate-related ODA could include the extent of alignment with stated needs. Moreover, alignment should be established as a key metric for assessing climate finance quality, contributing to more ambitious and multidimensional quantitative targets.

DEval 2024, Targets without traction? Do Nationally Determined Contributions fail to drive mitigation funding distribution?

References (click on source for link)

DEval Reports on Climate Change Mitigation

DEval Reports on Green Energy

DEval Reports on Protected Areas

Additional publications

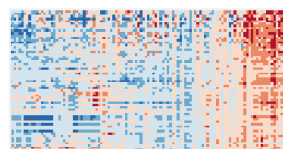
BenYishay et al. (2024): Irrigation strengthens climate resilience: Long-term evidence from Mali using satellites and surveys

Borst, Wencker and Niekler (2023), "Constructing a Credible Estimation for Overreporting of Climate Adaptation Funds in the Creditor Reporting System"

Giustarini et al. (2023): Simulating Changes in Hydrological Extremes—Future Scenarios for Morocco

Sergio Villamayor-Tomas et al. (2024): Developing countries can adapt to climate change effectively using nature-based solutions

Evaluation Reports (click on document)



CLIMATE CHANGE MITIGATION THROUGH DEVELOPMENT COOPERATION

Contribution of German development cooperation to mitigating greenhouse gas emissions in developing countries

2024



EVALUATION OF INTERVENTIONS FOR CLIMATE CHANGE ADAPTATION

Synthesis Report

2023



EVALUATION OF INTERVENTIONS FOR CLIMATE CHANGE ADAPTATION

Agriculture, water, environmental protection, Nationally Determined Contributions and National Adaptation Plans

2023



ACCESS TO (GREEN) ENERGY IN RURAL AFRICA

Evaluation report

2024

The German Institute for Development Evaluation (DEval) is mandated by the German Federal Ministry for Economic Cooperation and Development (BMZ) to independently analyse and assess German development interventions. Evaluation reports contribute to the transparency of development results and provide policy-makers with evidence and lessons learned, based on which they can shape and improve their development policies.



15 April 2026

Dear colleagues,

GRID-Arendal would like to provide input and information on how various research needs identified under the agenda item on “Research and Systematic Observation (RSO)” are being addressed by GRID-Arendal and partner organisations in the recent years.

We would like to thank you for considering our input in preparation of Chair’s information note to be presented during the eighteenth meeting of the research dialogue, to be held in conjunction with the June Subsidiary Bodies session (June 2026).

Kind regards,
GRID-Arendal Team

<i>A. Understanding climate change, related climate data, and scenarios development and use</i>				
Research	Description	Timeline	Geographical scope	Relevant links
Mountains in Motion: Global Linkages from Ridge to River	A science-based overview of how mountain systems shape water resources, biodiversity, climate resilience and pollution pathways far beyond their peaks. Drawing on recent peer-reviewed research, public datasets and national reporting under the Rio Conventions, the report connects mountain change to global systems. It examines shrinking glaciers and snow cover, groundwater recharge, biodiversity corridors, pollution flows, land degradation and environmental governance, while highlighting why mountain futures must be built through integrated, equitable and science-based action.	2025	Global, Andes, Caucasus, Central Asia, East Africa, Hindu Kush Himalaya	https://www.grida.no/publications/3014
<i>B. Adaptation, loss and damage and extreme events</i>				
Resilient Mountain Solutions: Ten local solutions for global impact	This book presents 10 efficient, cost-effective and custom-made nature-based solutions that have been tested in the Hindu Kush Himalayan (HKH) region and are suitable for up-scaling and out-scaling to other regions. Each solution can contribute to several of the United Nations Sustainable Development Goals (SDGs) and thus help ensure a better future for all. The 10 solutions showcased here are examples of many diverse, nature-based solutions that provide long-term benefits to local communities, their environment and livelihoods by increasing their resilience to change.	2023	Hindu Kush Himalaya	https://www.grida.no/publications/933
<i>C. Ecosystems and nature-based solutions</i>				
SEA-Quester Policy Assessment	Our analysis shows that blue carbon is acknowledged more widely by observers than by member states of the Arctic Council, and more often in a biodiversity (NBSAP) than in a climate (NDC) context. All interviewees agreed that multiple positive co-benefits	2025	Arctic	https://zenodo.org/records/19481042

	<p>could arise from more effective preservation and management of blue carbon ecosystems. While the concept of blue carbon has reached the Arctic to a small extent, it has been primarily associated with coastal ecosystems within international frameworks. Oceanic forms of blue carbon, such as those involving pelagic species, deep-sea ecosystems, and offshore habitats, were recognised in early discussions of blue carbon. However, these oceanic components were not mentioned or specified to a similar extent as were coastal ecosystems in either this analysis or in subsequent policy development and implementation.</p>			
<p><i>D. Mitigation and related technologies, and greenhouse gas (GHG) emissions and reporting</i></p>				
<p>Climate impacts of plastics: Global actions to stem climate change and end plastic pollution</p>	<p>This report demonstrated that existing measurement and reporting approaches for tracking plastic-related greenhouse gas emissions are fragmented and inconsistent in international climate governance. This gap hampers the development and implementation of effective transition strategies within the plastics industry. The report also presents the options for measures to strengthen governmental accountability in addressing the climate impacts of plastics.</p>	<p>2024</p>	<p>Global</p>	<p>https://www.grida.no/publications/1023</p>

I consulted my senior colleagues, and we identified the following project as an initiative aimed at strengthening research capacity in developing countries, focusing on the impacts of climate change on fisheries in the context of marine protected areas.

<p>Research to Inform Inclusive Management of the Cayar and Ufoyaal Kassa-Bandial MPAs in Senegal (Project)</p>	<p>The Lenfest project strengthened climate-resilient management of Senegal’s Marine Protected Areas (MPAs). It provided MPA managers and communities in Cayar and Uffoaaal Kassa-Bandial with practical tools to understand and monitor climate change impacts. By downscaling ocean and climate datasets to regional levels and combining them with ecological knowledge from fishers and community members, the project aimed to improve decision-making and long-term monitoring. It also supported training for local scientists, reinforced co-management structures, and helped build more</p>	<p>2023-2025</p>	<p>Senegal</p>	<p>https://www.grida.no/activities/1000</p> <p>https://www.lenfestocean.org/en/research-projects/research-to-inform-inclusive-management-of-the-cayar-and-uffoaaal-kassa-bandial-mpas-in-senegal</p>
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	resilient, community-driven MPAs.			
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Research and systematic observation (RSO), mapping of research needs:

Indicators of Global Climate Change (IGCC), led by the University of Leeds

IGCC responds to the following identified research gap:

Understanding climate change, related climate data, and scenarios development and use:

a) Near term climate change and its prediction

Description of the research

Robust, transparent, and timely climate indicators are essential for tracking progress towards the goals of the Paris Agreement. While the IPCC provides the most authoritative assessments of climate science, the multi-year assessment cycle means that policymakers and negotiators often lack access to the latest information on the state of the climate system.

To bridge this gap, the **Indicators of Global Climate Change (IGCC)** initiative, launched in 2021, provides annual updates of key indicators including greenhouse gas emissions, their atmospheric concentrations, radiative forcing, Earth's energy imbalance, surface temperature changes, human-induced warming, the remaining carbon budget, and related climatic impact drivers including temperature extremes, marine heatwaves, sea level rise and precipitation. These indicators are updated annually using state-of-the-art datasets, and methodologies assessed in the IPCC Sixth Assessment Report (AR6), modified where necessary to account for new or revised datasets and other key innovations.

From 2026, IGCC will be delivering an operational, annually updated suite of indicators through the Copernicus Climate Data Store (CDS), accompanied by communication and outreach platforms that provide timely, trusted and readily accessible evidence for consumers of climate data. This will ensure that IGCC, and the scientific evidence that it provides, is associated with an established and robust service and that it can reach a wider range of users with free, open-access climate data and tools.

Timeline of the research

The first edition of IGCC was published in June 2023. The fourth edition will be available for the 2026 Bonn Climate Conference.

Geographic scope (i.e. global, regional, multi-country, national or sub-national)

IGCC purposefully updates global level indicators of climate change. The latest edition involved 61 authors from 54 institutions across 17 countries.

Relevant links to the research page, publications, and other outputs

[Latest edition of IGCC](#)

[Description of latest results in Carbon Brief](#)

[Data repository](#)

Submission to UNFCCC SBSTA

Research and Systematic Observation

Institute of Meteorology and Climate Research (IMK)

Karlsruhe Institute of Technology (KIT), Germany

In response to Decision 9/CP.11 (2005) and the standing invitation by the Subsidiary Body for Scientific and Technological Advice (SBSTA) to research organisations to communicate how their activities address Convention-related research needs, the Institute of Meteorology and Climate Research (IMK) at Karlsruhe Institute of Technology (KIT), Germany, hereby submits the following summary of relevant research activities.

The activities below are presented thematically, organised by the research needs identified in SBSTA Conclusions from 2005 to 2023.

1. Atmospheric Composition and Systematic Observation

KIT operates a suite of complementary observing platforms for atmospheric composition that together address gaps in the global climate observing system. Satellite-based retrievals of trace gas distributions – including ozone, methane, nitrous oxide, water vapour and CO – are produced using algorithms applied to MIPAS, IASI and GLORIA instruments, generating long-term data records consistent with GCOS Essential Climate Variable (ECV) requirements. The GLORIA limb-sounder, deployed on the HALO research aircraft and stratospheric balloons, provides high-resolution 2D cross-sections of temperature and over ten trace gas species in the upper troposphere and lower stratosphere; recent campaigns include PHILEAS (2023) targeting extratropical tropopause transport. At the boundary layer and free troposphere, the mobile KITcube multi-sensor facility provides comprehensive in-situ and remote sensing measurements of atmospheric state and composition during field campaigns. KIT is also an active partner in IAGOS (In-service Aircraft for a Global Observing System), contributing routine ozone and CO measurements on commercial flights globally. Portable ice-nucleating particle (INP) instruments – PINE (Portable Ice Nucleation Experiment) and INSEKT – extend in-situ aerosol characterisation to field sites across Europe and Asia, filling a recognised gap in the aerosol observing system. All datasets are made openly accessible through international data infrastructures.

SBSTA needs addressed: Sustained systematic observation of the atmosphere, ocean, cryosphere and land (SBSTA 57 ¶1, ¶6–7; SBSTA 52–55 ¶73); filling gaps in the global climate observing system, especially for aerosols (SBSTA 57 ·10–11); long-term ECV data records and data management (Decision 19/CP.22, 2016; SBSTA 57 ¶9); multi-platform observational integration (SBSTA 57 ·11); open access to climate-relevant data (SBSTA 48 ·47a); global carbon cycle observation requirements (SBSTA 50; SBSTA 48 ·42d).

Further information: [Trace gas remote sensing](#) | [PHILEAS 2023](#) | [IAGOS](#) | [IMK-TRO research](#)

2. Cloud, Aerosol and Precipitation Processes

Understanding aerosol–cloud interactions and cloud microphysics is central to reducing the largest remaining uncertainty in climate projections. KIT addresses this through a combination of laboratory, ground-based and satellite approaches. The AIDA aerosol and cloud simulation chamber – one of the largest and most versatile facilities of its kind internationally – enables controlled experiments on ice nucleation, droplet nucleation, secondary ice formation and aerosol optical properties across the full range of atmospheric temperatures and pressures (–90°C to +60°C, 1–1000 hPa). Research outputs include cloud process parameterisations implemented in weather and climate models. KIT produces long-term satellite-derived climatologies of fog, low stratus and cloud properties for Europe and southern Africa, and applies machine-

learning methods to quantify aerosol effects on cloud liquid water path and cloud fraction – directly constraining aerosol radiative forcing estimates. The KLOCX ground-based platform (within ACTRIS-D) provides high-quality reference data for retrieval validation. KIT's tropospheric research addresses convective precipitation processes, orographic precipitation and soil moisture–convection feedbacks, supported by field campaigns and high-resolution convection-permitting model experiments. Several projects specifically focus on Africa, a region with critical observational gaps. The ICON model, and specifically the ICON-ART component receives active development contributions from KIT, which also takes a leading role in the ICON consortium.

SBSTA needs addressed: Reducing uncertainty in cloud feedbacks and climate projections (SBSTA 52–55 ¶75h, i; SBSTA 46 ·47c; SBSTA 56 ¶62a); improved parameterisation of cloud and precipitation processes (SBSTA 52–55 ¶75h; Decision 9/CP.11 ·4); Earth observation systems and long-term atmospheric records (SBSTA 57 ¶1); addressing observation gaps in developing countries and under-observed regions (SBSTA 57 ·10); sustained systematic observation of aerosols (SBSTA 57 ·6); evolution and dynamics of extreme precipitation (SBSTA 56 ¶62c); water cycle processes (SBSTA 52–55 ¶73).

Further information: [AIDA facility](#) | [Aerosol-cloud processes](#) | [Cloud microphysics](#) | [Satellite climatology](#) | [KLOCX / ACTRIS-D](#) | [AeroFog](#)

3. Regional Climate: Projections, Extremes and Downscaling

SBSTA has consistently identified high-resolution regional climate information as a critical gap for supporting adaptation and early warning. KIT addresses this need through convection-permitting regional climate modelling, dense observational networks and data-driven methods. High-resolution simulations of future extreme precipitation – including the ReSiPrec project for south-west Germany and large ensemble analyses of Mediterranean heavy-rain events in a warmer climate – produce locally actionable climate projections. Research shows robust increases in precipitation extremes and compound hot-dry events under warming scenarios. Machine-learning approaches are being applied to improve the skill of short-range precipitation forecasts. The 4SURE project (Smart Sensor System for Sustainable Urban Regions, developed with the University of Freiburg) deploys a dense urban sensor network focused on heat, drought and heavy precipitation extremes at local scale, generating freely accessible high-resolution observational datasets for model evaluation and adaptation planning. Hydro-meteorological research at KIT's Campus Alpin contributes to understanding regional water resources dynamics and ecoclimatology.

SBSTA needs addressed: High-resolution regional climate information and downscaling for decision-making (SBSTA 58 ¶50; SBSTA 56 ¶62a; SBSTA 52–55 ¶75e; SBSTA 46 ·47e); evolution and dynamics of extreme events and early warning systems (SBSTA 56 ¶62c); near-term climate projections at regional and local level (SBSTA 56 ¶62a); improving performance of regional and sub-regional climate models (SBSTA 52–55 ¶75h, i); long-term data collection and open data access (SBSTA 57 ¶9; SBSTA 48 ·47a); regional hydrology and water cycle (SBSTA 48 ·42a).

Further information: [IMK-TRO research](#) | [IMK-IFU regional climate](#)

4. Carbon Cycle, Greenhouse Gas Fluxes and Land–Atmosphere Interactions

Quantifying greenhouse gas fluxes between the atmosphere, terrestrial ecosystems and the ocean is fundamental to tracking progress under the Paris Agreement. KIT contributes to this need through complementary top-down and bottom-up approaches. Satellite-based retrievals of methane, CO₂, nitrous oxide and other GHG species from instruments including MIPAS and IASI provide top-down constraints on atmospheric concentrations and, in combination with transport models, regional flux estimates. At the surface, eddy-covariance and chamber flux measurements are conducted at field sites in central Europe and West Africa (including methane from rice cultivation and exchange at forest sites, through WASCAL collaboration), addressing the critical need for GHG flux observations in under-represented tropical and

subtropical regions. The Global Land Ecosystem Modelling Group (LEMG) develops and applies the dynamic global vegetation model LPJ-GUESS and coupled frameworks to simulate terrestrial carbon stocks and fluxes under changing climate and land use. KIT contributes annually to the Global Carbon Budget (published by the Global Carbon Project), one of the most widely cited science products informing UNFCCC deliberations on mitigation progress. KIT's activities in the TERENO observation network complement these activities.

SBSTA needs addressed: Global carbon cycle observation requirements and GHG flux monitoring (SBSTA 50; SBSTA 48 ·42d, ·47f); sustained systematic atmospheric observation including GHG species (SBSTA 57 ·6; Decision 19/CP.22); GHG flux observations in developing and tropical regions (SBSTA 57 ·10; Decision 19/CP.22 ECV requirements); land-based mitigation tracking and model-data integration (Decision 9/CP.11 ·4); open access to climate-relevant data (SBSTA 48 ·47a); science for tracking progress under the Paris Agreement (SBSTA 50 ·83a).

Further information: [LEMG – land ecosystem modelling](#) | [Trace gas remote sensing](#) | [IMK-IFU Campus Alpin](#)

5. Land Use Change, Ecosystem Modelling and Climate Solutions

Land use change is both a major driver of and response option to climate change, and SBSTA has repeatedly called for research on nature-based solutions, carbon dioxide removal and the synergies and trade-offs between mitigation, adaptation and sustainable development. KIT addresses these needs through integrated modelling of land systems and their socio-ecological consequences. The CRAFTY agent-based model simulates land use decision-making under multiple drivers at regional to global scales. The HILDA+ dataset provides the most comprehensive historic global land use change reconstruction available, widely used in carbon cycle and ecosystem assessments. The LandSyMM modelling framework couples ecosystem, hydrology and economic components to assess integrated impacts of land system change. Current EU-funded projects include ForestPaths (forest-based climate policy pathways across Europe) and wildE (rewilding and ecosystem restoration scenarios). This body of work directly informs the assessment of land-based mitigation options, the risks and opportunities of carbon dioxide removal, and the trade-offs between land for food, biodiversity and climate – all themes that have gained increasing prominence in SBSTA research dialogues.

SBSTA needs addressed: Potential, risks and co-benefits of carbon dioxide removal and nature-based solutions (SBSTA 58 ¶50; SBSTA 56 ¶62e); synergies and trade-offs between mitigation, adaptation and the SDGs (SBSTA 58 ¶50); nature-based solutions in land ecosystems for adaptation and mitigation (SBSTA 52–55 ¶75d); land-based mitigation and scenario analysis (Decision 9/CP.11 ·4); science for transformation of land and sectoral systems (SBSTA 50 ·83a); research on cross-cutting issues using multidisciplinary approaches (Decision 9/CP.11 ·4).

Further information: [LEMG group](#) | [Land Use Change & Climate](#) | [IMK-IFU Campus Alpin](#)

Contact

Institute of Meteorology and Climate Research (IMK) | Karlsruhe Institute of Technology (KIT)

Integrated Carbon Observation System (ICOS)

We have recently been working extensively on gaps of homogeneous indicators for CDR efficiency and environmental impact, and on a comprehensive assessment framework for marine CDR. The latter actively challenges the "feasibility" assessment framework of the IPCC.

[Monitoring marine carbon dioxide removal: quantitative analysis of indicators for carbon removed and environmental side-effects - IOPscience](#)

[A holistic assessment framework for marine carbon dioxide removal options - IOPscience](#)

Ref.: IPBES/SEC/EXT/2026/05

17 April 2026

SUBJECT: Input of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)

Dear Research and Systematic Observation (RSO) team,

With reference to your communication dated **25 March 2026**, requesting contributions to the information note that maps how research gaps identified since the twenty-second meeting of the Subsidiary Body for Scientific and Technological Advice (SBSTA) to the United Nations Framework Convention on Climate Change (UNFCCC), held in June 2005, under the agenda item on “Research and Systematic Observation (RSO)” are being addressed by the scientific community, it is my great honour to submit the following completed assessments of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as an input to the information note to be presented during the eighteenth meeting of the research dialogue, to be held in conjunction with the June Subsidiary Bodies session (June 2026).

You will recall that IPBES was established in 2012 and has completed 14 assessments on topics related to biodiversity in the 10 years between 2016 to 2015. IPBES does not undertake research, but, like IPCC, assesses available literature on the assessment topics.

Many of the assessments contribute to filling the knowledge gaps identified by SBSTA, in particular with regard to “Ecosystems and nature-based solutions”. Further, each assessment also identifies knowledge gaps related to the assessment topic, and IPBES catalyzes the generation of new research on these gaps, and thereby also contributes to filling similar gaps identified by SBSTA.

All IPBES assessments are available at: <https://www.ipbes.net/assessing-knowledge>

Of particular relevance are:

- **The first IPBES Global Assessment Report on Biodiversity and Ecosystem Services**
 - o Description: At the time of its release, the IPBES Global Assessment Report on Biodiversity and Ecosystem Services was the most comprehensive ever completed. It was the first intergovernmental Report of its kind and built on the landmark Millennium Ecosystem Assessment of 2005, introducing innovative ways of evaluating evidence. The assessment found that climate change is among the 5 direct drivers of change in nature with the largest global impact,

- and it addresses land-based climate change mitigation activities and nature-based solutions.
 - Timeframe: Summary for policymakers approved and chapters accepted at IPBES 7 in 2019
 - Geographic scope: global
 - Website: <https://www.ipbes.net/global-assessment>
- **The methodological Assessment Report on the Impact and Dependence of Business on Biodiversity and Nature’s Contributions to People (Business and Biodiversity Assessment)**
 - Description: The assessment highlights methods and more than 100 specific actions to measure and respond to business impacts and dependencies for businesses, governments, financial actors and civil society. Nature-based solutions and ecosystem-based approaches are addressed in the context of actions identified.
 - Timeframe: Summary for policymakers approved and chapters accepted at IPBES 12 in 2025
 - Geographic scope: global
 - Website: <https://www.ipbes.net/business-impact>
- **The thematic Assessment Report on Invasive Alien Species and their Control**
 - Description: The assessment addresses one of the 5 direct drivers of change in nature with the largest global impact: invasive alien species. Among its findings is that climate change interacting with land- and sea-use change is predicted to profoundly shape and amplify the future threat from invasive alien species.
 - Timeframe: Summary for policymakers approved and chapters accepted at IPBES 10 in 2023
 - Geographic scope: global
 - Website: <https://www.ipbes.net/ias>
- **The thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity (Transformative Change Assessment)**
 - Description: The assessment report explains what transformative change is, how it occurs, and how to accelerate it for a just and sustainable world. It addresses nature-based solutions and ecosystem-based approaches when assessing strategies for action.
 - Timeframe: Summary for policymakers approved and chapters accepted at IPBES 11 in 2024
 - Geographic scope: global
 - Website: <https://www.ipbes.net/transformative-change-assessment>
- **The thematic Assessment Report on IPBES Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health (Nexus Assessment)**
 - Description: Offers decision-makers the most ambitious scientific assessment ever undertaken of these complex interconnections and explores specific response options to maximize co-benefits across five ‘nexus elements’: biodiversity, water, food, health and climate change.
 - Timeframe: Summary for policymakers approved and chapters accepted at IPBES 11 in 2024
 - Geographic scope: global
 - Website: <https://www.ipbes.net/nexus-assessment>

As contribution to the development of the Nexus Assessment, IPBES and IPCC co-sponsored a workshop on biodiversity and climate change in 2020. The workshop highlighted the interconnections between biodiversity and climate change. **It is important to note that IPBES and IPCC co-sponsorship does not imply IPBES or IPCC endorsement of the workshop proceedings or any recommendations or conclusions of the meeting. Neither the papers presented at the workshop, nor the report of its proceedings were subject to IPBES or IPCC intergovernmental review.** Information on the outcomes of the workshop is available at:
<https://www.ipbes.net/events/ipbes-ipcc-co-sponsored-workshop-biodiversity-and-climate-change>

We thank you for the opportunity to provide input and wish you a successful meeting.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)

SUBMISSION

Scientific research information

Submission by the International Centre for Integrated Mountain Development (ICIMOD)

April 2026

The [International Centre for Integrated Mountain Development](#) (ICIMOD) is pleased to provide this submission under the Subsidiary Body for Scientific and Technological Advice (SBSTA) [agenda item 4](#) on Research and Systematic Observation (RSO) of the United Nations Framework Convention on Climate Change (UNFCCC), in response to the mandate agreed ([conclusion 13](#)) at SBSTA 62 (June 2025). ICIMOD is an intergovernmental knowledge and learning centre serving the Regional Member Countries (RMCs) of the Hindu Kush Himalaya (HKH): Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan.

At SBSTA 62, Parties underlined the importance of discussions on scientific advances and on research gaps and needs relevant to supporting work under the Convention and the [Paris Agreement](#) (Articles 4, 7, 8 and 14), as well as the need to ensure sustained systematic observation of the climate system as a fundamental basis for scientific research and for informing climate action ([FCCC/SBSTA/2025/4, Add.19-34](#)). SBSTA 62 requested its Chair to prepare, with the assistance of the secretariat ([FCCC/SBSTA/2025/L.5](#)), an information note that maps how research gaps identified since SBSTA 22 (June 2005, [FCCC/SBSTA/2005/4/Add.1](#), Page 31) under this agenda item are being addressed by the scientific community, for consideration at the eighteenth meeting of the research dialogue to be held in conjunction with the June 2026 session of the Subsidiary Bodies.

ICIMOD, an intergovernmental organisation with observer status at the UNFCCC, uses this submission to present an overview of its contributions to addressing the identified research needs and gaps under the RSO agenda item. The submission also highlights the need for dedicated attention to mountain regions and mountain people, who are experiencing warming rates higher than the global average and whose environments remain relatively data-sparse in global observation systems and assessments.

Institutional mandate and relevance to RSO priorities

ICIMOD's Strategy 2030, [Moving Mountains](#)¹, sets out a vision of a greener, more inclusive and climate-resilient HKH and a mission to build and share knowledge that drives regional policy and action and attracts investment for sustainable mountain development. The HKH provides essential ecosystem services as the source of ten major Asian river systems and as a global "water tower" that supports the wellbeing of almost two billion people downstream.

At the same time, the HKH is experiencing accelerated cryospheric change, increasing climate extremes and cascading transboundary risks, and has been recognised in successive assessment reports of the Intergovernmental Panel on Climate Change (IPCC) as a region where long-term, high-quality observations and integrated research remain comparatively limited. ICIMOD's work therefore responds directly to the priorities under [Article 5](#) of the UNFCCC on research and systematic observation and to SBSTA's calls to broaden representation of developing-country science in the research dialogue and related processes ([FCCC/SBSTA/2025/4, Add.19-34](#)).

¹ ICIMOD. (2023). ICIMOD Strategy 2030: Moving Mountains. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1027>

ICIMOD and RSO research needs categories

The UNFCCC secretariat, in its synthesis of research needs and gaps identified ([FCCC/SBSTA/2025/L.5](#)) since SBSTA 22 (June 2005), has structured these needs under five broad categories (A–E), as outlined in the [information note](#) prepared by the RSO co-chairs (March 2025). Specifically, Parties at SBSTA 62 requested mapping of progress against the following research dialogue foci:

- **Category A:** Understanding climate change, related climate data, and scenarios
- **Category B:** Adaptation, loss and damage, and extreme events
- **Category C:** Ecosystems and nature-based solutions
- **Category D:** Mitigation, related technologies, and GHG emissions and reporting
- **Category E:** Cross-cutting issues

The UNFCCC secretariat has compiled a [synthesis](#) of research needs and gaps identified under the RSO agenda item since SBSTA 22 ([FCCC/SBSTA/2005/4/Add.1](#)), structured under five broad categories (A–E). In line with this structure, ICIMOD’s submission:

- Describes how selected ICIMOD research, systematic observation and capacity-building initiatives undertaken since 2005 respond to specific elements of these categories, using concrete examples from across the HKH.
- Highlights, as far as possible, the regional and multi-country nature of the work and its relevance for Parties’ implementation of the Convention and the Paris Agreement, including in relation to adaptation, mitigation, loss and damage and means of implementation.
- Identifies cooperative and capacity-building dimensions, particularly those that strengthen the ability of institutions in developing-country Parties in the HKH to generate, access and effectively use climate-related data and knowledge.
- A set of one-page descriptions of selected ICIMOD projects and studies is provided in the annexes, using the standardised template described in the secretariat’s guidance. These one-page entries indicate the specific RSO research needs addressed (A–E), the timeline, geographic scope, methods and observation systems used, and links to outputs and data.

ICIMOD contributes to all five categories through research, systematic observation and capacity-building initiatives implemented since 2005, directly responding to SBSTA's mandate to identify how the scientific community has addressed these gaps. Table 1 (next page) summarizes selected ICIMOD initiatives mapped against these categories, with brief descriptions in the table and detailed one-page notes, as requested by the RSO, provided in the annexes.

Table 1: Overview of selected ICIMOD initiatives responding to RSO research needs (A–E)

No.	Project / study title	Brief Note	RSO categories (A–E)	Geographic scope	Timeline
1	Hindu Kush Himalaya Assessment and related flagship publications (including WISE Outlook)	Comprehensive HKH assessment synthesising climate, cryosphere, water and ecosystem data for IPCC and national planning	A, B, C, E	HKH region	Ongoing
2	SANDEE – The South Asian Network for Development and Environmental Economics	Regional network building capacity in environmental economics through 250+ grants and 1,500+ trainees	A, E	South Asia and HKH	1999–ongoing
3	Action research on residential space heating as a gender-inclusive and socially responsible solution	Rocket stove pilot showing 51% fuelwood/emission reduction and health benefits in Bhutan high-altitude households	B, D, E	Bhutan and Nepal, with major focus on high-altitude settlements in Bhutan.	2024–2025
4	Clean Bricks	Zig-zag kiln conversion avoiding 106k tonnes CO ₂ across 7,000 South Asian kilns with regional stakeholder platform	B, D, E	Nepal, Pakistan, India, Bangladesh (major focus on Nepal and Pakistan)	2014–2021
5	Kailash Sacred Landscape Conservation and Development Initiative	Transboundary ecosystem approach benefiting communities across China-India-Nepal with first Himalayan GLORIA site	B, C, E	Transboundary Kailash Sacred Landscape (China, India, Nepal)	2012–2022
6	Springshed Management for Sustainable Water Resources	Six-step protocol documenting springs drying in 74% of Nepal LGUs and scaling NbS for water security	B, C, E	HKH region	2015–ongoing
7	Sustainable Management of High-Altitude Rangelands as Nature-based Solutions	Community-led rangeland restoration increasing soil carbon and fodder by 20% across HKH pastoralist systems	C, E	Afghanistan, Bhutan, China, India, Nepal, and Pakistan	1999–ongoing (with phased programmes)
8	Disability and disaster in the HKH region – cross-country analysis of disability patterns and disaster linkages	Harmonised analysis showing disaster exposure drives disability prevalence in remote HKH hazard zones	B, E	Bangladesh, India, Nepal, Pakistan	2023–2025
9	Thame Valley Glacial Lake Outburst Flood 2024 – Causes, impacts and future risks	Post-GLOF analysis of cascading lake breaches destroying 25 homes, school, health post; risk assessment of 5 lakes	A,B,C,E	Thame Valley, Dudh Koshi basin, Everest region, Nepal (HKH)	2024-2025

10	Changing dynamics of glaciers in the Hindu Kush Himalayan region from 1990 to 2020	HKH-wide dataset documenting 12% glacier area loss and 9% ice reserve decline with accelerating post-2010 retreat	A, B, C, E	HKH region	1990–2020 (analysis); report 2026
11	HKH Glacier Outlook 2026 – Insights from 50 years of Himalayan glacier monitoring	Synthesis of 302 mass-balance observations from 38 glaciers identifying monitoring gaps and benchmark sites	A, B, C, E	HKH region	1974–2026
12	HIGRID – Building capabilities for green, climate-resilient and inclusive development in the Lower Koshi River Basin	GEDSI-responsive DRR planning across 28 Nepal municipalities scaling flood EWS and inclusive value chains	A, B, E	Lower Koshi River Basin, eastern Nepal (Terai, mid-hills, high hills)	2022–ongoing (as of 2025)
13	2025 drought in Nepal’s Madhesh Province – A rapid situational analysis	Analysis of cascading meteorological-hydrological-agricultural drought projecting 400-450k tonne rice shortfall	A, B, E	Madhesh Province, south-eastern Terai, Nepal	2025 (event and analysis)
14	Himalayan Climate Change Adaptation Programme (HICAP)	Basin-scale climate and water scenarios, vulnerability and gendered adaptation research, and pilots such as CB-FEWS and Resilient Mountain Villages	A, B, C, E	China, India, Nepal, Pakistan	2011-2018
15	Himalayan Adaptation, Water and Resilience (HI-AWARE) – Research on glacier and snowpack dependent river basins	Comparative, transdisciplinary research in Indus, Ganges, Gandaki and Teesta basins on climate projections, vulnerability, adaptation pathways and pilots	A, B, C, E	Bangladesh, India, Nepal, Pakistan	2014-2018

These initiatives were selected to illustrate the breadth of ICIMOD's contributions across the five categories and to demonstrate how research, systematic observation and capacity-building interventions address the research needs identified under the RSO agenda item. The following subsections link these initiatives explicitly to each of the RSO categories.

Category A: Understanding climate change, related climate data, and scenarios

ICIMOD contributes to Category A: Understanding climate change, related climate data, and scenarios by generating higher-resolution regional climate information and by advancing understanding of warming pathways and associated uncertainties in the HKH. The *Hindu Kush Himalaya Assessment*² and the *Water, Ice, Societies and Ecosystems in the HKH: An Outlook*³ (HI-WISE) synthesise long-term observation records, regional climate and hydrological modelling, and scenario analysis to characterise elevation-dependent warming, changing monsoon dynamics and projected cryosphere loss under different warming levels.

Key strands of work include generation and analysis of downscaled climate projections and high-resolution regional climate information for the HKH, including basin-scale hydrological and cryospheric modelling in the Indus and Koshi basins, which provide information relevant to near-term climate risks and to seasonal to decadal changes in hydrology and extremes. Scenario analyses presented in these assessments indicate that, even if global warming is limited to 1.5 degrees, the HKH is projected to lose a substantial share of its glacier volume by the end of the century, with cascading implications for water, energy and food security.

Collaborative work with regional and global modelling centres on multi-model ensembles and event attribution contributes to advances in attribution science and understanding of changing monsoon patterns at regional scale. *SANDEE* complements this physical-science work by building regional capacity in environmental and development economics, enabling researchers to analyse the socio-economic impacts of climate change and to apply climate and hydrological data to policy-relevant questions on growth, poverty and environmental sustainability.

Recent cryosphere studies deepen the evidence base for Category A by providing long-term, HKH-wide glacier change information based on consistent methods. The *Changing dynamics of glaciers in the Hindu Kush Himalayan region from 1990 to 2020*⁴ develops the first comprehensive, multi-decadal glacier change dataset for the entire HKH, showing a 12 per cent loss of glacier area and a 9 per cent loss of ice reserves between 1990 and 2020, with accelerated retreat after 2010 and marked basin- and range-specific differences. The *HKH Glacier Outlook 2026*⁵ synthesises 50 years of field-based mass-balance observations from 38 glaciers (302 annual measurements, of which 270 are negative), identifies benchmark glaciers and major monitoring gaps, and sets priorities for strengthening cryosphere observation networks during the *International Year of Glaciers' Preservation 2025* and the *Decade of Action for Cryosphere Science (2025-2034)*.

The *Himalayan Climate Change Adaptation Programme (HICAP)* and the *Himalayan Adaptation, Water and Resilience (HI-AWARE)* programme both provide basin-scale climate and water information that directly responds to Category A needs. HICAP developed downscaled climate and water-availability scenarios for sub-basins of the Indus, Ganges, Brahmaputra and Salween–Mekong, synthesised in the *Himalayan Climate and Water Atlas*⁶ launched at COP21 and widely accessed by policy and research communities. HI-AWARE generated robust, region-specific climate projections for the Indus, Ganges and Brahmaputra river basins,

² Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (2019). *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-92288-1>

³ ICIMOD. (2023). *Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook*. (P. Wester, S. Chaudhary, N. Chettri, M. Jackson, A. Maharjan, S. Nepal, & J. F. Steiner [Eds.]). ICIMOD. <https://doi.org/10.53055/ICIMOD.1028>

⁴ Maharjan, S. B., & Sherpa, T. C. (2026). *Changing dynamics of glaciers in the Hindu Kush Himalayan region from 1990 to 2020*. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1122>

⁵ Azam, M. F. (2026). *HKH Glacier Outlook 2026: Understanding Change Through 50 Years of Field Observation* (p. 14 p.). International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1123>

⁶ HICAP. (2015). *The Himalayan Climate and Water Atlas; Impact of Climate Change on Water Resources in Five of Asia's Major River Basins*. International Centre for Integrated Mountain Development (ICIMOD).

using advanced model-selection and downscaling approaches to improve representation of high-altitude precipitation and extremes, and to support national adaptation planning processes.

Category B: Adaptation, loss and damage, and extreme events

ICIMOD's observations and research on cryosphere change, hydrometeorology and climate impacts underpin risk assessments and early-warning systems for extreme events such as floods, droughts, landslides and glacial lake outburst floods in the HKH. Across the initiatives listed in Table 1, Category B: Adaptation, loss and damage, and extreme events is addressed through long-term monitoring and analysis of snow, glaciers, glacial lakes and river flows, evaluations of community-based adaptation and livelihood diversification, integrated assessments of climate risks, and research on differentiated impacts for vulnerable groups.

The [Kailash Sacred Landscape Conservation and Development Initiative \(KSLCDI\)](#) has established long-term socio-ecological monitoring sites, including the first permanent GLORIA high-altitude vegetation monitoring site in the Himalayan region, alongside harmonised vegetation and cultural heritage maps and improved information on glaciers, land use and rangelands. Evidence from KSLCDI shows that ecosystem-based and nature-based approaches can enhance the resilience of mountain communities to climate-related hazards and stresses, benefitting more than 91,000 people, including over 37,000 women, while informing planning for water security, biodiversity conservation and livelihoods.

Recent event-focused studies in Nepal also contribute directly to Category B by analysing the evolution and cascading impacts of extreme events, and by informing early-warning systems and risk reduction. The [Thame Valley Glacial Lake Outburst Flood 2024⁷](#) investigation combines high-resolution satellite imagery, field surveys, UAV mapping and lake-risk classification to reconstruct how a rock avalanche into Upper Ngole Cho triggered a displacement wave, breached two moraine-dammed lakes in sequence and generated a hyper-concentrated flood that destroyed 25 houses and guesthouses, a school, a health post, a bridge and the intake of the Khumbu hydropower plant, displacing 135 people. The study classifies remaining lakes by risk and recommends targeted structural and non-structural measures, including geophysical surveys, channel stabilisation, and installation of hydrometeorological monitoring and early-warning systems, illustrating how post-disaster analysis can strengthen adaptation and loss-and-damage responses.

The rapid situational [analysis⁸](#) of the 2025 drought in Nepal's Madhesh Province addresses slow-onset extremes by combining rainfall and forecast analysis, satellite-based vegetation indices and ground data on groundwater and agriculture. It documents the progression from meteorological to hydrological and agricultural drought, with groundwater depletion, a rice transplantation rate of only 52 per cent compared with 92 per cent in 2024, an estimated 35–40 per cent of rice area under extreme drought stress (rising to 60–78 per cent in some districts) and a potential national rice production shortfall of 400,000–450,000 tonnes. The study highlights the disproportionate burden on women and smallholders and sets out immediate relief and longer-term adaptation options, including climate-resilient agronomic practices, groundwater recharge and strategic water-infrastructure investments.

The [HIGRID](#) project in the Lower Koshi River Basin complements these analyses by focusing on how local governments and communities respond to “too much and too little water” (floods and droughts) in an inclusive manner. Through support to 28 municipalities, HIGRID integrates gender equality, disability and social inclusion (GEDSI) into disaster risk-reduction planning and budgeting, scales community-based flood early-warning systems and nature-based solutions, and develops climate-resilient, inclusive value chains,

⁷ Maharjan, S. B., Sherpa, T. C., & Shrestha, A. B. (2025). Thame Valley Glacial Lake Outburst Flood 2024: Causes, impacts and future risks. International Centre for Integrated Mountain Development (ICIMOD); National Disaster Risk Reduction & Management Authority (NDRRMA). <https://doi.org/10.53055/ICIMOD.1101>

⁸ Shrestha, S., Shrestha, S., Dulal, B., & Khadgi, V. R. (2025). 2025 Drought in Nepal's Madhesh Province: A rapid situational analysis. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1097>

thereby providing practical examples of how adaptation progress can be designed, implemented and tracked at basin scale.

The [Springshed Management for Sustainable Water Resources](#) initiative treats springs as critical socio-ecological systems and documents how high-discharge perennial springs in Nepal and other HKH countries are under stress from in-migration, rising demand, rainfall decline and land-use change. Empirical studies reveal that springs have dried up in around three quarters of surveyed local government units in Nepal, with medium to severe problems in nearly half, and that drying trends are linked to roads and infrastructure, earthquakes, climate change, and other environmental drivers.

In Bhutan, action [research](#) on residential space heating compares traditional *bukhari* stoves with Himalayan rocket stoves in ten high-altitude households using low-cost air quality sensors and fuelwood measurements. The study finds that, despite confounding forest fire events, households using Himalayan rocket stoves exhibit lower indoor PM_{2.5} and CO concentrations and achieve substantial reductions in fuelwood consumption (up to 66 per cent in Uesu and 46 per cent in Katsho), indicating mitigation and health co-benefits alongside reduced exposure to cold stress.

The cross-country [analysis](#)⁹ of disability and disaster in the HKH region brings an explicit focus on non-economic losses and damages and on intersectional vulnerability to climate-related disasters. Using harmonised national surveys and disaster data for Bangladesh, India, Nepal and Pakistan, the research shows that disability is concentrated among older populations, people with low literacy and residents of remote, hazard-prone mountain areas, and that living in high-hazard districts is independently associated with higher disability prevalence after controlling for socio-economic factors. The study concludes that disaster risk is a structural driver of inequality, and that disability must be considered as a climate justice and adaptation challenge in policy and practice.

[HICAP](#) and [HI-AWARE](#) also contribute substantially to Category B by analysing climate risks and adaptation options across glacier- and snowmelt-dependent river basins and piloting concrete responses. HICAP's action-research and piloting pillars include [Resilient Mountain Villages](#) and community-based flood early-warning systems ([CB-FEWS](#)), which provided communities with tools, technologies and capacities to detect and respond to floods and other water-induced hazards. CB-FEWS was [recognised](#) through the UNFCCC Momentum for Change - Lighthouse Activity Award in 2016, and HICAP's work on gender-sensitive vulnerability assessments and livelihood diversification highlighted the importance of flexibility, empowerment and social protection in reducing risks for poor and marginalised groups. HI-AWARE's comparative, cross-scalar research across 12 sites in the Indus, Ganges, Gandaki and Teesta basins documents how increasing temperatures, heat waves and more intense precipitation events interact with socio-economic drivers to shape vulnerability. Its findings show that projected temperature increases of 3.5–6 degrees by 2100 in these basins far exceed the 1.5–2 degree global targets and that downstream water consumption, driven by socio-economic development, will be a dominant driver of future water gaps, with important implications for agriculture and food security. HI-AWARE's pilot interventions and adaptation pathways work – including climate-smart water-management practices, gender-sensitive livelihood measures and migration as an adaptive strategy – provide evidence on the effectiveness, limits and scalability of community-based adaptation across mountain and downstream contexts.

Category C: Ecosystems and nature-based solutions

Category C: Ecosystems and nature-based solutions is addressed through ICIMOD's portfolio of landscape, biodiversity and ecosystem-based adaptation work, which contributes to understanding climate impacts on ecosystems and to testing and scaling nature-based solutions (NbS) in mountain and downstream environments. The Kailash, Springs and Rangelands initiatives, in particular, respond to Category C

⁹ ICIMOD. (2026). HKH Disability and Disaster Report 2025-2026. HimalDoc.

sub-items on opportunities and challenges of implementing NbS, climate change impacts and risks for cryosphere-related ecosystems, and vulnerability and resilience of coupled human–natural systems.

[KSLCDI](#) operationalises a transboundary ecosystem approach to conserve biodiversity, sustain ecosystem services and enhance livelihoods in the Kailash Sacred Landscape across China, India and Nepal. The initiative applies integrated ecosystem management, ecosystem-based adaptation, sacred landscape and value-chain approaches, and establishes long-term environmental and socio-ecological monitoring sites, including GLORIA vegetation plots, to track climate and land-use change impacts on high-altitude ecosystems.

The [Springshed Management initiative](#) applies a six-step protocol that includes spring inventory and mapping, hydrogeological assessment, analysis of social, gender and governance dimensions, recharge-area and springshed planning, and hydrological and socio-economic impact assessment. This approach demonstrates how springshed management functions as a nature-based solution that can improve water security while generating co-benefits for biodiversity, climate resilience and local livelihoods in mountain communities.

The [Sustainable Management of High-Altitude Rangelands as Nature-based Solutions](#) intervention addresses alpine and sub-alpine rangelands and wetlands as critical socio-ecological systems that support biodiversity, carbon storage, water regulation and the livelihoods and cultures of an estimated 20 million pastoralists and agro-pastoralists in the HKH. Through co-management pilots, rotational grazing, restoration activities and tools such as the Bhutan *tsamdro* and herder mobility dashboard, the programme shows that community-led interventions can increase fodder availability and soil organic carbon within a few years while reducing degradation and strengthening pastoralist resilience.

Both [HICAP](#) and [HI-AWARE](#) incorporate ecosystem-based and nature-based approaches into their adaptation portfolios, responding to Category C priorities. HICAP demonstrates how ecosystem-based adaptation and payment for ecosystem services can be tailored to different agro-ecological zones, for example through [Resilient Mountain Villages](#) that refine local practices such as *jholmol* bio-pesticide and fertiliser using scientific knowledge, alongside sustainable energy technologies such as solar power and biogas. HI-AWARE pilots and evaluates ecosystem-based measures such as wetland restoration and sustainable water management as part of climate-resilient water and livelihood strategies, underscoring the importance of integrating NbS into basin-level adaptation planning.

The Thame GLOF [investigation](#), the HKH-wide glacier-change [analysis](#) and the [HKH Glacier Outlook](#) all speak to Category C(b) by documenting how rapid cryospheric change reshapes mountain ecosystems and hazard regimes. Together they link multi-decadal glacier mass-balance trends and regional patterns of retreat to increased risks of glacial lake outburst floods and downstream geomorphic change, thereby providing essential evidence for ecosystem-based and nature-based solutions that account for evolving cryosphere–water–ecosystem interactions.

Category D: Mitigation, related technologies, and GHG emissions and reporting

ICIMOD supports Category D: Mitigation, related technologies, and GHG emissions and reporting by improving understanding of emissions, removals and co-benefits of mitigation actions in mountain and regional contexts and by informing science-based reporting and policy decisions. This includes methodological support and data for REDD+ and land-use, land-use change and forestry (LULUCF), analyses of short-lived climate pollutants such as black carbon, and work on sustainable mountain economies, renewable energy and just transitions.

The [Clean Bricks initiative](#) exemplifies sector-specific mitigation and technology transition informed by systematic observation and measurement. The project generated evidence for policy reform by measuring stack emissions from traditional fixed-chimney bull’s-trench kilns and improved zig-zag kilns in Nepal and Pakistan, conducting energy audits for kilns using coal and biomass pellets, and establishing demonstration

kilns that served as training and learning sites. The findings show that adoption of zig-zag technology can reduce emissions by up to 600 tonnes of carbon dioxide per kiln annually, and that conversion of approximately 7,000 kilns in South Asia has already avoided an estimated 106,326.6 tonnes of carbon dioxide, with significant potential for further reduction if cleaner technologies are scaled to the region's roughly 100,000 kilns.

The residential space-heating [pilot](#) in Bhutan, described under Category B, provides complementary evidence that cleaner, more efficient heating technologies can simultaneously reduce indoor air pollution, lower fuelwood demand and decrease emissions in cold, high-altitude settlements. Together, these initiatives contribute to improved understanding of mitigation options and co-benefits in sectors that are highly relevant for mountain communities and for national climate and air-quality goals.

Category E: Cross-cutting issues

ICIMOD's work is inherently cross-sectoral and engages with knowledge systems, equity and sustainable development, thereby contributing to Category E: Cross-cutting issues. [Strategy 2030](#) and the [HKH Call to Action](#)¹⁰ emphasise the need to harness synergies between mitigation, adaptation and the Sustainable Development Goals, and to manage trade-offs in ways that benefit mountain communities and ecosystems.

Many of the initiatives listed in Table 1 co-produce knowledge with local communities and Indigenous Peoples, integrating Indigenous and traditional knowledge with scientific methods in risk assessments, adaptation planning and landscape management. The disability and disaster [study](#) provides a clear example of intersectional analysis that recognises disability as a climate justice and adaptation issue at the interface of gender, poverty, geography and access to services, and translates these insights into recommendations for inclusive climate and disaster risk reduction policy frameworks.

[SANDEE](#) plays a central cross-cutting role by building a critical mass of environmental and development economists in South Asia and the HKH, linking training, mentoring, research grants and policy engagement. Over two and a half decades, SANDEE has supported more than 250 research grants, trained over 1,500 professionals through summer and winter schools and other courses, and contributed more than 300 peer-reviewed journal articles and book chapters, thereby strengthening the analytical foundations for climate- and environment-related policymaking in the region. The [HIGRID](#) project and the Madhesh drought analysis further illustrate how cross-cutting approaches can integrate equity, gender and disability into climate and disaster risk governance. [HIGRID](#) works with municipalities, organisations of persons with disabilities, Indigenous and local communities, entrepreneurs and youth to embed GEDSI principles in disaster risk-reduction planning, gender-responsive budgeting and the design of nature-based and livelihood solutions in the Lower Koshi. The Madhesh drought [study](#) explicitly examines differentiated drought impacts on women and smallholder farmers and connects drought response to [Sustainable Development Goals](#) on poverty, food security, water, gender equality and climate action, thereby linking local evidence to global climate-justice discussions under the Convention and the Paris Agreement.

[HICAP](#) and [HI-AWARE](#) are also central to Category E through their emphasis on gender, equity, upstream-downstream linkages and translation of science into policy and practice. HICAP explicitly placed poor and vulnerable women and men at the centre of its research, using gender-disaggregated vulnerability assessments and targeted measures such as financial literacy training for remittance-receiving women, and generated evidence on how a combination of multiple drivers, beyond climate alone, shapes vulnerability across the region. HI-AWARE combined biophysical, socio-economic and governance analysis with stakeholder-driven adaptation pathways and has informed IPCC assessments and national adaptation processes through its contributions to the IPCC Special Reports and the Sixth Assessment Report, as well as

¹⁰ ICIMOD. (2020). The HKH Call to Action to sustain mountain environments and improve livelihoods in the Hindu Kush Himalaya. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1>

through datasets and working papers on climate projections, vulnerability, migration and adaptation costs and benefits.

Cooperation and capacity-building dimensions

Beyond specific research themes, ICIMOD's research and systematic observation activities are implemented through extensive cooperation with RMC governments, academic and research institutions, civil society and international partners. Regional networks such as the [Himalayan University Consortium](#), the [Upper Indus Basin Network](#) and [SANDEE](#) foster joint research, data and knowledge sharing, and capacity building for early-career and established researchers in the HKH.

Targeted training, fellowships and technical support strengthen institutional capacities in RMCs for climate and hydrological modelling, cryosphere monitoring, GHG and short-lived climate pollutant inventories, and ecosystem-based adaptation and mitigation planning. The Springs and Rangelands initiatives, for example, have delivered practitioner manuals, field-based training, regional trainings for municipalities and sector institutions, gender-responsive capacity-building and the establishment of community resource-person networks to support sustained local observation and management¹¹.

Open-access data and knowledge platforms, and flagship assessments such as the [Hindu Kush Himalaya Assessment](#) and thematic outlooks on [water](#), [energy](#)¹² and shocks such as [COVID-19](#)¹³, improve access to regional information for Parties and for global assessments. Cooperation with the UNFCCC secretariat under the [ICIMOD-UNFCCC partnership](#) links regional research more directly to the needs of Parties for implementation of the Paris Agreement, including the Enhanced Transparency Framework (ETF) and processes under the Global Stocktake and the Global Goal on Adaptation. These cooperative and capacity-building elements respond directly to SBSTA's call to broaden participation from developing-country scientific communities in the research dialogue and to strengthen systematic observation in developing countries ([FCCC/SBSTA/2025/4, Add.19-34](#)).

Looking ahead

We appreciate the opportunity provided by the SBSTA research dialogue and the RSO work programme to share an overview of research and systematic observation in the Hindu Kush Himalaya (HKH). The mapping of research needs since SBSTA 22 and the request at SBSTA 62 to assess progress offer an important platform to better integrate mountain-focused evidence into the Convention and the Paris Agreement.

Despite this progress, the HKH region remains underrepresented in global observation networks, assessments, and climate finance and technology frameworks. Many data gaps identified since SBSTA 22 persist, and scientific contributions from HKH developing countries remain under reflected. The current RSO process provides a timely opportunity to enhance the visibility of HKH-specific risks and solutions, while strengthening regional capacities through sustained support for long-term observations, inclusive research partnerships, and better integration into global processes.

ICIMOD stands ready to continue working with the UNFCCC secretariat, Parties, and partners to advance RSO in the HKH region, including on cryosphere change, extremes, slow-onset events, and nature-based solutions, and to support key processes such as the Enhanced Transparency Framework, Global Stocktake, Global Goal on Adaptation, and work on loss and damage. Sustained investment in observation systems,

¹¹ Verma, R; Khadka, M (eds) (2016) Gender and pastoralism in the rangelands of the Hindu Kush Himalayas: Knowledge, culture, and livelihoods at the margins of the margins. Kathmandu: ICIMOD

¹² Hussain, A., Malla, A., Dhananjayan, P., Ahmad, B., Bajracharya, S., Maharjan, A., Nepal, M., Pandey, A., Qamer, F. M., Rasul, G., Sarangi, G. K., Shrestha, A. B., Silpakar, S., Siyal, A. W., Vaidya, R. A., & Wester, P. (2025). Together we have more power: Status, challenges, and the potential for regional renewable energy cooperation in the Hindu Kush Himalaya. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1090>

¹³ ICIMOD. (2020). COVID-19 impact and policy responses in the Hindu Kush Himalaya - Policy Paper. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.2>

interdisciplinary research, and institutional capacity will be critical to inform ambitious and equitable climate action in the decade ahead.

Annex 1: Flagship HKH assessments and outlooks relevant to SBSTA

Geographic scope: HKH regional

Timeline: Ongoing

RSO research needs (A–E)

- Category A: Understanding climate change, related climate data, and scenarios. Integrated assessment of climate trends, cryosphere change and scenarios.
- Category B: Adaptation, loss and damage, and extreme events. Analysis of climate impacts, risks and adaptation responses.
- Category C: Ecosystems and nature-based solutions. Evidence on ecosystem services, NbS and ecosystem vulnerability.
- Category E: Cross-cutting issues. Regional synthesis and support to global assessment processes.

Summary of research

The [Hindu Kush Himalaya Assessment](#) provides the first comprehensive assessment of the state of the HKH environment, societies and economies, synthesising data on climate trends, cryosphere change, water resources, biodiversity, livelihoods and governance. The [WISE Outlook](#) and related publications build on this foundation to provide updated analysis of water, ice, societies and ecosystems and to explore future scenarios under different warming pathways and policy choices.

These assessments combine observational data, remote-sensing products, modelling, scenario analysis and stakeholder engagement to inform both regional policy processes and global assessments, including IPCC reports. They highlight, among other findings, that even under 1.5-degree global warming, substantial glacier loss is expected in the HKH; that climate change is intensifying extremes and compounding risks across water, energy and food systems; and that mountain communities face intersecting vulnerabilities that require integrated, multi-sectoral responses. These publications have provided contributions to IPCC assessment cycles and other global science–policy processes and have enhanced the visibility of the HKH region and its research gaps and needs within global climate and development agendas.

Key outputs

1. **The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people.** (Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (2019). The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people. Springer International Publishing. <https://doi.org/10.1007/978-3-319-92288-1>).
2. **Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook.** (Wester, P., Chaudhary, S., Chettri, N., Jackson, M., Nepal, S., & Steiner, J. F. (2023). Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1028>).
3. **Together we have more power: Status, challenges, and the potential for regional renewable energy cooperation in the Hindu Kush Himalaya.** (Hussain, A., Malla, A., Dhananjayan, P., Ahmad, B., Bajracharya, S., Maharjan, A., Nepal, M., Pandey, A., Qamer, F. M., Rasul, G., Sarangi, G. K., Shrestha, A. B., Silpakar, S., Siyal, A. W., Vaidya, R. A., & Wester, P. (2025). Together we have more power: Status, challenges, and the potential for regional renewable energy cooperation in the Hindu Kush Himalaya. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1090>).

4. **Review of climate action and environmental policies of the Hindu Kush Himalayan region - Summary for policymakers.** (Kandel, P. (2025). Review of climate action and environmental policies of the Hindu Kush Himalayan region - Summary for policymakers. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1092>).
5. **COVID-19 impact and policy responses in the Hindu Kush Himalaya - Policy Paper.** (ICIMOD. (2020). COVID-19 impact and policy responses in the Hindu Kush Himalaya - Policy Paper. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.2>).
6. **Lessons from the COVID-19 pandemic for the Hindu Kush Himalaya countries to prepare for future shocks and disruptions.** (ICIMOD. (2025). Lessons from the COVID-19 pandemic for the Hindu Kush Himalaya countries to prepare for future shocks and disruptions. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1095>).

Annex 2: SANDEE – The South Asian Network for Development and Environmental Economics

Geographic scope: South Asia and the HKH region

Timeline: 1999-ongoing

RSO research needs (A–E)

- Category A: Understanding climate change, related climate data, and scenarios. Economic research that interprets climate and environmental data for policy.
- Category E: Cross-cutting issues. Capacity-building in environmental and resource economics and support for policy-relevant research.

Summary of activities and relevance

SANDEE is a regional network that strengthens the capacity of researchers and institutions to conduct rigorous, policy-relevant research at the intersection of economic development, poverty and environmental change. It operates through competitive research grants, structured mentoring, training programmes and policy engagement, with an explicit focus on building a critical mass of environmental and development economists in South Asia and the HKH.

Over 25 years, SANDEE has supported more than 250 research grants, trained over 1,500 professionals through summer and winter schools and other courses, and produced around 300 peer-reviewed publications and 100 policy briefs, contributing to a pipeline of economists who use climate and environmental data to inform development and environmental policy. Alumni surveys in 2019, 2022 and 2025 show that SANDEE researchers are actively engaged in teaching, policy advising and applied research on climate- and environment-related topics.

For more information about SANDEE, please visit here: <https://www.icimod.org/initiative/sandee/>.

Key outputs

1. Research grants and publications on the economics of climate change, natural resource management and environmental policy. For a complete list of publications, please visit this link: <https://www.icimod.org/initiative/sandee-publications/>.
2. Training programmes in environmental and resource economics, research methods and policy communication.
3. A regional community of practice linking universities, research institutes, policymakers and practitioners.

Annex 3: Action research on residential space heating as a gender-inclusive and socially responsible solution

Main partner organisations: Foreign, Commonwealth & Development Office (FCDO), Government of the United Kingdom; local governments of Katsho and Uesu Gewogs in Haa; Dzongkhag Administration, Haa, Royal Government of Bhutan; Jigme Singye Wangchuck School of Law (JSW Law), Bhutan.

Timeline: 2024–2025 (ongoing pilot)

Geographic scope: Bhutan and Nepal, with major focus on high-altitude settlements in Bhutan.

RSO research needs (A–E)

- Category B (Adaptation, loss and damage, and extreme events): The project contributes to understanding how improved space-heating technologies can reduce health risks and vulnerability to cold stress and indoor air pollution in climate-vulnerable mountain communities.
- Category D (Mitigation, related technologies, and GHG emissions and reporting): The study generates evidence on emission reductions and fuelwood savings associated with cleaner residential heating technologies.
- Category E (Cross-cutting issues): The project adopts a gender-inclusive, socially responsible approach that considers differentiated impacts and benefits for women and marginalised groups.

Summary of research

Objective: By examining the household air pollution levels and fuelwood consumption rates between the two stove types, the study seeks to generate evidence-based recommendations to inform policies and programmes that promote cleaner, more efficient and sustainable heating technologies in rural communities. The main objectives of the pilot action research are:

1. To measure and compare PM_{2.5} levels from the use of traditional Bukhari and Himalayan Rocket Stoves, using before and after design.
2. To assess and compare the amount of fuelwood consumed by each stove type under similar household conditions.

Methodology: Ten households were randomly selected across Katsho and Uesu Gewogs (village blocks) using a lottery system to avoid bias. These households, located between 2640–3100 meters elevation, used traditional Bukhari stoves and later adopted Himalayan Rocket Stoves. Air quality and fuelwood use were analysed during two selected periods. Non-intervention data with Bukhari stoves was collected from 28 February to 12 March 2025. Himalayan rocket Stoves were installed on March 13, followed by post-intervention data collection from 14 to 25 March 2025. The measured PM (particulate matter) 2.5 and CO (carbon monoxide) was used to assess indoor air quality and correspondingly measured ambient air quality in the two Gewogs (Katsho and Uesu). Atmos low-cost air quality monitoring sensors were used in ten households and AirBeam air quality monitoring sensors were used for measuring the ambient air quality in two Gewog offices. A structured questionnaire survey was conducted to assess fuelwood consumption, and each household was also provided with a pre-weighed quantity of fuelwood for meticulous estimation of fuelwood consumption. In addition, emissions of PM_{2.5}, CO, and CO₂ in the Haa district were estimated using emission factors sourced from published South Asian literature.

Main findings and conclusions: The concentrations of indoor air pollutants were compared during the usage/operations of old Bukhari stoves and Himalayan rocket stoves. Overall, households while using

Himalayan rocket stoves showed slightly lower PM2.5 and CO concentrations as compared to those at the time of using old Bukhari stoves. Results showed that only three out of ten households exhibited higher concentrations during the use of Himalayan rocket stoves. The increase in indoor and ambient air pollution during the Himalayan rocket stove installation and measurement period can be attributed to a massive forest fire (18 to 21 March 2025) near the settlement, which significantly impacted air quality. The findings indicate that the Himalayan rocket stove offers significant potential to reduce indoor air pollution compared to traditional old Bukhari stoves. The rocket stove not only consumes less fuelwood for heating but also demonstrates substantial reductions in household fuelwood usage up to 66% in Uesu and 46% in Katsho. These results suggest that the Himalayan rocket stoves have the potential to reduce indoor air pollutants compared to traditional old Bukhari stoves. It can also reduce emissions and fuelwood consumption by 51%. Further analysis is planned to address inconsistencies and to consolidate findings, but the pilot already demonstrates that cleaner heating technologies can play an important role in climate-resilient and low-emission development pathways in cold, high-altitude settings.

Key outputs

1. **Comparative Study of Traditional and Improved Heating Stoves: Impacts on Indoor Air Quality and Fuelwood Use in Rural Bhutan.** (ICIMOD. (2026). Comparative Study of Traditional and Improved Heating Stoves: Impacts on Indoor Air Quality and Fuelwood Use in Rural Bhutan. HimalDoc. Access at: <https://lib.icimod.org/records/y84nt-42p52>)
2. **Pilot datasets** on indoor and ambient air quality and household fuelwood use in high-altitude settlements in Bhutan.
3. **Practical learning** for scaling cleaner heating technologies in collaboration with local governments and communities.
4. Strengthened **collaboration** between ICIMOD, development partners and national agencies on integrated air-pollution, health, gender and climate objectives.

Annex 4: Clean Bricks

Main partner organisations: Foreign, Commonwealth & Development Office (FCDO), Government of the United Kingdom; Climate and Clean Air Coalition (CCAC); national partners in Nepal, Pakistan, India and Bangladesh

Timeline: 2014–2021

Geographic scope: Nepal, Pakistan, India and Bangladesh, with major focus on Nepal and Pakistan

RSO research needs (A–E)

- Category B (Adaptation, loss and damage, and extreme events): By reducing air pollution and improving working conditions, the project supports more resilient livelihoods in a sector that employs many vulnerable workers.
- Category D (Mitigation, related technologies, and GHG emissions and reporting): The project generates empirical evidence on the mitigation potential of improved brick-kiln technologies and alternative fuels.
- Category E (Cross-cutting issues): The initiative strengthens regional collaboration and knowledge exchange among brick sector stakeholders and supports policy reform.

Summary of research

Objective: The overarching objective is to support transformation of the South Asian brick sector into a cleaner and healthier industry with significantly reduced environmental impacts. The project seeks to demonstrate the technical and economic feasibility of improved kiln designs and cleaner fuels, and to inform policy reforms and sectoral strategies.

Methodology: The project generated evidence for policy reform by measuring stack emissions from both traditional and improved kilns. It combined capacity building with targeted policy recommendations to support the adoption of zig-zag technology. Showcase kilns were established across five provinces in Nepal, serving as demonstration sites where nearby kiln owners could observe, learn, and adopt the technology; these early adopters also acted as master trainers. In addition, two similar demonstration kilns were set up in Punjab, Pakistan. Energy audits were conducted in brick kilns using biomass pellets, coal, and mixed fuels (coal and biomass pellets) to assess the feasibility of replacing coal with densified biomass. Given the sector's heavy reliance on coal, both climate and economic considerations strongly support a transition to cleaner alternative fuels.

Main findings and conclusions: The project has delivered a trifecta of benefits, social, environmental, and economic. The brick sector in South Asia, often viewed as informal, neglected, and highly polluting, has seen a positive shift through ICIMOD's efforts. By building trust and confidence among brick entrepreneurs, the project has encouraged greater openness to change, learning, and continuous improvement. The adoption of zig-zag technology, along with associated mechanization options, has the potential to reduce up to 600 tons of CO₂ emissions per kiln annually. Around 7,000 kilns in South Asia had converted from fixed-chimney to zig-zag designs, leading to an estimated reduction of 106,326.6 tonnes of carbon dioxide and associated reductions in short-lived climate pollutants such as black carbon. Additionally, the promotion of renewable energy sources, such as biomass pellets, further contributes to emission reduction. The initiative has also strengthened regional collaboration among brick sector stakeholders from Nepal, Bangladesh, Pakistan, and India, culminating in the establishment of the Federation of South Asian Brick

Kiln Associations (FABKA). There are 100000 brick kilns in South Asia, adopting zig-zag or cleaner technologies will have potential in reducing CO₂ and Black carbon. However, zig-zag remains an intermediate cleaner technology. More advanced options, such as tunnel kilns, are significantly more efficient and cleaner, but their high capital cost remains a major constraint.

For more information on the project, please visit: <https://www.icimod.org/initiative/air-pollution-solutions/>.

Key outputs

1. **A Comparative Study of Stack Emissions from Straight-Line and Zigzag Brick Kilns in Nepal.** (Nepal, S., Mahapatra, P. S., Adhikari, S., Shrestha, S., Sharma, P., Shrestha, K. L., Pradhan, B. B., & Puppala, S. P. (2019). A Comparative Study of Stack Emissions from Straight-Line and Zigzag Brick Kilns in Nepal. *Atmosphere*, 10(3), 107. <https://doi.org/10.3390/atmos10030107>).
2. **Brick sector in Pakistan - Fact Sheet.** (ICIMOD. (2019). Brick sector in Pakistan - Fact Sheet. International Centre for Integrated Mountain Development (ICIMOD), access here: <https://lib.icimod.org/records/hbn2k-xkm21>).
3. **Brick sector in Nepal - Fact Sheet.** (ICIMOD. (2019). Brick sector in Nepal - Fact Sheet. International Centre for Integrated Mountain Development (ICIMOD), access here: <https://lib.icimod.org/records/1t4jt-maf42>).
4. **Brick sector in Bangladesh - Fact Sheet.** (ICIMOD. (2019). Brick sector in Bangladesh - Fact sheet. International Centre for Integrated Mountain Development (ICIMOD), access here: <https://lib.icimod.org/records/yvvez-8yt13>).
5. **Burnt clay brick sector in India - Fact Sheet.** (ICIMOD. (2019). Burnt clay brick sector in India - Fact sheet. International Centre for Integrated Mountain Development (ICIMOD), access here: <https://lib.icimod.org/records/7g3bz-qnp57>).
6. Demonstration kilns and training modules that support technology transfer and adoption of cleaner kiln designs.
7. Regional **collaboration** among brick sector stakeholders and the establishment of FABKA.

Annex 5: Kailash Sacred Landscape Conservation and Development Initiative (KSLCDI)

Main partner organisations

- **China:** Kunming Institute of Botany (KIB) and Chengdu Institute of Biology (CIB) of the Chinese Academy of Sciences (CAS)
- **India:** Ministry of Environment, Forest and Climate Change (MoEFCC); G.B. Pant National Institute of Himalayan Environment and Development (GBPIHED); Wildlife Institute of India (WII), Central Himalayan Environment Association (CHEA); Uttarakhand State Biodiversity Board
- **Nepal:** Ministry of Forests and Environment (MoFE); Department of Forest and Soil Conservation (DoFSC); Department of Hydrology and Meteorology (DHM); Department of National Parks and Wildlife Conservation (DNPWC); Department of Plant Resources (DPR), Tribhuvan University; Research Centre for Applied Sciences and Technology (RECAST); Ujyalo Nepal; HIMAWANTI Nepal, National Trust for Nature Conservation (NTNC); Dabur Nepal; Provincial and district forest authorities in Far-Western Province, Community forest user groups; Women's cooperatives, and local governments.
- **International:** ICIMOD (lead); UNEP, GIZ, DFID

Timeline: 2012–2022 (Phase I and II completed; activities now being institutionalised)

Geographic scope: Regional/Transboundary. The initiative was implemented across the Kailash Sacred Landscape spanning the Tibet Autonomous Region of **China**, Uttarakhand in **India**, and western **Nepal** (Humla, Baitadi, Bajhang, and Darchula), covering about 31,000 km² around Mount Kailash and linked headwater ecosystems and communities.

RSO research needs (A–E)

- Category C(a): Opportunities and challenges of implementing nature-based solutions in land systems in support of climate adaptation and mitigation. The project addressed it with the primary focus on the holistic NBS via participatory ecosystem management, livelihoods, and transboundary governance.
- Category C(b): Climate change impacts and risks for the cryosphere and related ecosystems. Activities like the glacier retreat/snowmelt variability monitoring, glacial lake outburst flood (GLOF) risk mapping, cryosphere-water-ecosystem linkages in high-altitude basins were also carried out in the project.
- Category C(d): Vulnerability of natural and human ecosystems and strengthening their resilience. Was addressed via land cover/fragmentation analysis, human-wildlife conflict (HWC) mitigation, and resilience-building pilots, including studies on high-altitude grazing lands.
- The initiative also has a secondary contribution to C(c): Emissions and removals from terrestrial ecosystems, and information on ecosystems with high-carbon reservoirs through agroforestry, ecosystem-service management, and landscape interventions with mitigation co-benefits.

Summary of research

Objective: KSLCDI aimed to operationalise a transboundary ecosystem approach to conserve biodiversity, sustain ecosystem services and enhance livelihoods in the Kailash Sacred Landscape amidst climate change and socioeconomic pressures. The initiative has a twenty year goal to ensure the transboundary Kailash Sacred Landscape is conserved and developed sustainably. Phase I laid this foundation through five major components: innovative livelihoods, ecosystem management, access and benefit sharing, long-term

conservation and monitoring, and regional cooperation/knowledge management. Phase II specifically focused on institutionalizing the Regional Cooperation Framework (RCF), scaling up climate-resilient livelihoods, and establishing long-term socio-ecological monitoring.

Methodology: The KSLCDI employed an integrated landscape approach based on the Regional Cooperation Framework, community based local ecosystem management plans, action research in pilot sites, harmonized research protocols, and long term environmental and socio ecological monitoring. Core methods include Integrated Ecosystem Management (IEM) and Ecosystem based Adaptation (EbA), supported by standardized GLORIA vegetation monitoring sites. The approach integrated ecosystem service valuation, land use and cultural heritage mapping, and vulnerability assessments measuring exposure, sensitivity, and adaptive capacity. It also applied a Value Chain approach to strengthen "sacred" mountain brands. Transboundary cooperation was facilitated through harmonized research protocols, "Landscape Journeys" for policy dialogue, and community-based monitoring systems. Scientific evidence was paired with local knowledge, capacity building, and participatory natural resource management to design conservation and livelihood interventions aligned with multi-scale realities across borders.

Main findings and conclusions: The initiative generated strong evidence that nature-based and ecosystem-based approaches can be operationalized in transboundary mountain systems through locally grounded yet regionally coordinated action. Key achievements included community-based ecosystem management plans, harmonized three-country vegetation and cultural heritage maps, long-term environmental and socio-ecological monitoring sites, the first permanent GLORIA site in the Himalayan region, and improved information on glaciers, forests, land use land cover, rangelands, and socioeconomic conditions. These outputs helped fill critical data gaps while also informing planning for water security, biodiversity conservation, livelihoods, and ecosystem resilience. Through Kailash project, 91,370 people benefited from project activities, including 37,844 women, people and produced 120 publications and related knowledge products and pilot value-chain interventions increased incomes by up to 10% or more in some communities. Recent research linked to the landscape strengthens this evidence base: a 2021 study on KSL China found that integrated landscape management reduced socio-ecological vulnerability and improved resilience, while a 2024 glacier study in the transboundary KSL reported 1,941 glaciers covering $1,169.04 \pm 27.71 \text{ km}^2$ in 2020 and a 25.5% area retreat since 1990, underscoring mounting cryosphere risks for ecosystems and livelihoods.

KSLCDI serves as a global model for the CBD (Convention on Biological Diversity) Programme of Work on Mountain Biodiversity. It contributes to the Paris Agreement's emphasis on NBS for adaptation and mitigation (Articles 5 and 7) goals by monitoring cryosphere changes and promoting ecosystem-based adaptation (EbA) in one of the world's most climate-sensitive regions. It provides ground-level evidence for IPCC AR7 regarding high-altitude tipping points and supports the UN Decade on Ecosystem Restoration. The initiative also has strong linkages to other global science and policy with engagement to the CBD, IPBES, UNFCCC, CITES, and the Global Landscapes Forum, while Phase II deepened the science-policy interface through academic platforms such as Kailash CAFE and through locally grounded planning and scaling processes. KSLCDI provide a strong example of how mountain landscape research can translate into action on ecosystem resilience, community adaptation, and cross-border cooperation.

For more information on the project, please visit: <https://www.icimod.org/initiative/ksl/>.

Key outputs

1. KSLCDI has produced 120 publications and related knowledge products. Some major ones include:
 - a. ICIMOD. (2020). Kailash Sacred Landscape Conservation and Development Initiative (KSLCDI) Phase I report 2012-2017. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.945>.

- b. Nepal, M., Das, S., Rai, R. K., Bhatta, L. D., Somanathan, E., Kotru, R., Khadayat, M. S., Rawal, R. S., & Negi, G. C. S. (2017). Valuation of Ecosystem Services in the Kailash Sacred Landscape; ICIMOD Research Report 2017/2. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/jbheg-v3796>.
 - c. Bubb, P., Soesbergen, A. V., Bisht, N., Singh, G., Joshi, S., Aryal, K., Danks, F. S., Rawat, G. S., Bhuchar, S., Wu, N., Kotru, R., & Yi, S. (2017). Planning Management for Ecosystem Services: An Operations Manual. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/6ayrd-yfh98>.
 - d. NA, . (2015). An Integrated Springshed Management Approach Linking Science, Policy, and Practice; Collaborative applied research in the Kailash Sacred Landscape (India and Nepal). International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/c06pm-qce77>.
 - e. Shi, P.-li ., Duan, C., Wang, L., Wu, N., Kotru, R., & Gurung, J. (2021). Integrated landscape approaches to building resilience and multifunctionality in the Kailash Sacred Landscape, China. In Journal of Mountain Science (Numbers 08 April 2021). <https://doi.org/10.1007/s11629-020-6500-x>
2. The **Kailash Knowledge-based Information System (KBIS) and other data platforms** that support long-term monitoring and planning.
 3. KSLCDI is built around **regional cooperation** among China, India, and Nepal and operationalized through multi-level partnerships linking governments, research institutions, civil society, communities, and the private sector.
 4. **Capacity-building** has included community-based ecosystem management, responsible tourism, participatory NRM planning, agroforestry, transboundary forums and exchanges, and academic/research networking through Kailash CAFE.

Annex 6: Springshed Management for Sustainable Water Resources

Main partner organisations

- **Bhutan:** Ministries of Water Resources (Bhutan) Watershed Management Division and Department of Water; Department of Forests and Park Services (Bhutan)
- **India:** Ministries of Water Resources (India); GIZ India; Advanced Center for Water Resources Development and Management (ACWADAM); NITI Aayog; G.B. Pant National Institute of Himalayan Environment; Indian Institute of Technology (IIT) Roorkee; Local communities and local governments in India
- **Nepal:** Ministries of Water Resources (Nepal, India, Bhutan; Local Provincial Economic Development (LPED) project in Nepal; various local municipalities in Nepal (e.g., Kavre, Dhankuta); local NGOs (e.g., Nepal Water Conservation Foundation, Himalayan Grassroots Women’s Network); Local communities and local governments in Nepal
- **Bangladesh:** Watershed Management Division
- **International:** ICIMOD (lead); Swiss Agency for Development and Cooperation (SDC); GIZ; FAO

Timeline: 2015–ongoing (initial pilot projects commenced in 2015, ongoing efforts for springshed management)

Geographic scope: Regional / multi-country. Over the spring dependent mountain systems across HKH, with documented work and outputs in Nepal, India, Bhutan and Bangladesh, and knowledge products framed for all ICIMOD regional member countries.

RSO research needs (A–E)

- Category C(a): Opportunities and challenges of implementing nature-based solutions in land systems in support of climate adaptation and mitigation. Focus on springs as critical water sources under threat from climate and land-use change, and on springshed restoration as a nature-based solution.
- Category C(d): Vulnerability of natural and human ecosystems and strengthening their resilience. Analysis of the vulnerability of coupled human–natural systems that depend on springs, and interventions to build resilience.
- Category B: Adaptation, loss and damage, and extreme events. Evidence on how springshed management can reduce water insecurity and associated climate risks in mountain communities.

Summary of research

Objective: The Springshed Management initiative aims to enhance community resilience to water scarcity by reviving and sustainably managing springsheds. This project focuses on restoring groundwater recharge, improving water quality, and promoting integrated water resource management practices in the HKH region, benefitting rural communities reliant on spring water.

Methodology: The initiative is built around a six-step protocol developed by ICIMOD and partners, combining spring inventory and mapping, hydrogeological assessment, analysis of social, gender and governance dimensions, recharge-area and springshed planning, and hydrological and socio-economic impact assessment to support evidence-based scaling. The protocol was developed through regional consultation and adapted to RMC contexts; implementation emphasises participatory science, local government engagement and women’s participation in decision-making and technical training.

Main findings and conclusions: The initiative has generated a strong body of applied research and decision-support evidence. A 2021 ICIMOD working paper on Godavari, Nepal documented how high-discharge perennial springs are under stress from in-migration, rising demand, and long-term rainfall decline. A 2025 ICIMOD-linked citizen science dataset mapped spring sources in Kavre, Nepal and made them available for broader analysis and decision support. A 2023 Nepal-wide study found that springs had dried up in 74% of local government units, with medium to severe problems in 44%, and identified roads and infrastructure, earthquakes, and climate change as major drivers. A 2024 watershed study in far-west Nepal mapped 1,122 springs, found that 73% showed a continuous decline in flow and 2% had already dried up, and linked drying trends to land-use change, rising temperature, intense rainfall, population growth, and road expansion. A 2024 socioeconomic assessment found positive benefit-cost ratios in three of four scenarios, showing that spring revival can be economically justified under suitable local conditions. Research indicates that roughly 50% of springs in the Indian Himalayan Region have either dried up or show significantly reduced discharge due to climate change and land-use shifts.

The project contributes to SDG 6 (Clean Water and Sanitation) and supports national climate goals (NAPs) in Nepal, Bhutan, and India. The data is also relevant for IPCC assessments on mountain water cycles and groundwater depletion. The project aligns with global initiatives such as the Sustainable Development Goals (SDGs), particularly Goal 6 (Clean Water and Sanitation) and Goal 13 (Climate Action). It contributes to the objectives of the UN Framework Convention on Climate Change (UNFCCC) by promoting adaptive practices in vulnerable regions.

For more information on the project, please visit: <https://www.icimod.org/initiative/rms/springshed-revival-and-management/>.

Key outputs

1. ICIMOD's springs and springshed management work has produced practitioner manuals, technical and policy papers, peer-reviewed journal articles, datasets, and digital decision-support tools. Some major ones are as follows:
 - a. Shrestha, R. B., Desai, J., Mukherji, A., Dhakal, M., Kulkarni, H., Mahamuni, K., Bhuchar, S., & Bajracharya, S. (2018). Protocol for reviving Springs in the Hindu Kush Himalayas: A Practitioner's Manual. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/icimod.735>.
 - b. ICIMOD. (2021). Springshed management in the Himalaya: Ensuring water security and enhancing climate resilience. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/25d10-afz68>.
 - c. Dhakal, M. P., Khadka, K., Pokhrel, G., Desai, J., Kingsley, C., Barola, Y., & Bhuchar, S. (2021). Springs in the Godavari landscape, Nepal: Mapping, governance, and revival. Working paper. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/yg93x-7qz60>.
 - d. Thapa, S., Pandit, A., Bhuchar, S., & Dhakal, M. (2025). Citizen science approach for springshed management: A comprehensive community-driven mapping and dataset of spring sources in Kavre, Nepal. *Data in Brief*; 60, Article 111466. <https://doi.org/10.1016/j.dib.2025.111466>.
 - e. Thapa, B., Bhattarai, C., Dahal, N., Tiwari, S., & Jacobsen, D. (2023). Drying of Springs in the Himalayan Region of Nepal: Perspectives of Local Government Leaders on Causes, Consequences, and Conservation Efforts. In *Mountain Research and Development* (Vol. 43, Number 4, pp. R9–R15). <https://doi.org/10.1659/mrd.2023.00007>.
 - f. Pandit, A., Batelaan, O., Pandey, V.P., & Adhikari, S. (2024). Depleting Spring Sources in the Himalayas: Environmental Drivers or Just Perception? *Journal of Hydrology: Regional Studies*; Vol. 53:101752. <https://doi.org/10.1016/j.ejrh.2024.101752>.

- g. Butte, G., Khadka, K., Aldinucci, A., Macaulay, B., & Bhuchar, S. (2024). Spring Revival in the Mid-Hills of the Himalaya: A Socioeconomic Assessment Using Benefit–Cost Analysis. In *Mountain Research and Development* (Vol. 44, Number 4, pp. R12–R25). <https://doi.org/10.1659/mrd.2024.00020>
2. The [HKH Springs portal and decision-support system](#), which provides spatial and socio-economic information on springs to support planning and knowledge exchange.
3. The initiative is strongly collaborative and capacity oriented. It actively works with **local communities, local governments**, and sector agencies to mainstream springshed management into local climate-resilience planning.
4. Capacity-building has included practitioner manuals, field-based training, regional trainings for municipalities and institutions from India and Nepal, GESI-responsive trainings, and country-specific engagement in Bhutan with the Watershed Management Division and Department of Water. It has conducted regional training for over 125 practitioners on geohydrology and spring revival. Established "Community Resource Person" networks in 7 municipalities of Nepal to ensure sustained systematic observation at the local level. More recent regional cooperation also includes the HKH Springs Alliance, convened with IWMI, to align action for long-term water security and socio-ecological resilience.

Annex 7: Sustainable Management of High-Altitude Rangelands as Nature-based Solutions

Main partner organisations

- **Afghanistan:** Ministry of Agriculture, Irrigation and Livestock (MAIL);
- **Bhutan:** National Land Commission Secretariat (NLCS); Department of Livestock (DoL); and Department of Forests and Park Services (DoFPS); Bhutan Highland Development Programme
- **China:** Chengdu Institute of Biology, Chinese Academy of Sciences (CAS); Ministry of Agriculture and Rural Affairs of the People's Republic of China (MARA); National Forestry and Grassland Administration (NFGA); Sichuan Grassland Sciences Academy (SGSA); Lanzhou University; Tibetan Academy of Agricultural Animal Sciences; Institute of Geographical Sciences and Natural Sciences Research, CAS.
- **India:** G.B. Pant National Institute of Himalayan Environment and Development (GBPIHED); Wildlife Institute of India (WII), Government of Ladakh; Ashoka Trust for Research in Ecology and the Environment (ATREE)
- **Nepal:** Department of Livestock Services (DoLS); Department of National Parks and Wildlife Conservation (DNPWC); Nepal Agriculture Research Council (NARC); Nepal Yak Federation; Institute of Forestry, Tribhuvan University; Global Institute of Interdisciplinary Studies (GIIS);
- **Pakistan:** Pakistan Agricultural Research Council
- **International:** ICIMOD (Lead); FAO, IFAD, GIZ; IUCN

Timeline

- Regional Rangeland Programme (Phase I, II and III): 1999 –2011
- Transboundary Landscape Programmes: 2012 to 2022 (rangeland management was a component in all the transboundary landscape initiatives except HILIFE)
- 2023 – ongoing: ICIMOD formally launched this current intervention

Geographic scope: Regional / multi-country. The program works over HKH rangelands (~3.8M km²) across 5 countries regional member countries: Afghanistan, Bhutan, China, India, Nepal, and Pakistan, with focused field action on high-altitude rangelands and agro-pastoral systems in Bhutan, Nepal, and Pakistan.

RSO research needs (A–E)

- Category C(a): Opportunities and challenges of implementing nature-based solutions in land systems in support of climate adaptation and mitigation. The project addresses this item through rangeland restoration, sustainable grazing NBS and fodder management systems enhancing the adaptive capacity.
- Category C(c): Emissions and removals from terrestrial ecosystems and information on ecosystems with high carbon reservoirs. Addresses it through taking rangelands as carbon sinks: quantifying soil organic carbon stocks in alpine/sub-alpine pastures and monitoring emissions from rangeland degradation/overgrazing.
- Category C(d): Vulnerability of natural and human ecosystems and strengthening their resilience. The project addresses this item primarily through work on improving pastoralist livelihoods, degradation tipping points, and developing climate-resilient rangelands.

Summary of research

Objective: The intervention addresses high-altitude rangelands and associated wetlands as critical socio-ecological systems that support biodiversity, ecosystem services, carbon functions, water regulation and the livelihoods and cultures of pastoralist and agro-pastoralist communities (around 20 million people in HKH rangelands). ICIMOD has prioritized rangeland management for multiple benefits as a core intervention to help HKH countries adopt inclusive policies and innovative practices to conserve, restore, manage, and sustainably use rangelands and wetlands and reverse their degradation. ICIMOD framing identifies three pillars: (i) generating robust data for policy support and advocacy, (ii) piloting innovative nature-based solutions for improved rangeland management, and (iii) strengthening national and regional networks of pastoralists and institutions through technology transfer, knowledge exchange, and capacity-building.

Methodology: The intervention combines policy and institutional analysis, participatory planning, geospatial monitoring and mapping, field-based restoration pilots and digital decision-support tools. National consultations in Nepal and Bhutan identify policy and institutional gaps and co-develop implementation plans. Key methodologies include piloting nature-based solutions (NbS) such as rotational grazing, "Landscape Journeys" for policy incentivization, and developing sustainable energy options (e.g., the DESER project) to reduce biomass pressure on fragile rangelands.

Main findings and conclusions: The intervention is producing actionable evidence on ecosystem condition, governance, and resilience. The program findings show that HKH rangelands are under pressure from climate change, environmental degradation, and socio-economic transformation, while pastoralists remain marginalized in policy processes. Its research confirmed that HKH rangelands (covering 60% of the land area) are warming at twice the global average. Piloted co-management models in Nepal and China demonstrated that community-led restoration can increase soil organic carbon and improve fodder availability by up to 20% within five years. ICIMOD's successful advocacy led to the inclusion of rangeland management in National Adaptation Plans (NAPs) and the formation of the Asian Highland Pastoralist Network. In Bhutan, ICIMOD-supported work has helped map and monitor tsamdros and herders, with the modified Tsamdros App and the dashboard that integrates grazing-area and mobility information for planning and monitoring.

The intervention also has wider science policy relevance. It provides critical data for the UNCCD on land degradation neutrality and the IPCC (AR6) on high-altitude ecosystem vulnerability, CBD (rangeland biodiversity), UNCCD (LDN targets), HKH Assessment, and Paris NDC support (NBS mitigation). ICIMOD is acting as the regional scientific hub for the UN International Year of Rangelands and Pastoralists (IYRP 2026). Through IYRP 2026, ICIMOD is using this work to elevate pastoralist voices in regional and global dialogues, support the formation of national yak herder federations in Bhutan and Nepal, and build toward a broader HKH Yak Network. This strengthens the role of Indigenous and local knowledge, peer exchange, and cross-border collaboration in resilient rangeland governance.

For more information on the intervention, please visit: <https://www.icimod.org/ecosystems-landscapes/rangelands/>.

Key outputs

1. ICIMOD's rangeland work has produced a mix of peer-reviewed papers, technical publications, governance/process documents, and digital decision-support tools. Some major publications include:
 - a. Uddin, K., Shaoliang, Y., Shakya, B. *et al.* Monitoring spatio-temporal change of rangeland vegetation in Bhutan to inform sustainable rangeland management. *Discov Geosci* 4, 56 (2026). <https://doi.org/10.1007/s44288-026-00434-4>.

- b. ICIMOD. (2026). Rangeland and wetland management in the Hindu Kush Himalaya: Compendium of best practices (p. 98). International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1112>.
 - c. Wangchuk, K., Wangdi, J. & Dorji, T. Governance of rangeland in Bhutan: Institutions and policy initiatives. *Pastoralism* 13, 20 (2023). <https://doi.org/10.1186/s13570-023-00284-6>.
 - d. Ning, W., Joshi, S., & Shaoliang, Y. (2025). Introduction: Pastoral resilience in a changing world in the Hindu Kush Himalaya. In *Nomadic Peoples* (Vol. 29, Number 1, pp. 1–11). Liverpool University Press (LUP). <https://doi.org/10.3828/whpnp.63837646691062>.
 - e. Verma, R., & Khadka, M. (2016). Gender and Pastoralism in the Rangelands of the Hindu Kush Himalayas: Knowledge, Culture, and Livelihoods at the Margins of the Margins. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.633>.
2. The Bhutan *tsamdros* and herder mobility [dashboard](#) and other geospatial tools that support grazing-area and mobility planning.
 3. The intervention is explicitly built on regional cooperation, national policy engagement, and capacity strengthening. It has been supporting country consultations, policy harmonization, institutional coordination, and regional work planning; promotes technology transfer and knowledge exchange; and strengthens pastoralist and institutional networks.
 4. Documented capacity-building elements include participatory planning workshops in Nepal and Bhutan, use of ecosystem-service planning tools, training on digital rangeland data collection, co-development of *tsamdros* management processes, and support for pastoralist federations and regional herder networks.
 5. It has established the Nepal Yak Federation in Bhutan, India, and Nepal to enhance their capacity to raise their agenda, influence national policies, map grazing areas and empower local herders. These networks were also used as platforms for practical work such as grazing area mapping. It has conducted regional training on Geo-informatics for Rangeland Resources Management for RMC government officials to improve systematic observation.

Annex 8: Disability and disaster in the HKH region- a cross-country analysis of disability patterns and disaster linkages in Bangladesh, India, Nepal and Pakistan

Timeline: July 2025-ongoing

Geographic scope: Pakistan, India, Nepal and Bangladesh

RSO research needs (A–E)

- Category B: Adaptation, loss and damage, and extreme events. Analysis of how climate-related disasters contribute to disability and multi-dimensional vulnerability.
- Category E: Cross-cutting issues. Intersectional analysis of disability, gender, poverty and geography, and implications for climate justice and inclusive adaptation.

Summary of research

Objective: The study compiles and analyses secondary data on the socio-economic characteristics of persons with disabilities (PwDs) in the HKH region and examines linkages between disability and disaster risk, with four specific objectives: to explore data availability and comparability; to assess data quality; to analyse socio-economic characteristics of PwDs; and to examine relationships between disaster exposure and disability in mountain contexts.

Methodology: The research adopts a comparative, cross-country analytical framework, drawing on nationally representative household surveys harmonised across four countries (Bangladesh HIES 2022; India NSS 76th Round 2018; Nepal NLSS-IV 2022–23; Pakistan DHS 2017–18 and Census 2023). To ensure comparability, the study applies the Washington Group Short Set (WG-SS) functional approach, defining disability as “some difficulty or worse” in at least one functional domain (seeing, hearing, mobility, cognition, self-care, communication). Analytical steps include construction of harmonised disability indicators, disaggregation by age, gender, literacy, wealth and rural–urban location, subnational analysis to capture mountain-specific disparities, and regression and correlation analyses linking disaster exposure to disability prevalence, including a Nepal case study on multi-hazard risk.

Main findings and conclusions: The main finding of the study reflects that disability is not randomly distributed: it is concentrated among older populations, individuals with low literacy and residents of remote, high-risk mountain areas where access to services is limited. Evidence from Nepal indicates that living in high-hazard districts is independently associated with higher disability prevalence, even after controlling for socio-economic factors, and that disaster-related damage to health systems, livelihoods and social protection structures contributes to the accumulation of disability over time. The study finds that gendered impacts are uneven across countries, that literacy is a key protective factor, and that the HKH region faces multi-hazard exposure, with landslides, floods and earthquakes playing distinct roles in disability outcomes. The conclusion is that climate-related disaster risk is a structural driver of inequality and that disability must be recognised as a climate justice and adaptation issue.

For policy and practice, the findings highlight the need to:

- Integrate disability inclusion into climate adaptation and disaster risk reduction frameworks
- Design inclusive early warning systems, evacuation protocols, and recovery programme
- Invest in education especially for women and girls as a resilience strategy
- Strengthen health and social protection systems in remote mountain regions

- Ensure that climate policies explicitly address intersectional vulnerabilities, including disability, gender, and geographic isolation

Overall, the study reinforces the urgency of embedding intersectional and inclusive approaches within climate research, policy, and finance mechanisms under the UNFCCC, particularly for high-risk regions such as the HKH

Key outputs

1. The report "Disability and Disaster in the HKH region- a cross-country analysis of disability and disaster linkages". As it is an ongoing report - close to completion, the plan for post dissemination is to share the findings across regional and global platforms including ICIMOD's Regional Member Countries and partners.

Annex 9: Thame Valley Glacial Lake Outburst Flood 2024 – Causes, impacts and future risks

Main partner organisations: National Disaster Risk Reduction and Management Authority (NDRRMA), Asian Development Bank (ADB), BGC Engineering, Khumbu Pasang Lhamu Rural Municipality, Sagarmatha Pollution Control Committee (SPCC)

Timeline: August 2024 event; field investigation November–December 2024; report published 2025

Geographic scope: Thame Valley, Dudh Koshi basin, Everest region, Solukhumbu district, Nepal (HKH)

RSO research needs (A–E)

- Category A(a), A(g): Near-term climate change and its prediction; advances and gaps in attribution science (event attribution, regional signals). Attribution of a specific GLOF event to a rock avalanche trigger under climate change.
- Category B(a), B(b), B(d): Evolution and dynamics of extreme events, early-warning systems and climate services; assessing adaptation progress; understanding complex, cascading and transboundary risks. Understanding extreme event dynamics, cascading (multi-lake) and transboundary risks
- Category C(b): Climate change impacts and risks for the cryosphere and related ecosystems. Climate change impacts on cryosphere and downstream hazards
- Category E(a), E(c): Synergies and trade-offs with SDGs; research supporting work under the Convention and Paris Agreement (e.g. Nairobi Work Programme). Supports Sendai Framework, SDGs (1, 6, 9, 11, 13), UNFCCC loss and damage mechanisms, the Nairobi Work Programme on impacts, vulnerability and adaptation and provides evidence for early warning system design and transboundary risk management in the HKH.

Summary of research

Objectives

- To investigate the causes and trigger mechanisms of the August 16, 2024 Glacial Lake Outburst Flood (GLOF) in Thame Valley, Nepal.
- To assess the cascading impacts of the flood on downstream communities, infrastructure (homes, schools, health post, hydropower plant), and geomorphology.
- To evaluate future risks from remaining glacial lakes in the watershed and provide recommendations for disaster risk reduction and climate adaptation.

Methodology

- **Satellite analysis:** Pre- and post-event high-resolution Planet satellite imagery (August 15, 16, 17, 31, 2024) to identify lake area changes, breach locations, and flood paths.
- **Field investigation (Nov 29 – Dec 8, 2024):** Multi-disciplinary team (ICIMOD, NDRRMA, ADB, BGC Engineering) conducted visual inspections, differential GPS (dGPS) measurements, and geological/geomorphological assessments.
- **UAV survey:** Uncrewed Aerial Vehicle (drone) survey paired with dGPS to produce ultra-high resolution orthomosaic imagery of Thame village and downstream areas (UAV not feasible at lake site due to gusty winds).

- **Lake risk classification:** Based on dam type, freeboard, connectivity to glaciers, surrounding slope stability, and evidence of past/future hazards (rock/ice avalanches, landslides).

Main findings and conclusions

- **Trigger and cause:** A rock avalanche from a steep (~200 m high) hillslope on the left flank of Upper Ngole Cho (GL-5) generated a displacement wave, eroding 4.5 m of moraine on the bedrock dam. This released $\sim 1.56 \times 10^5 \text{ m}^3$ of water, which then caused a cascading breach of Lower Ngole Cho (GL-4), releasing an additional $\sim 3.03 \times 10^5 \text{ m}^3$ and eroding a 22 m deep, 51 m wide breach.
- **Cascading impacts:** The flood transformed into a hyper-concentrated flow, eroding moraines, forming a temporary pond at Thyanbo outwash plain, and then breaching again – intensifying downstream destruction. It destroyed 25 homes/guesthouses, a school, a health post, a bridge, and the intake of Khumbu hydropower plant, displacing 135 people.
- **Future risks:** Upper Ngole Cho remains moderate-to-high risk (rock/ice avalanches, but bedrock outlet reduces outburst probability; overflow remains a threat). Rindhi Cho (GL-1) is classified as high-risk (no visible outlet, ice-cored moraine, seasonal fluctuations). Homey Cho (GL-2) is moderate-risk. Lower Ngole Cho and Parchemuche Cho (GL-3, GL-4) are low-risk.
- **Conclusion:** The Thame GLOF highlights the cascading, multi-hazard nature of cryospheric disasters in the HKH. Urgent measures include filling tension cracks, riverbank protection, channelisation, installation of hydrological monitoring and early warning systems, and detailed geophysical surveys of high-risk lakes.

Key outputs

1. Maharjan, S. B., Sherpa, T. C., & Shrestha, A. B. (2025). Thame Valley Glacial Lake Outburst Flood 2024: Causes, impacts and future risks. International Centre for Integrated Mountain Development (ICIMOD); National Disaster Risk Reduction & Management Authority (NDRRMA). <https://doi.org/10.53055/ICIMOD.1101>.
2. ICIMOD GLOF database of High Mountain Asia. <https://doi.org/10.26066/RDS.1973283>.
3. UAV orthomosaic and dGPS data: Available from [ICIMOD Cryosphere Initiative](#)
4. Strong multi-institutional collaboration: ICIMOD, NDRRMA (Nepal), ADB, BGC Engineering, KPLRM (local rural municipality), SPCC.
5. Capacity building of local authorities and communities through field engagement and knowledge sharing.
6. Use of high-resolution satellite imagery (Planet) accessed via NASA SERVIR HKH Program, demonstrating operational use of Earth observation for disaster response.
7. Recommendations for installation of hydrological/meteorological monitoring stations and early warning systems, directly building local and national capacity for GLOF risk reduction.
8. The report provides a replicable methodology for post-disaster GLOF investigation (satellite + field + UAV + risk classification) applicable across the HKH region.

Annex 10: Changing dynamics of glaciers in the Hindu Kush Himalayan region from 1990 to 2020

Main partner organisations: General Directorate of Water Resources and National Water Affairs Regulation Authority (Afghanistan); Central Department of Geology and Central Department of Hydrology and Meteorology (Tribhuvan University, Nepal); Department of Geology, Tri-Chandra Multiple Campus, Nepal

Timeline: Data studied from 1990 – 2020; Report published 2026.

Geographic scope: HKH region across Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan, covering 10 major river basins and 16 mountain sub-ranges.

RSO research needs (A–E)

- Category A(a), A(f), A(g): Near-term climate change; high-resolution regional climate and cryosphere information; advances and gaps in attribution science.
- Category B(a), B(b), B(d): Dynamics of cryosphere-related extremes and risks; adaptation progress; complex and transboundary risks.
- Category C(b): Climate change impacts and risks for cryosphere-dependent ecosystems.
- Category E(a), E(c): Synergies with SDGs; evidence for UNFCCC and Paris Agreement processes (e.g. NAPs).

Summary of research

Objectives

- To develop and refine the first comprehensive, multi-decadal (1990–2020) glacier change dataset for the entire Hindu Kush Himalaya (HKH) region using consistent data sources and methods.
- To analyse the influence of topographic parameters (elevation, slope, aspect) and glacier size on spatial distribution and retreat patterns.
- To provide scientifically robust evidence base for water resource planning, climate adaptation, disaster risk reduction, and transboundary cooperation.

Methodology

- **Data sources:** Consistent Landsat satellite imagery (target years 1990, 2000, 2010, 2020; ± 1 year) and SRTM digital elevation model (DEM).
- **Approach:** Semi-automatic object-based image classification combining automated algorithms (e.g., NDSI for clean ice) with extensive manual validation and correction, particularly for debris-covered glaciers, shadows, and low-contrast areas.
- **Validation:** Cross-checked with high-resolution Google Earth imagery and compared against global/regional inventories (RGI, GAMDAM, Chinese Second Glacier Inventory). Uncertainty estimated at 2–3% of total area.
- **Parameters:** Glacier ID, area, elevation (min/mean/max), slope, aspect, hypsometry; ice reserves estimated via area–thickness empirical relation.

Main findings and conclusions

- **Status (2020):** 63,761 glaciers covering 55,782 km² with estimated ice reserves of 5,736 km³. Small glaciers (<0.5 km²) dominate in number (74%) but large glaciers (≥10 km²) hold 40% of ice reserves.
- **Decadal change (1990–2020):** Total glacier area decreased by 12% and ice reserves by 9%, with the rate of loss accelerating markedly after 2010 (4.9% area loss in 2010–2020 vs. 3.2% in 1990–2000).
- **Regional patterns:** Highest absolute losses in Indus, Ganges, Brahmaputra basins (e.g., Ganges – 21%). Highest percentage losses in eastern basins (Salween –33%, Yangtze –23%). Karakoram showed stability (–0.9%, “Karakoram anomaly”).
- **Topographic controls:** Greatest area loss at 4,500–5,500 masl, on slopes of 20–30°, and on NE, E, and SE aspects (higher solar radiation).
- **Fragmentation:** Number of smallest glaciers (<0.5 km²) increased due to fragmentation of larger glaciers, even as their total area continued to shrink.
- **Conclusions:** Accelerating glacier retreat threatens dry-season water availability, increases risks of GLOFs and other cascading hazards, and demands urgent climate action, basin-specific adaptation, and transboundary water cooperation. The dataset also serves as a training resource for AI-based automated glacier monitoring. Supports IPCC reports (e.g., SROCC), SDGs 6, 13, 15, Sendai Framework for DRR, and Paris Agreement by providing open-access, standardized evidence for climate adaptation, disaster risk reduction, and transboundary water planning in the HKH region.

Key outputs

1. Maharjan, S. B., & Sherpa, T. C. (2026). Changing dynamics of glaciers in the Hindu Kush Himalayan region from 1990 to 2020. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1122>.
2. Decadal glacier changes dataset. <https://doi.org/10.26066/vds.1973447>. The dataset is available in electronic form at www.icimod.org/himaldoc.
3. The project involved extensive collaboration with national partners in Afghanistan (GDWR, NWARA) and academic institutions in Nepal (Tribhuvan University). The standardized, basin-wide dataset serves as a crucial resource for training automated monitoring systems using satellite imagery and artificial intelligence, thereby building regional capacity for continuous and responsive glacier tracking.

Annex 11: HKH Glacier Outlook 2026: Insights from 50 years of Himalayan glacier monitoring

Main partner organisations: World Glacier Monitoring Service (WGMS); Geological Survey of India; national monitoring agencies in India, Nepal, Pakistan, Bhutan and China

Timeline: 1974 – 2026 (50 years of monitoring); Report published 2026

Geographic scope: Hindu Kush Himalaya (HKH) region, with specific focus on western Himalaya (India), central Himalaya (Nepal), and underrepresented regions including Karakoram, Sikkim, Zaskar, and Bhutanese Himalaya.

RSO research needs (A–E)

- Category A(a), A(g): Near-term climate change and attribution of glacier mass loss.
- Category B(a), B(b), B(d): Data for early-warning and risk assessment (e.g. GLOFs), adaptation planning and transboundary water risk.
- Category C(b): Climate impacts on cryosphere and related ecosystems.
- Category E(a), E(c): Supporting SDGs 6 and 13 and UNFCCC/Paris Agreement adaptation and loss-and-damage processes.

Summary of research

Objectives

- To present an updated overview of glacier status in the HKH based on five decades (1974–2026) of field-based mass balance monitoring.
- To identify monitoring achievements, gaps, and priority actions for strengthening cryosphere observation networks.
- To inform ministers, development partners, and regional institutions about the evidence base for glacier change and to highlight where coordinated support is most urgently needed, particularly during the International Year of Glaciers' Preservation (2025) and the Decade of Action for Cryosphere Science (2025–2034).

Methodology

- Compilation and analysis of all available glacier-wide mass balance measurements conducted in the Himalaya since September 1974.
- Data from 38 glaciers, comprising 302 annual observations (32 positive, 270 negative mass balance years).
- Identification of WGMS benchmark glaciers (minimum 10 years of continuous observations): Mera, Pokalde, Rikha Samba, West Changri Nup, Yala (central Himalaya, Nepal), Chhota Shigri and Hoksar (western Himalaya, India).
- Representativeness assessment: systematic comparison of field-based glaciological measurements with satellite-based geodetic estimates of glacier mass balance to evaluate how well benchmark glaciers represent broader regional trends.

Main findings and conclusions

- **Mass balance trends:** 89% of annual observations (270 out of 302) showed negative mass balance, indicating widespread and persistent glacier mass loss over 50 years.
- **Monitoring gaps:** Out of approximately 63,700 glaciers in the HKH, only 38 have been monitored in the field. Observations are unevenly distributed, with major gaps in Karakoram, Sikkim, Zaskar, and Bhutanese Himalaya. Seventeen mass balance series have been discontinued.
- **Benchmark glaciers:** Only seven glaciers currently qualify as WGMS benchmark glaciers. Mera and Rikha Samba are representative of the central Himalaya; Chhota Shigri represents the western Himalaya.
- **Way forward:** Priority actions include expanding monitoring to underrepresented regions, sustaining long-term observations of benchmark glaciers, standardising methodologies, and sharing data with WGMS to improve global representation of Himalayan glacier response to climate change.
- **Conclusion:** Sustained long-term glacier monitoring is essential climate infrastructure for hydrological forecasting, GLOF risk assessment, transboundary water cooperation, and climate-resilient development. The IYGP 2025 and Decade of Action for Cryosphere Science provide a strategic framework for mobilising investments and regional collaboration.

Key outputs

1. Azam, M. F. (2026). HKH Glacier Outlook 2026: Understanding Change Through 50 Years of Field Observation (p. 14 p.). International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1123>.
2. Azam, M. F. (2026). Fifty years of Himalayan glacier mass-balance monitoring: Recommendations in honour of IYGP 2025. *Journal of Glaciology*, 72, e43. <https://doi.org/10.1017/jog.2026.10151>
3. Shared mass-balance datasets via ICIMOD and WGMS, built on long-term collaboration with national agencies.
4. The report builds on five decades of collaboration between ICIMOD, national monitoring agencies (Geological Survey of India, Nepal, Bhutan, Pakistan), and the World Glacier Monitoring Service (WGMS). It identifies priority regions (Karakoram, Sikkim, Zaskar, Bhutan) for expanding field monitoring networks, which will require capacity building and technology transfer.
5. Recommends standardisation of monitoring methodologies and data sharing with WGMS to enhance global representation and regional comparability. Aligns with the International Year of Glaciers' Preservation (2025) and the Decade of Action for Cryosphere Science (2025–2034), providing a strategic framework for mobilising investments and enhancing collaboration among HKH member countries.

Annex 12: HIGRID – Building capabilities for green, climate-resilient and inclusive development in the Lower Koshi River Basin

ICIMOD Action Area: DRR Intervention, HIGRID project

ICIMOD focal point: Saswata Sanyal, HIGRID Project Coordinator and DRR Intervention Manager

Main partner organisations: Australian Government (funder); 28 municipalities across Koshi and Madhesh provinces; organisations of persons with disabilities; Indigenous groups; community-based organisations; entrepreneurs and local leaders.

Timeline: Ongoing (as of 2025).

Geographic scope: Lower Koshi River Basin in eastern Nepal (Terai lowlands, mid-hill and high-hill districts).

RSO research needs (A–E)

- Category A(a), A(f): Near term climate information and high resolution local climate data for action.
- Category B(a), B(b), B(d), B(e): Evolution and dynamics of extreme events and early warning systems; assessing adaptation progress; understanding cascading water related risks; climate risks for vulnerable groups (including persons with disabilities and women).
- Category E(a), E(c): Synergies between mitigation, adaptation and SDGs; inclusive research and practice supporting UNFCCC adaptation and loss and damage work.

Summary of research

Objectives

- To support municipalities in integrating Disaster Risk Reduction (DRR) approaches into planning and budgeting that are responsive to Gender Equality, Disability and Social Inclusion (GEDSI).
- To scale up GEDSI-responsive innovative DRR solutions and enterprises based on green, climate-resilient, and inclusive development (GRID).
- To enhance community resilience to “Too Much and Too Little” (TMTL) water challenges (floods, droughts, and other water-induced hazards) in the Lower Koshi River Basin.

Methodology

- Strengthening inclusive DRR governance: Partnering with local governments to integrate GEDSI principles into DRR plans, ensuring responsiveness to disadvantaged groups (women, persons with disabilities).
- Solutions to tackle TMTL water: Building capacity of communities and decision makers to scale innovative solutions, including Nature based Solutions, responsible tourism, sustainable watershed management, and Community Based Flood Early Warning Systems (CBfEWs).
- Developing GRID value chains: Developing and integrating GRID based value chains (vegetable, mango, Mithila art) to diversify income sources and promote entrepreneurship for disadvantaged communities (women, youth).
- Ensuring inclusive gender responsive budgeting: Enhancing capacity of local governments to implement mandated Gender Responsive Budgeting (GRB) in 11 municipalities to ensure fair resource allocation and GEDSI inclusive decision making.

Main findings and conclusions

- The Lower Koshi River Basin (LKRB) is home to nearly 8 million people at risk from climate induced changes to the hydrological cycle (altered precipitation, evaporation, and increased frequency/intensity of floods and droughts).
- A large proportion of the population relies on water intensive agriculture, making them highly vulnerable to TMTL water challenges.
- Disadvantaged groups, particularly organisations of persons with disabilities, face even higher risks.
- The project is delivering three key outputs: 3 GRID based solutions, 5 municipalities incorporating GEDSI inclusive DRR plans, and 7 TMTL water value chains.
- **Conclusion:** Integrating GEDSI into DRR governance, scaling Nature based Solutions and early warning systems and developing inclusive value chains are effective strategies for building climate resilience in the LKRB.
- This project also supports the Sendai Framework for Disaster Risk Reduction (Targets A, B, C, D, E – inclusive DRR), UN Sustainable Development Goals (SDG 1 – poverty, SDG 5 – gender equality, SDG 10 – reduced inequalities, SDG 11 – sustainable cities and communities, SDG 13 – climate action, SDG 17 – partnerships), and the Paris Agreement (adaptation and resilience). Also contributes to National Adaptation Plans (NAPs) and local climate action in Nepal.

Key outputs

1. International Centre for Integrated Mountain Development (ICIMOD). (2025). HI-GRID: Building Capabilities for Green, Climate-Resilient and Inclusive Development in the Lower Koshi River Basin. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/9txrr-ks753>.
2. **Tools:** Community Based Flood Early Warning Systems (CBfEWs); Gender Responsive Budgeting (GRB) frameworks; GRID value chain development guides (vegetable, mango, Mithila art).
3. Strong **multi stakeholder cooperation:** Australian Government (funder), ICIMOD (implementer), 28 local municipalities, organisations of persons with disabilities, indigenous groups, community members, entrepreneurs, and municipality leaders.
4. **Capacity building** for local governments on GEDSI inclusive DRR planning, gender responsive budgeting, and watershed management. Community based flood early warning systems empower local communities to manage risks and adapt to changing climate conditions.
5. Promotion of inclusive entrepreneurship (value chains) for women, youth, and disadvantaged groups, contributing to livelihood diversification and climate resilience.

Annex 13: 2025 drought in Nepal's Madhesh Province: A rapid situational analysis

Main partner organisations: Ministry of Agriculture and Livestock Development (MoALD), Nepal; Australian Embassy in Nepal

Timeline: 2025 drought event; analysis and report in 2025.

Geographic scope: Madhesh Province in the south-eastern Terai region of Nepal.

RSO research needs (A–E)

- Category A(a), A(f), A(g): Near-term climate change; high-resolution local climate information; attribution of monsoon failure and drought persistence.
- Category B(a), B(b), B(d), B(e): Evolution of slow-onset extreme events and cascading risks; adaptation progress and impacts; climate risks for vulnerable groups (including women and smallholder farmers).
- Category E(a), E(c): Synergies with SDGs 1, 2, 5, 6 and 13; evidence for UNFCCC adaptation and loss-and-damage work and the Nairobi Work Programme.

Summary of research

Objectives

- To conduct a rapid situational analysis of the 2025 drought in Nepal's Madhesh Province following its declaration as a "disaster crisis zone" (23 July 2025).
- To assess meteorological, hydrological, and agricultural drought conditions, including impacts on groundwater, drinking water, and paddy cultivation.
- To estimate potential rice production shortfalls and associated food security risks.
- To provide short-term and long-term recommendations for drought mitigation, adaptation, and policy interventions.

Methodology

- **Rainfall analysis:** Analysis of observed and forecasted rainfall data from Nepal's Department of Hydrology and Meteorology (DHM) and University of California's Climate Hazard Center (CHC), including winter (Dec 2024–Feb 2025) and monsoon (Jul–Sep 2025) rainfall anomalies.
- **Satellite-based remote sensing:** Use of Sentinel 2 imagery to compare cropland greenness (vegetation cover) on 15 July 2024 vs. 18 July 2025; use of MODIS-derived Vegetation Condition Index (VCI) and Standardised Precipitation Index (SPI) to identify drought stress and vegetation stress concentration.
- **Ground data integration:** Reports from Ministry of Agriculture and Livestock Development (MoALD) on rice transplantation rates (as of 27 July 2025) and field observations on groundwater levels and borehole status.
- **Impact estimation:** Assessment of rice area under drought stress (percentage and spatial distribution) and estimation of potential production shortfall (metric tons) based on satellite-derived stress levels and historical production data.

Main findings and conclusions

- **Meteorological drought:** Prolonged dry conditions began with below-normal winter rainfall (Dec 2024–Feb 2025), followed by erratic monsoon onset and weak progress in July 2025, with forecasts indicating continued dry spells through August.
- **Hydrological drought:** Groundwater levels critically low; >30% of community boreholes reportedly dried up; hand pumps non-functional in Parsa and Bara districts; acute drinking water crisis with disproportionate burden on women and girls.
- **Agricultural drought:** Rice transplantation rate stood at only 52% as of 27 July 2025, compared to 92% during the same period in 2024. An estimated 35–40% of rice growing area is under extreme drought stress, rising to 60–78% in Mahottari, Dhanusha, and Siraha districts. Potential rice production shortfall of 400,000–450,000 metric tons (~10% of national rice supply).
- **Conclusion:** The drought represents a cascading crisis – from meteorological to hydrological to agricultural – with severe implications for food security, rural livelihoods, gender equity, and the national economy. Immediate relief and long term adaptation (e.g., direct seeding, crop diversification, groundwater recharge, completion of Sunkoshi Marin Diversion Project) are urgently needed.
- The project also provides evidence for National Adaptation Plans (NAPs) and early warning systems for slow onset hazards in South Asia.

Key outputs

1. Shrestha, S., Shrestha, S., Dulal, B., & Khadgi, V. R. (2025). 2025 Drought in Nepal's Madhesh Province: A rapid situational analysis. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.1097>.
2. **Tool:** [National Agriculture Drought Watch Nepal](#) (dynamic, science based drought monitoring for early warning and decision support) – maintained by ICIMOD.
3. **Data sources:** Sentinel 2 and MODIS satellite imagery; DHM rainfall data; CHC forecasts.
4. **Capacity building** for local institutions and farmers on climate resilient farming practices (direct seeding, crop diversification, nature based solutions for groundwater recharge).
5. ICIMOD provided technical support for satellite based drought monitoring (SPI, VCI) and risk communication and continues to update the National Agriculture Drought Watch Nepal.

Annex 14: Himalayan Climate Change Adaptation Programme (HICAP)

Main partner organisations

Regional Member Country Institutions: Institute of Water Modelling (IWM), Bangladesh; Asia International Rivers Centre (AIRC)/Yunnan University; China, Chengdu Institute of Biology (CIB), China; Ecological Environment Protection Research Centre, Yunnan Institute of Environmental Science, China; Institute of Geographic Sciences and Natural Resources Research (IGSNRR), China; Kunming Institute of Botany (KIB) – including Centre for Mountain Ecosystem Studies (CMES), China; Social Development Institute, Sichuan University, China; Women and Development Research Centre (WAD), Yunnan Academy of Social Sciences (YASS), China; Aaranyak, India; Indian Institute of Technology (IIT) Delhi, India; Indian Institute of Sciences (IISc) Bangalore, India; Centre for Environmental and Agricultural Policy Research, Extension and Development (CEAPRED), Nepal; Koshi Victim Society (KVS), Nepal; South Asian Network of Environmental Economists (SANDEE), Nepal; Nepal Development Research Institute (NDRI), Nepal; World Wide Fund for Nature (WWF), Nepal; Women Organizing for Change in Agriculture and NRM (WOCAN), Nepal; Aga Khan Rural Support Programme (AKRSP), Pakistan; International Water Management Institute (IWMI), Pakistan; Pakistan Agriculture Research Council (PARC), Pakistan; and World Wide Fund for Nature (WWF), Pakistan.

International Institutions: ICIMOD; Bjerknes Centre for Climate Research (BCCR), Norway; FutureWater, the Netherlands; International Institute of Social Studies, The Hague, Netherlands; University of Sussex, United Kingdom; [CICERO](#) [Promoter Organization]; and [GRID-Arendal](#) [Promoter Organization].

Timeline: 2011–2017, with some activities continuing into 2018.

Geographic scope: HICAP research spans across five sub-basins of major Himalayan river systems: two sub-basins of the Brahmaputra and one each of the Indus, Ganges, and Salween-Mekong [Upper Indus (Pakistan), Koshi Sub-basin (Nepal), Eastern Brahmaputra (India), Upper Brahmaputra (Tibetan Autonomous Region, China), Upper Salween-Mekong (China)].

RSO research needs (A–E)

- Category A(f): High-resolution local and regional climate and water-scenario information.
- Category B(b, d, e): Assessing adaptation progress; understanding complex, cascading and transboundary risks; climate risks for vulnerable groups including women and the poor.
- Category C(a): Opportunities and challenges for implementing NbS, including ecosystem-based approaches.
- Category E(a, b, c): Synergies and trade-offs with SDGs; integrating gender and equity; research supporting UNFCCC work including NAPs, NDCs and the Nairobi Work Programme.

Summary of research

Objectives

- Increase understanding of uncertainties influencing climate change scenarios and water availability and demand projections for parts of major river basins, and to encourage the use of the knowledge thus created.
- Enhance capacities to assess, monitor, communicate, prepare for, and undertake actions to respond to challenges and opportunities from impacts of climate change and other drivers of change.
- Make concrete and actionable proposals on strategies and policies (with particular reference to women and the poor) for uptake by stakeholders, including policy makers.

Methodology: HICAP an interdisciplinary, transdisciplinary approach combining natural and social science. It connects the thematic components of [Climate change scenarios](#); [Water availability and demand scenarios](#); [Ecosystem services](#); [Food security](#); [Vulnerability and adaptation](#); [Gender and adaptation](#); [Communications and outreach](#). All HICAP research has been based on the three concepts of salience, credibility and legitimacy, while ensuring stakeholder engagement, with work being organised under four pillars, namely science, action research, piloting and communication. Lastly, action research was undertaken research to systematically test adaptation practices on ground, with pilot projects such as Resilient Mountain Villages and Community-Based Flood Early Warning Systems to demonstrate and promote adaptation approaches. Policy champions were also identified to advocate for research uptake.

Main findings and conclusions

- The region is warming, especially in winter and at higher altitudes, leading to more extreme and unpredictable weather, increased glacial melt, increased community vulnerability, and challenges for ecosystems and agriculture. The total annual water availability is not changing.
- The concept of ‘flexibility’ has emerged as a key notion and includes local empowerment, agro-diversity, social security and gender-friendly diversification of livelihoods. Smart planning can help adaptation and create new opportunities.
- Although initially focused on climate change, research has also clearly established that it is a combination of multiple drivers – which differ across the region and socioeconomic scales – that influences vulnerability and adaptation needs.
- There is a need for more holistic and upstream–downstream solutions, embracing different approaches in different situations and regions. These may include Payment for Ecosystem Services approaches or cost-effective Ecosystem Based Adaptation incorporating local knowledge and practices. However, different agroecological zones may have different solutions, which must be analysed individually.
- Improved communication with policymakers, and community capacity-building (particularly for women) are two ways of minimizing risks and vulnerabilities.
- Regional key messages include the need for a greater focus on water stress and adaptation in Nepal; greater emphasis on gender in livelihood diversification and risk management in India; and greater integration of adaptation, gender, migration and other social factors in adaptation strategies in China. Global lessons point to the connections between mountain areas in the regional (upstream–downstream) and global context, with a need for cross-learning between mountain regions.
- The knowledge generated from HICAP science, action research and piloting has contributed to the understanding of how 15 of the 17 Sustainable Development Goals can be achieved in the Hindu Kush Himalayas, to a greater or lesser extent. Contribute to the UNFCCC and Nairobi Work Programme. HICAP results and approach has been integrated into 6 national/state-level development policies and plans making use of HICAP work.
- The Himalayan Climate and Water Atlas was launched at UNFCCC COP-21 in Paris (2015) (downloaded over 10,000 times) and the CB-FEWS won the UNFCCC “Momentum for Change – Lighthouse Award” (2016).

Key outputs

1. HICAP has led to 87 (41 peer-reviewed) publications, with some major ones highlighted below:
 - a. Agrawal, N. K., Alftan, B., van Oort, B., Leikanger, I., & Schoolmeester, T. (2017). Adaptation in the Himalayas: Knowledge, Action and Results; Highlights from the Himalayan Climate Change Adaptation Programme (HICAP), 2012–2017. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/ka6xg-ae059>.

- b. Aase, Tor H. (ed.), *Climate Change and the Future of Himalayan Farming* (Delhi, 2017; online edn, Oxford Academic, 19 Sept. 2019), <https://doi.org/10.1093/oso/9780199475476.001.0001>.
 - c. Quincey, D.J. (2017). The Himalayan Climate and Water Atlas. In *Mountain Research and Development* (Vol. 37, Number 1, pp. 155–156). <https://doi.org/10.1659/mrd.mm197>.
 - d. Gerlitz, J.-V., Banerjee, S., Hoermann, B., Hunzai, K., Macchi, M., & Tuladhar, S. (2014). Poverty and Vulnerability Assessment – A survey instrument for the Hindu Kush Himalayas. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/zya8h-x3304>.
 - e. ICIMOD. (2016). Gender in Water Management; Considerations for Nepal's Koshi River Basin. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/aegav-h9p30>.
2. HICAP has generated household-level poverty and vulnerability assessment datasets for [Eastern Brahmaputra sub-basin in India](#), [Koshi sub-basin in Nepal](#), [Upper Brahmaputra sub-basin in China](#) and [Upper Indus sub-basin in Pakistan](#).
 3. Cooperation and capacity-building elements include training for 19 communities and 18 institutions; training 47 journalists (leading to around 70 articles and news stories); ten investigative journalism grants (resulting in 37 investigative stories); and strong co-design of pilots and research with local communities and strategic partners.

Annex 15: Himalayan Adaptation, Water and Resilience (HI-AWARE) Research on Glacier and Snowpack Dependent River Basins for Improving Livelihoods

Main partner organisations

Consortium Partners: ICIMOD (lead); Bangladesh Centre for Advanced Studies (BCAS), Bangladesh; The Energy and Resources Institute (TERI), India; and Climate Change, Alternate Energy and Water Resources Institute of the Pakistan Agricultural Research Council (CAEWRI-PARC), Pakistan

International Partner: Alterra – Wageningen University and Research, the Netherlands.

Strategic Partners: Megh Pyne Abhiyan (“Cloud Water Campaign”), India; The Mountain Institute India, India; The Centre for Ecology, Development and Research (CEDAR), India; Practical Action – South Asia Office; and LEAD Pakistan.

Timeline: 2014–2018.

Geographic scope: HI-AWARE research spans across four study basins: the Indus, Upper Ganga, Gandaki and Teesta focus in 12 sites that represent a range of climates, altitudes, hydro-meteorological conditions, rural-urban continuums, and socio-economic contexts. The research sites encompass four countries, namely Bangladesh, India, Nepal, and Pakistan.

RSO research needs (A–E)

- Category A(f): High-resolution local and regional climate information and projections.
- Category B(b, d, e): Assessing adaptation progress; understanding complex, cascading and transboundary risks; climate risks for vulnerable groups.
- Category C(a, b, c): NbS and ecosystem-based approaches; climate impacts on cryosphere-linked ecosystems; emissions and removals from terrestrial systems and high-carbon reservoirs (through land and water interventions).
- Category E(a, b, c): Synergies between adaptation, mitigation and SDGs; equity and gender; research supporting UNFCCC processes, including NAPs and NDCs, and the Nairobi Work Programme.

Summary of research

Objectives

- Generate scientific knowledge on the biophysical, socio-economic, gender, and governance conditions and drivers leading to vulnerability to climate change
- Develop robust evidence to improve understanding of the potential of adaptation approaches and practices, with an explicit focus on gender and livelihoods
- Develop stakeholder-driven adaptation pathways based on the up- and out-scaling of institutional and on-the-ground adaptation innovations
- Promote the uptake of knowledge and adaptation practices at various scales by decision-makers and citizens
- Strengthening the interdisciplinary expertise of researchers, students, and related science-policy-stakeholder networks

Methodology: HI-AWARE adopted a comparative, participatory, cross-scalar trans-disciplinary, gender-inclusive and integrative approach looking into the short and long-term climate trends, physical and social vulnerabilities, and adaptation strategies at various scales. The research areas included water, energy, food security, human health, water-induced hazards (such as floods, landslides and droughts) and extreme

weather events. The program conducted research and pilot interventions, capacity building and policy engagement on climate resilience and adaptation in the mountains and flood plains of the Indus, Ganges, and Brahmaputra river basins. The sub-basins for the research and pilot interventions were selected through stakeholder consultation.

The program design focussed on:

- **Generating Knowledge:** five interlinked Research Components focusing on knowledge generation on climate change impacts, the causes that lead to vulnerability, and adaptation practices and policies.
- **Research into Use:** systematically promote the uptake of knowledge and adaptation practices at various scales by practitioners and policymakers, to reduce vulnerabilities of communities and build livelihood resilience.
- **Strengthening Expertise:** build the capacity of researchers, students, and science and policy stakeholder networks to do interdisciplinary research on climate change vulnerability, resilience, and adaptation.

Main findings and conclusions

- The Indus, Ganges and Brahmaputra river basins are extremely susceptible to temperature increase. Higher elevation will experience an even greater wetter conditions in the future and increases in extreme precipitation. The projected temperature increases for the basins (3.5 and 6 °C by 2100 under the more likely climate change scenario) exceed the global target 1.5 -2 °C. events, indicating that the 1.5 and 2 °C scenarios are not suitable for adaptation planning in South Asia
- Heat waves are expected to increase in intensity and duration in South Asia, especially in the cities. Poor people are especially vulnerable due to living in dense built-up neighbourhood. Individual solutions are not sufficient, concerted efforts are needed in the urban landscape both at community and individual level to address urban heat in South Asia.
- Robust region-specific climate change projections developed by HI-AWARE for the Indus, Ganges and Brahmaputra (IGB) river basins indicate that extreme precipitation events, the main driver of flood, will likely increase in frequency and severity in the coming decades. However, floods need not result in tragedy if planning and management are inclusive
- 130 million farmers in the downstream plains of the Indus and the north-western part of the Ganges basin depend on water originating from glacier and snow melt from the mountains. Any changes in the future availability of meltwater or further groundwater depletion will therefore impact agriculture. Understanding the links between sources of water demand and sources of water supply is important for developing appropriate adaptation measures
- Mean annual water availability is likely to increase by 36-42%, 37-46% and 17-46% in the IGB, however, the water consumption in downstream areas of the IGB basins is projected to increase by 24%, 42% and 107%, respectively, during the 21st century. Socio-economic development leading to increase in water demand will become the main driver of the future water gap, not climate change.
- There is a high dependence on springs (ranging between 50-100%) for water supply in three-fourths of the urban areas of the Himalaya. A holistic approach to manage water that includes springshed management along with planned adaptation is of the utmost importance for securing safe water supply in the urban Himalaya.
- Vulnerabilities are shaped by the interaction of both climatic stresses and socio-economic drivers and conditions in the local context. Relevant policies, strategies and plans should address differential vulnerabilities. Greater resources allocations are to be made for the climate affected HKH region and the most vulnerable communities and groups.
- HI-AWARE has contributed to global scientific discourse on climate change adaptation through a plethora of knowledge products including peer-reviewed, reports, simulations, datasets and media products. HI-AWARE project framework and findings are also designed to directly support national

reporting and policy process. The localized climate data and adaptation pathways provided evidence base that directly helps member countries formulate National Adaptation Plans (NAPs).

- 9 HI-AWARE researchers were directly involved in development of IPCC report (IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), IPCC Special Report on Climate Change and Land (SRCCL), IPCC Sixth Assessment Report (AR6).
- More outputs and information can be found here: <https://hi-aware.org/>.

Key outputs and cooperation

1. HI-AWARE has produced over 28 papers in leading peer-reviewed journals, 21 working papers and two special issues (including on gendered vulnerability and urban water). Some major ones include:
 - a. HI-AWARE. (2018). Himalayan Adaptation, Water and Resilience Research (HI-AWARE); Highlights 2014-2018. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.722>.
 - b. Lutz, A., Immerzeel, W., Biemans, H., Maat, H., Veldore, V., & Shrestha, A. (2016). Selection of Climate Models for Developing Representative Climate Projections for the Hindu Kush Himalayan Region; HI-AWARE Working Paper 1. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/hwdbs-j8c53>.
 - c. Lutz, A. F., & Immerzeel, W. (2016). Reference Climate Dataset for the Indus, Ganges, and Brahmaputra River Basins; HI-AWARE Working Paper 2. International Centre for Integrated Mountain Development (ICIMOD). Access here: <https://lib.icimod.org/records/rjdcz-ktt36>.
 - d. Dasgupta, P. (2016). Assessing Costs and Benefits of Climate Change Adaptation; HI-AWARE Working Paper 3. Himalayan Adaptation, Water and Resilience (HI-AWARE). Access here: <https://lib.icimod.org/records/yh811-hgk89>.
 - e. Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2017). Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, 549(7671), 257–260. <https://doi.org/10.1038/nature23878>.
 - f. Biemans, H. & Siderius, Christian & Lutz, Arthur & Nepal, Santosh & Ahmad, Bashir & Hassan, Tagraid & Von Bloh, Werner & Wijngaard, René & Wester, Philippus & Shrestha, Arun & Immerzeel, W. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*. 2. 594-601. <https://doi.org/10.1038/s41893-019-0305-3>.
 - g. Vij, S., Moors, E., Ahmad, B., Uzzaman, A., Bhadwal, S., Biesbroek, R., Gioli, G., Groot, A., Mallick, D., Regmi, B., Saeed, B. A., Ishaq, S., Thapa, B., Werners, S. E., & Wester, P. (2017). Climate Adaptation Approaches and Key Policy Characteristics: Cases from South Asia. *Environmental Science and Policy* 78, 58-65. <http://dx.doi.org/10.1016/j.envsci.2017.09.007>
 - h. Maharjan, A., Hussain, A., Bhadwal, S., Ishaq, S., Saeed, B. A., Sachdeva, I., Ahmad, B., T., H. S. M., Tuladhar, S., & Ferdous, J. (2018). Migration in the Lives of Environmentally Vulnerable Populations in Four River Basins of the Hindu Kush Himalayan Region; HI-AWARE Working Paper 20. International Centre for Integrated Mountain Development (ICIMOD). <https://doi.org/10.53055/ICIMOD.729>.
2. Key datasets include high-resolution reference climate data for the Indus, Ganges and Brahmaputra. Some of these include:
 - a. Lutz, A. F., ter Maat, H. W., Biemans, H., Shrestha, A. B., Wester, P., & Immerzeel, W. W. (2016). Selecting representative climate models for climate change impact studies: An advanced envelope based selection approach. *International Journal of Climatology*. <http://doi.org/10.1002/joc.4608>.
 - b. Novel high-quality and high-resolution reference climate covering the IGB river basins with a particular focus on improved representation of high-altitude precipitation, covering from 1 January 1981 to 31 December 2010. This dataset was used for the downscaling of the 8

GCMs (4 GCM each for RCP4.5 and 8.5) to analyse future projections for the period of 2016-2045 (representing 2030s) and 2036-2065 (representing 2050s) for the National Adaptation Plan process of Nepal.

- c. Survey of 1,987 households (A sample size of 402 households was determined using Cochran's sample size formula for each river basin) examining the patterns of migration, and its role in building adaptive capacities of households in four critical sectors – agriculture, livestock, forests, and water.
3. Capacity-building highlights include support to about ten PhD and 28 master's candidates, research institutes and NGOs from the region for conducting interdisciplinary research on climate change vulnerability, adaptation and resilience.
4. Gender-sensitivity training sessions and climate change vulnerability and adaptation workshops in the study sites for stakeholders to foster common understanding of critical Hi-AWARE issues, including challenges and opportunities.
5. Science-Policy Dialogue brought together key stakeholders, including researchers and policymakers, working on climate change adaptation.

Research Addressing SBSTA Research Gaps under Research and Systematic Observation (RSO)

Strengthening Loss and Damage Response Capacity in the Global South (STRENGTH) – Case Study on Climate-Induced Loss and Damage, Adaptation Limits, and Migration in Barisal Region, Bangladesh (coastal south-central belt near the Bay of Bengal).

Summary Description of the Research:

This research, conducted by the International Centre for Climate Change and Development (ICCCAD) under the STRENGTH Project, examines how recurrent climate-induced loss and damage (L&D) shape migration patterns, adaptation limits, and vulnerability in coastal Bangladesh, with a particular focus on the Barisal region. Bangladesh ranks 13th in the long-term Climate Risk Index 2025, reflecting its acute exposure due to compounding hydro-climatic and socio-economic vulnerabilities, including low-lying topography, sea-level rise, salinity intrusion, and extreme weather events.

As a highly vulnerable riverine-coastal district, Barisal exemplifies structural challenges common in developing countries: high dependence on climate-sensitive sectors such as agriculture and fisheries, widespread poverty, and limited livelihood diversification. These factors interact with observed climatic trends, including a rise in minimum temperatures (~0.11°C per decade), a drier pre-monsoon season, shifting precipitation patterns with increased rainfall during the fall months, as well as frequent cyclones, storm surges, tidal flooding, river erosion, and salinity intrusion.

The study grounds national and international L&D discussions in community realities by –

- Documenting economic losses (primarily housing/property and livelihoods) and non-economic losses and damages (NELD), such as loss of ancestral lands, traditional knowledge, social cohesion, mental/physical health, and children's education.
- Assessing thresholds of adaptation limits, where existing measures (e.g., embankments, drainage) provide limited sustained benefits for many households.
- Analyzing migration as both a distress-driven adaptive strategy and a last resort, with over 90% of surveyed migrants citing climate-induced asset/livelihood loss as the primary driver (coastal erosion 59%, flooding 44%, cyclones 24%). Recent migration has accelerated (30.9% in the past decade; 27.9% in the last three years).
- Evaluating access to services, finance, and support mechanisms, revealing heavy reliance on self-coping (savings, asset sales, high-interest debt), with 91.2% receiving no post-shock financial support and significant barriers like corruption/bias in aid distribution.
- Capturing community preferences for financing (direct cash transfers/grants preferred via trusted government channels) and recommendations for participatory, locally led solutions to build long-term resilience and reduce future displacement.

The work highlights how adaptation actions often fall short in reducing risk for the most marginalized, particularly in developing-country contexts, and informs more consistent, robust

approaches to assessing adaptation progress and limits. It also links L&D to broader sustainable development challenges, equity/justice considerations, and the need for targeted support beyond current adaptation efforts.

This community-level documentation of specific climate drivers (coastal erosion, repeated flooding, shifting seasonal precipitation patterns, and salinity intrusion) and their translation into measurable economic and non-economic impacts provides granular, ground-truthed evidence that directly helps address gaps in attribution science at national and regional levels. Current attribution methods often lack fine-scale resolution in developing countries, particularly for monsoon-influenced regions and slow-onset processes. By linking observed local climatic trends—such as drier pre-monsoon conditions and altered rainfall timing in a monsoon-affected coastal zone—to tangible loss and damage outcomes and accelerated distress migration, the study supplies empirical “impact attribution” data. These bottom-up insights from the Global South can strengthen methodologies for attributing changes in monsoon patterns and compound risks at sub-national scales, supporting more robust science-based assessments for policy and finance.

Timeline:

Fieldwork (surveys and in-depth interviews with 68 migrant households in Barisal Sadar and Mehediganj) was conducted as part of the ongoing STRENGTH project (supported by IDRC Canada, in collaboration with the Institute for Study and Development Worldwide – IFSD). Key outputs, including a 2025 policy brief synthesizing local insights with national policy, were produced in 2024–2025, with continued analysis and dissemination into 2026.

Geographic scope:

Sub-national (Barisal Division, Bangladesh), with relevance to broader coastal and Global South contexts in vulnerable developing countries.

Relevant links:

- Policy brief: Addressing Climate-Induced Loss and Damage in South Coastal Bangladesh (January, 2025). <https://iccad.net/publications/policy-brief/addressing-climate-induced-loss-and-damage-in-south-coastal-bangladesh/>
- STRENGTH project page: <https://iccad.net/strength-project/>
- Additional related ICCAD outputs on L&D and displacement: <https://iccad.net/publications/climate-induced-displacement-loss-and-damage-in-bangladesh/>
- Journal Article (March, 2026): Loss and damage financing for climate justice and transformation: local insights from the climate frontline. https://link.springer.com/article/10.1007/s10584-026-04146-z?utm_source=rct_congratemail&utm_medium=email&utm_campaign=oa_20260310&utm_content=10.1007%2Fs10584-026-04146-z

Cooperative efforts and capacity-building:

The research is implemented by ICCCAD with strong engagement of local communities, incorporating participatory and qualitative methodologies. It contributes to capacity-building through field-based learning, local stakeholder engagement, and knowledge translation into policy-relevant outputs, including policy briefs and dialogue platforms (e.g., Loss and Damage Policy Labs).

The STRENGTH project is a collaborative effort between ICCCAD (lead, Bangladesh), IFSD, and partners in other Global South countries (e.g., Nepal, Vanuatu), supported by the International Development Research Centre (IDRC). It emphasizes South-South learning and includes capacity-strengthening components, such as bridging grants for early-career researchers (MSc/PhD level) from Bangladesh and other developing countries. The Barisal study involved direct engagement with affected migrant communities (farmers, fishers, small vendors) through participatory surveys, life-history interviews, and Loss and Damage Policy Labs (LDPLs) at local, subnational, and national levels. These activities bridge frontline voices with policymakers, enhancing research and institutional capacity in developing countries by prioritizing locally led evidence generation and inclusive planning. This research directly responds to key identified needs, including: Advances and gaps in attribution science at national and regional levels (e.g., monsoon pattern changes); Advances, research needs and gaps in assessing the impact of adaptation action on reducing risk, particularly in developing countries; Consistent and robust assessment of adaptation progress and limits; Synergies and trade-offs between adaptation, sustainable development, equity and justice; Complex, cascading and transboundary risks; and Enabling environments, including finance and support. We are happy to provide the full case study materials or further details if helpful for the information note. Please feel free to contact us for any clarifications.

Relevant cryosphere research that addresses SBSTA research gaps and needs identified since SB22

Submission by the International Cryosphere Climate Initiative (ICCI)
Main submission contact: Dr. James Kirkham, james@iccinet.org

Context: The information below is provided to feed into an information note that maps how research gaps identified since SBSTA 22 under the agenda item on Research and Systematic Observation (RSO) are being addressed by the scientific community. In this submission, we have focussed on how recent scientific research, specifically on **the cryosphere, polar oceans and interactions with other elements of the Earth System**, has addressed the relevant gaps and needs identified by SBSTA (red text), including only those sections where these cryosphere aspects have relevance.

Immediately below is a general summary of the main themes for each section covered. This is followed by an Annex that includes these same summaries of main themes and trends covered in relevant research, followed by key published research. Each individual study is listed with a brief title, a detailed description, a summary of its geographical scope, and a reference and link to further resources. We stress, however, that this is not an exhaustive list given that this field has expanded dramatically over the last two decades in response to the rapid rates of change observed in the Earth's frozen regions.

A. Understanding climate change, related climate data, and scenarios development and use:

c. Advances in climate model simulations, particularly by combining multiple lines of evidence and on a wider range of climate variables to improve parameterization of the physical climate system and understanding of scenarios

Improved geophysical model development over the last two decades means that the future mass balance, volume and geometry of almost any glacier in the world can now be simulated over multi-centennial timescales, providing a much stronger connection between emissions pathways and downstream impact scenarios at global, regional and local levels. Informed by a much larger base of observations and greater understanding of glaciological processes, major advances in the capability of simulating polar ice sheets have been achieved, allowing their risks and temperature thresholds to be quantified with greater certainty. In turn, these advances have improved projections of future sea-level rise, understanding of tipping points, and the impact of ice loss on the wider climate system such as knock-on impacts on global ocean circulation. Model intercomparison exercises have helped to quantify the possible range of possible scenarios and timelines for future ice loss and have provided a way to identify areas of model divergence which need to be further investigated. A major theme of these findings is the stark difference between low and high emissions scenarios in terms of limiting loss and damage from cryosphere loss and ensuring that adaptation can remain feasible for many communities.

d. Addressing sensitivities of climate simulations to varying scenarios and parameterizations

Recent developments in modelling have improved parameterization and representation of key processes in ice sheet models such as coupled ice-ocean interactions, representation of subglacial processes that may accelerate ice retreat, and small-scale processes at ice sheet grounding zones. As a result, improvements have been made in understanding the vulnerability of ice sheets to climate warming and their thresholds for irreversible change.

e. Addressing uncertainties identified in the Intergovernmental Panel on Climate Change (IPCC) Reports (from the Fourth Assessment Report to date)

Research on the cryosphere since IPCC AR4 has included addressing gaps on the inclusion of dynamical ice loss processes (e.g., rapid ice sheet flow, calving, ice shelf collapse) in ice sheet projections, greater understanding of the sensitivity and stability of the West Antarctic Ice Sheet, and improved understanding of ice shelf basal melting and ice sheet wide mass balance trends. Substantial research has also been undertaken on the drivers of emergent phenomena such as the abrupt decline in Antarctic sea ice since 2015. Alongside improvements in model capability and process representation (such as calibration of models with satellite observations) complementary approaches for predicting the future evolution of the ice sheets and quantifying uncertainties, such as structured elicitation approaches, have also been developed. Improvements have also been made in understanding the future evolution of key elements of the global ocean circulation such as the Atlantic Meridional Overturning Circulation (AMOC) and identifying potential precursors of significant change. Many studies have highlighted the great vulnerability of the Earth's cryosphere to even low levels of warming, with even today's temperature being identified as not safe for the cryosphere.

f. High resolution local and regional climate information, as well as improving the development and application of downscaled regional and sub regional climate models, for understanding risks and implementing climate actions

Substantial effort has gone into improving regional information used to feed into models of cryosphere change. In addition, one particularly notable study recently highlighted a methodological blind spot present in most coastal hazard studies used to inform previous IPCC assessments, suggesting that existing coastal hazard assessments may underestimate exposure to sea-level rise risks.

g. Advances and gaps in attribution science, including at regional and national scale, as well as attribution of monsoon pattern changes.

Advances have and are being made in attributing the role of anthropogenic climate change to extreme events in the cryosphere, including in Antarctica, and the potential role of cryosphere loss on event and weather pattern attribution.

B. Adaptation, loss and damage and extreme events:

a. The evolution and dynamics of extreme events, and early warning systems and climate services

Extreme melt events have been increasingly documented in Greenland, Svalbard and in the European Alps. In Antarctica, alarming increases in extreme heatwaves, all-time low sea ice conditions, ice shelf collapse and species population crashes have occurred which risk triggering cascading impacts across the rest of the planet.

b. Assessing adaptation progress, and the impact of adaptation actions on reducing risks, to inform adaptation planning and action

Research has highlighted the risks to adaptation efforts associated with cryosphere loss, with some studies highlighting that current coastal adaptation measures are designed largely based on past and current experiences of hazards, exposure and vulnerability, rather than on future projections that take into account emissions pathways and resulting cryosphere loss. If such cryosphere loss becomes too severe, the limits of many adaptation measures are likely to be exceeded, leading to growing loss and damage.

c. Climate impacts across 1.5 °C warming scenarios at local and regional levels

Research published over the last two decades has made abundantly clear the importance of limiting global warming to 1.5°C for preserving the cryosphere and limiting the extent of global impacts from its

progressive loss. Limiting warming to 1.5°C is predicted to halve glacier extinction rates in the coming decades; globally, nearly 50% of today's glaciers could still exist by 2100 under 1.5°C warming, whereas only 20% will still exist under current policies (2.7°C). These projections have serious consequences for regional water management and mountain communities. Additional work has also examined the impact of temporarily overshooting and then returning to below 1.5 °C. Research has found that overshoot will have irreversible consequences for glacier mass and runoff over centuries, leading to substantially more ice mass loss by 2500 in a 3.0 °C peak-and-decline scenario compared with limiting warming to 1.5 °C without overshoot. However, recent research also consistently demonstrates that even 1.5°C will lead to substantial cryosphere losses and impacts globally. In one recent synthesis, researchers argued that even then-current warming levels at 1.2°C, if sustained, will likely lead to several meters of sea-level rise over coming centuries, resulting in extensive loss and damage to coastal populations and challenging the implementation of adaptation measures. To limit loss and damage associated with cryosphere loss, global mean temperature must return closer to 1°C or below as soon as possible through strong and immediate cuts in greenhouse gas emissions.

d. Understanding of complex, cascading and transboundary risks

Research has shed greater light on the complex, cascading and transboundary risks stemming from cryosphere loss. Risks to human lives, agriculture, within watersheds and on world heritage sites and infrastructure have been elucidated for populations ranging from local communities to billions across the world. Many impacts of cryosphere loss also carry the risk of cascading into other areas, emphasising the wide range of indirect and multisystem impacts stemming from changes to the cryosphere.

C. Ecosystems and nature-based solutions:

a. Opportunities and challenges of implementing nature-based solutions in land and ocean systems in support of climate adaptation and mitigation

Research has outlined the risk that escalating cryosphere loss will pose to nature-based solutions in coastal environments. Many coastal ecosystems used to stabilise coastal margins, such as marshes and mangroves, will face decline under rates of relative sea-level rise faster than 7mm per yr. This rate of sea-level rise, which potentially could be reached before 2100 under 3°C of warming, would affect nearly all the world's mangrove forests and coral reef islands and almost 40% of mapped tidal marshes. Such high rates of sea-level rise may even be realised shortly after 2050 if the currently observed acceleration in sea-level rise continues.

b. Climate change impacts and risks for the ocean and cryosphere and related ecosystems

There is an enormous body of literature (including all of the studies detailed in other sections) that has improved understanding of the impacts and risks of climate change on the cryosphere. Headline messages from the IPCC SROCC and AR6 outline the increasing hazards from glacier retreat and snow loss, increasing weather extremes and ocean acidification that threaten communities and ecosystems, and escalating rates of sea-level rise from increasing ice loss. In addition, major findings published since AR6 reveal that glaciers globally are losing ice at an alarming rate, averaging 270 billion tonnes annually from 2000 to 2023, with a significant acceleration in recent years. The European Alps and similar regions with relatively small glaciated areas have experienced disproportionately larger losses, up to 40% of glacier ice during this period. Climate change is also affecting Arctic shorelines, with thawing permafrost increasing coastal erosion, particularly as storms intensify and coastal sea ice thins. Increasingly early Antarctic sea ice breakup has led to catastrophic die-off events of emperor penguin chicks in several breeding seasons.

D. Mitigation and related technologies, and greenhouse gas (GHG) emissions and reporting:

a. GHG emissions by sources, removals by source and all reservoirs

Arctic permafrost represents a substantial component of the Earth's carbon system. The thawing of permafrost contributes additional greenhouse gas emissions, with the scale of these emissions increasingly characterized since AR4, including better understanding of projected emissions at different anthropogenic emissions scenarios. These are now understood to be on the scale of a major (top-10) emitter, and with such emissions continuing for several centuries after initial thaw. Some of this permafrost thaw occurs gradually, but some occurs in "abrupt thaw" events, for example in association with wildfires, or when a hillside collapses and leads to exposure of permafrost soils. Many global models however only include gradual permafrost thaw in their emissions estimates, overlooking abrupt thaw processes as well as emissions from increasing wildfires in permafrost regions. At least 30% of the boreal zone of Arctic permafrost is now releasing more carbon than it takes up during the growing season, which will increasingly contribute to global warming as more permafrost thaws with rising temperatures, including in extreme heat events.

Annex: Detailed Input

A. Understanding climate change, related climate data, and scenarios development and use:

c. Advances in climate model simulations, particularly by combining multiple lines of evidence and on a wider range of climate variables to improve parameterization of the physical climate system and understanding of scenarios

Summary:

Improved geophysical model development over the last two decades means that the future mass balance, volume and geometry of almost any glacier in the world can now be simulated over multi-centennial timescales, providing a much stronger connection between emissions pathways and downstream impact scenarios at global, regional and local levels. Informed by a much larger base of observations and greater understanding of glaciological processes, major advances in the capability of simulating polar ice sheets have been achieved, allowing their risks and temperature thresholds to be quantified with greater certainty. In turn, these advances have improved projections of future sea-level rise, understanding of tipping points, and the impact of ice loss on the wider climate system such as knock-on impacts on global ocean circulation. Model intercomparison exercises have helped to quantify the possible range of possible scenarios and timelines for future ice loss and have provided a way to identify areas of model divergence which need to be further investigated. A major theme of these findings is the stark difference between low and high emissions scenarios in terms of limiting loss and damage from cryosphere loss and ensuring that adaptation can remain feasible for many communities.

New 2100 Glacier Projections Show Stark Choices between Low and High Emissions Policies

Description:

Improved glacier-specific projections forecast greater glacier loss already by 2100 with continued high emissions of today (resulting in 4°C by 2100), versus rapid emissions reduction this decade which keep global mean temperatures close to 1.5°C. The difference is especially stark for the mid-latitude glaciers of Western Canada and the US, Scandinavia, North Asia, Central Europe/Alps, New Zealand, the Caucasus, and low latitude glaciers. For many glaciers in these regions, total or near-total loss would occur with continued high emissions already by 2100, sooner than previous less detailed model projections. Up to 40% of the total ice of glaciers in these regions would be preserved however with rapid emissions reductions consistent with the 1.5°C Paris Agreement limit. Several of these regions, including the Alps, Scandinavia, the Caucasus and New Zealand would pass a point of no return (total glacier loss) by 3°C.

In High Mountain Asia, including glaciers of the Himalayas providing seasonal water resources to over 2 billion people, losses with low emissions would be slowed to maintain two-thirds of current ice, with risks of exceptional flooding moderated by mid-century. Glaciers in Central Asia and the southern Andes (Chile and Argentina) would preserve twice as much ice with rapid emissions reductions (about 50% globally by 2030) consistent with the 1.5°C limit. The study underlines that every increase in temperature has significant consequences with respect to glacier contribution to sea level rise, the loss of glaciers around the world, and changes to hydrology, ecology, and natural hazards. Regardless of the temperature change scenario, all regions will experience considerable deglaciation, with roughly half of the world's glaciers by number projected to be lost by 2100, even if temperature increase is limited to +1.5°C. Warming levels of 2.7°C would cause the near-complete deglaciation of entire regions including Central Europe, Western Canada and US, and New Zealand compared with the Paris Agreement.

Geographical scope:

Global

Reference and link:

Rounce, D.R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L. and Farinotti, D., 2023. Global glacier change in the 21st century: Every increase in temperature matters. *Science*, 379(6627), pp.78-83. <https://www.science.org/doi/10.1126/science.abo1324>

Glacier preservation doubled by limiting warming to 1.5°C versus 2.7°C

Description:

This study finds that glaciers are even more sensitive to global warming than previously estimated, with only 24% of present-day glacier mass remaining if the world warms to 2.7°C, the trajectory set by current climate policies. In contrast, limiting warming to 1.5°C would preserve 54% of glacier mass. These figures however are global, skewed mostly by the very large glaciers around Antarctica and Greenland. The glacier regions important to human communities are even more sensitive, with several losing nearly all ice at 2°C. This includes the glaciers of the European Alps, the Rockies of the Western U.S. and Canada, and Iceland, with only 10-15% of their 2020 ice levels remaining at 2°C sustained warming. Most hard-hit would be Scandinavia, with no glacier ice remaining at 2°C at all. All four of these regions are committed to losing at least half their ice at or below 1°C; starkly mirroring a paper released last week setting the safe margin for Antarctic and Greenland ice sheets at or below that same 1°C level. Even the Hindu Kush Himalaya, where glaciers feed river basins supporting 2 billion people, show only 25% of 2020 ice remaining at 2°C. Staying close to 1.5°C on the other hand preserves at least some glacier ice in all regions, with 20-30% remaining in the four most sensitive regions and 40-45% in the Himalayas and Caucuses, stressing the growing urgency of the 1.5°C temperature goal.

Geographical scope:

Global

Reference and link:

Zekollari, H., Schuster, L., Maussion, F., Hock, R., Marzeion, B., Rounce, D.R., Compagno, L., Fujita, K., Huss, M., James, M. and Kraaijenbrink, P.D., 2025. Glacier preservation doubled by limiting warming to 1.5° C versus 2.7° C. *Science*, 388(6750), pp.979-983. [10.1126/science.adu4675](https://doi.org/10.1126/science.adu4675)

Mapping tipping risks from Antarctic ice basins under global warming

Description:

This study found that the Antarctic Ice Sheet does not respond to warming as a single system, but rather many separate regions or drainage basins — each with its own “tipping point” (risk of long-term ice loss). Some basins would lose ice gradually as temperatures rise, while others reach thresholds where large amounts of ice eventually collapse after a specific level of warming occurs. Temperatures as low as 1-2°C above pre-industrial levels could trigger the long-term collapse of about 40% of West Antarctica’s ice basins, committing roughly 2 meters of sea-level rise. In East Antarctica, large regions might become unstable at only slightly higher warming levels, with 2-5°C of warming at risk of contributing up to 5 meters; and warming beyond 6°C committing more than 26 meters. One of the most vulnerable regions is West Antarctica’s Amundsen Sea Embayment, which could lose about 70% of its ice volume after crossing its threshold, contributing roughly 1 meter of sea-level rise. This shows that parts of West Antarctica may already be close to, or past, critical thresholds at current warming levels, where rapid and irreversible ice loss triggered in coming years or decades would continue for centuries into the future, even if temperatures later stabilize.

Geographical scope:

Antarctica

Reference and link:

Winkelmann, R., Garbe, J., Donges, J.F. *et al.* Mapping tipping risks from Antarctic ice basins under global warming. *Nat. Clim. Chang.* **16**, 341–349 (2026). <https://doi.org/10.1038/s41558-025-02554-0>

The Antarctic Peninsula under present day climate and future low, medium-high and very high emissions scenarios**Description:**

The Antarctic Peninsula has been warming 0.3-0.5°C per decade since the 1950s, up to two times faster than the global average. If global warming exceeds 2°C, the region faces substantial and irreversible damage, including major losses of sea ice, collapse of ice shelves, and rapid glacier retreat. These changes increase the risk of self-reinforcing processes that would amplify warming and contribute to greater sea-level rise, altered ocean circulation, and other impacts well beyond Antarctica. The loss of sea ice and increased extreme weather have already led to flooded penguin nesting sites and failures of Emperor Penguin breeding colonies, while shifts in krill distribution threaten the stability of marine food webs and fisheries. Rapid reductions in carbon emissions could limit the most severe long-term impacts, while continued warming will require more transformative conservation strategies to protect biodiversity, fishing, tourism, and other operations governed under the Antarctic Treaty system.

Geographical scope:

Antarctica

Reference and link:

Davies BJ, Atkinson A, Banwell AF, Brandon M, Caton Harrison T, Convey P, De Rydt J, Dodds K, Downie R, Edwards TL, Gilbert E, Hubbard B, Hughes KA, Marshall GJ, Orr A, Rogelj J, Seroussi H, Siegert M, Stroeve J and Rumble J (2026) The Antarctic Peninsula under present day climate and future low, medium-high and very high emissions scenarios. *Front. Environ. Sci.* 13:1730203. <https://doi.org/10.3389/fenvs.2025.1730203>

Antarctic surface melt will expand through the 21st century**Description:**

Surface melting in Antarctica is projected to increase this century, with the area experiencing surface melt expanding by more than 10% by 2100 under high emissions. Only low emissions scenarios will keep the spread of surface melting from increasing beyond present levels. Surface melting alters how much solar heat the ice absorbs, drives greater meltwater pooling and drainage through the ice, and contributes to faster ice loss and sea-level rise. It also poses a serious risk to ice shelves, especially in the West Antarctic Peninsula and Amundsen Sea Embayment, where increased surface water can promote hydrofracturing and structural weakening of the ice. Looking beyond 2100, the differences between emission scenarios grow more pronounced, with major implications for long-term ice sheet stability and resulting sea-level rise.

Geographical scope:

Antarctica

Reference and link:

Zheng, Y., Golledge, N.R., Gossart, A. *et al.* Expansion of Antarctic surface melt through the 21st century. *Nat Commun* (2026). <https://doi.org/10.1038/s41467-026-71114-7>

Collapse of the Atlantic meridional overturning circulation would lead to substantial oceanic carbon release and additional global warming

Description:

The potential collapse of the major system of global ocean currents known as the Atlantic Meridional Overturning Circulation (AMOC) could cause release of large amounts of carbon from the Southern Ocean, increasing atmospheric CO₂ and adding roughly 0.2°C of additional global warming. The AMOC transports warm surface water northward in the Atlantic and returns colder, denser water southward, helping regulate global climate and ocean carbon storage. Using the Earth system model CLIMBER-X, researchers simulated AMOC collapse under different warming levels and found that its collapse could trigger substantial carbon release from the Southern Ocean. Surface waters around Antarctica would sink and mix with deep carbon-rich waters, allowing stored ocean carbon to escape into the atmosphere. In addition to increasing net global warming, AMOC collapse would have extreme impacts on regional temperatures: the Arctic would cool by about 7°C, while Antarctic regions would warm by 6°C. These results highlight the role of the AMOC as a key regulator of global climate, and show how disruptions in AMOC circulation could weaken the ocean's role as a carbon sink and dramatically alter regional temperatures.

Geographical scope:

Global

Reference and link:

Nian, D., Willeit, M., Wunderling, N. *et al.* Collapse of the Atlantic meridional overturning circulation would lead to substantial oceanic carbon release and additional global warming. *Commun Earth Environ* 7, 295 (2026). <https://doi.org/10.1038/s43247-026-03427-w>

Today's Temperatures Could Lock-in Major Sea Level Rise from West Antarctica

Description:

Improved ice sheet modeling techniques in this study indicate that current rates of ice loss from the West Antarctic Ice Sheet show a strong possibility of future collapse in the region, even with no further warming. If ocean temperatures simply remain at present-day levels for several centuries, the models project that two of the largest glaciers in West Antarctica, Thwaites and Pine Island, will collapse, resulting in global sea-level rise of at least 1.2 meters from these two glaciers alone. Simulations of immediate cooling temperatures down to pre-industrial slowed, but in most cases could not prevent the collapse. This research highlights the potential for significant sea-level rise even without additional warming, emphasizing the long-term consequences communities could face under current climate conditions.

Geographical scope:

Antarctica

Reference and link:

van den Akker, T., Lipscomb, W. H., Leguy, G. R., Bernal, J., Berends, C. J., van de Berg, W. J., and van de Wal, R. S. W.: Present-day mass loss rates are a precursor for West Antarctic Ice Sheet collapse, *The Cryosphere*, 19, 283–301, <https://doi.org/10.5194/tc-19-283-2025>, 2025.

The influence of realistic 3D mantle viscosity on Antarctica's contribution to future global sea levels

Description:

The response of the Antarctic Ice Sheet (AIS) to climate change is the largest uncertainty in projecting future sea level. The impact of three-dimensional (3D) Earth structure on the AIS and future global sea levels is assessed here by coupling a global glacial isostatic adjustment model incorporating 3D Earth structure to a dynamic ice-sheet model. We show that including 3D viscous effects produces rapid uplift in marine sectors and reduces projected ice loss for low greenhouse gas emission scenarios, lowering Antarctica's contribution to global sea level in the coming centuries by up to ~40%. Under high-emission scenarios, ice retreat outpaces uplift, and sea-level rise is amplified by water expulsion from Antarctic marine areas.

Geographical scope:

Antarctica

Reference and links:

[10.1126/sciadv.adn1470](https://doi.org/10.1126/sciadv.adn1470)

Every Increment of Warming Above 1.5°C Increases the Risk of Crossing Tipping Points – Even if Overshoot is Temporary

Description:

Current climate policies are not ambitious enough to prevent tipping points from being crossed, even if long-term temperatures return to 1.5°C by 2300, new analysis shows. The authors investigated the risk of tipping where warming temporarily overshoots 1.5°C, but global temperatures are then brought back down using negative emissions technologies. They found that the longer the 1.5°C threshold is breached, and the higher the peak temperature; the greater the risk of crossing tipping points for the West Antarctic and Greenland ice sheets, the Atlantic Meridional Overturning Circulation (AMOC), and the Amazon rainforest. Scenarios following pledged NDCs under the UNFCCC in 2020 until 2100 would lead to a 10–90% chance of tipping points being crossed (median estimate: 30%), even when subsequently designed such that temperatures return to 1.5°C after overshoot. Tipping risk was found to increase with every 0.1°C of overshoot peak temperature, and risk accelerates non-linearly for peak overshoot temperatures above 2°C. This research underscores the importance of the Paris Agreement climate objective to hold warming to 'well below 2°C', with as little and as brief overshoot of even 1.5°C as possible.

Geographical scope:

Global

Reference and link:

Möller, T., Högner, A.E., Schleussner, C.F. *et al.* Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. *Nat Commun* **15**, 6192 (2024). <https://doi.org/10.1038/s41467-024-49863-0>

Widespread seawater intrusions beneath the grounded ice of Thwaites Glacier, West Antarctica

Description:

We present evidence for seawater intrusions occurring at tidal frequencies over many kilometers beneath the grounded ice of Thwaites Glacier, West Antarctica, a major contributor to sea level rise. The results call into question the traditional approach of modeling a fixed, abrupt transition from grounded ice to ice floating in the ocean with no ice melt at the transition boundary. We delineate a tidally controlled grounding zone, 2 to 6 km in length, and additionally irregular seawater intrusions extending another 6 km inland at spring tide. The

rushing of seawater beneath grounded ice over considerable distances makes the glacier more vulnerable to melting from a warmer ocean than anticipated, which in turn will increase projections of ice mass loss.

Geographical scope:

Antarctica

Reference and link:

E. Rignot, E. Ciraci, B. Scheuchl, V. Tolpekin, M. Wollersheim, & C. Dow, Widespread seawater intrusions beneath the grounded ice of Thwaites Glacier, West Antarctica, *Proc. Natl. Acad. Sci. U.S.A.* 121 (22) e2404766121, <https://doi.org/10.1073/pnas.2404766121> (2024).

Unavoidable Future Increase in West Antarctic Ice Shelf Melting over the 21st Century

Description:

A state-of-the-art model suggests that a widespread increase in West Antarctic ice shelf melting, including in regions crucial for maintaining the stability of the bordering ice sheet, is now locked in to occur through at least 2100. This is because water temperatures in the Amundsen Sea off West Antarctica could be up to 2°C warmer than pre-industrial by 2100, even if global mean temperature is limited to 1.5°C of warming. With widespread loss of ice shelves from warmer waters now to some degree inevitable, the opportunity to preserve the West Antarctic Ice Sheet in its present-day state has probably passed. If it were to collapse completely, this ice sheet would raise sea levels by 5 meters. The authors stress that policymakers must therefore prepare to adapt to several meters of sea-level rise over the coming centuries. However, the study finds that if warming is held at 1.5°C, rates of ice shelf melting start to slow by 2100, suggesting that further losses beyond 2100 may still be preventable; or at least slowed by strict adherence to the lower Paris 1.5°C goal. Reducing sea-level rise after 2100, or even slowing it down, could save many coastal cities and prevent trillions of dollars of damage to coastlines worldwide.

Geographical scope:

Antarctica

Reference and link:

Naughten, K.A., Holland, P.R. & De Rydt, J. Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century. *Nat. Clim. Chang.* **13**, 1222–1228 (2023). <https://doi.org/10.1038/s41558-023-01818-x>

Current Climate Warming Enough to Set West Antarctica on Path to Irreversible Collapse

Description:

Two studies reveal that remaining at today's 1.2°C could trigger the slow but certain loss of parts of West Antarctica over coming centuries, even with no additional warming beyond current temperatures. Once initiated, this ice loss and sea level rise cannot be reversed. Experts from major European research institutions joined together to create the first systematic inspection of the ice sheet's current stability. Their conclusion: while runaway retreat has not yet started, staying even at present-day temperatures would, over time, cause 2.7 to 3.5 meters of global sea level rise from this section of Antarctica alone. This is because many regions of the West Antarctic ice sheet are precariously balanced on sloped bedrock that could produce unstoppable ice loss if this retreat crosses a threshold, triggering a domino-effect of ice breaking away and slipping into the ocean. Authors warn that given already-warming waters around West Antarctica, this threshold might be reached within 300 years even if temperatures remain stable at today's 1.2°C. Anthropogenic fossil fuel emissions are on track however to hit 2.7°C by 2100 under current trajectories,

which several studies show could cause far more rapid irreversible ice loss. A full collapse of West Antarctica would take centuries to millennia, but can be avoided with urgent climate action. Only rapid emissions reductions provide the best possible chance to avoid crossing this dangerous threshold of irreversible, multi-meter sea-level rise from West Antarctica.

Geographical scope:

Antarctica

Reference and link:

Hill, E. A., Urruty, B., Reese, R., Garbe, J., Gagliardini, O., Durand, G., Gillet-Chaulet, F., Gudmundsson, G. H., Winkelmann, R., Chekki, M., Chandler, D., and Langebroek, P. M.: The stability of present-day Antarctic grounding lines – Part 1: No indication of marine ice sheet instability in the current geometry, *The Cryosphere*, 17, 3739–3759, <https://doi.org/10.5194/tc-17-3739-2023>

Reese, R., Garbe, J., Hill, E. A., Urruty, B., Naughten, K. A., Gagliardini, O., Durand, G., Gillet-Chaulet, F., Gudmundsson, G. H., Chandler, D., Langebroek, P. M., and Winkelmann, R.: The stability of present-day Antarctic grounding lines – Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded, *The Cryosphere*, 17, 3761–3783, <https://doi.org/10.5194/tc-17-3761-2023>

Increased Antarctic Ice Sheet Melt Could Cause 40% Slowdown of Deep Ocean Currents by 2050

Description:

The abyssal ocean circulation is a key component of the global meridional overturning circulation, cycling heat, carbon, oxygen and nutrients throughout the world ocean. The strongest historical trend observed in the abyssal ocean is warming at high southern latitudes. This study applied a high-resolution coupled ocean–sea-ice model to show that under a high-emissions scenario, abyssal ocean warming is set to accelerate over the next 30 years. We find that meltwater input around Antarctica drives a contraction of Antarctic Bottom Water (AABW), opening a pathway that allows warm Circumpolar Deep Water greater access to the continental shelf, enhancing Antarctic glacier melt.

Geographical scope:

Antarctica

Reference and link:

Li, Q., England, M.H., Hogg, A.M. *et al.* Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature* **615**, 841–847 (2023). <https://doi.org/10.1038/s41586-023-05762-w>

Ice-sheet losses track high-end sea-level rise projections

Description:

A review published in 2020 demonstrated that observed ice-sheet losses track the upper range of the IPCC Fifth Assessment Report sea-level predictions, recently driven by ice dynamics in Antarctica and surface melting in Greenland. The authors recommend that ice-sheet models must account for short-term variability in the atmosphere, oceans and climate to accurately predict sea-level rise.

Geographical scope:

Antarctica and Greenland

Reference and link:

Slater, T., Hogg, A.E. & Mottram, R. Ice-sheet losses track high-end sea-level rise projections. *Nat. Clim. Chang.* **10**, 879–881 (2020). <https://doi.org/10.1038/s41558-020-0893-y>

Contribution of the Greenland Ice Sheet to sea level over the next millennium

Description:

The Greenland Ice Sheet holds 7.2 m of sea level equivalent and in recent decades, rising temperatures have led to accelerated mass loss. Current ice margin recession is led by the retreat of outlet glaciers, large rivers of ice ending in narrow fjords that drain the interior. This study paired an outlet glacier–resolving ice sheet model with a comprehensive uncertainty quantification to estimate Greenland’s contribution to sea level over the next millennium. They find that Greenland could contribute 5 to 33 cm to sea level by 2100, with discharge from outlet glaciers contributing 8 to 45% of total mass loss. They project that Greenland will very likely become ice free within a millennium without substantial reductions in greenhouse gas emissions.

Geographical scope:

Greenland

Reference and link:

Aschwanden, A., Fahnestock, M.A., Truffer, M., Brinkerhoff, D.J., Hock, R., Khroulev, C., Mottram, R. and Khan, S.A., 2019. Contribution of the Greenland Ice Sheet to sea level over the next millennium. *Science advances*, 5(6), p.eaav9396. [10.1126/sciadv.aav9396](https://doi.org/10.1126/sciadv.aav9396)

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Description:

Resting atop a deep marine basin, the West Antarctic Ice Sheet has long been considered prone to instability. Using a numerical model, this study investigated the sensitivity of Thwaites Glacier to ocean melt and whether its unstable retreat is already under way. Simulated losses are moderate (<0.25 mm per year at sea level) over the 21st century but generally increase thereafter. Except possibly for the lowest-melt scenario, the simulations indicate that early-stage collapse has begun. Less certain is the time scale, with the onset of rapid (>1 mm per year of sea-level rise) collapse in the different simulations within the range of 200 to 900 years.

Geographical scope:

West Antarctica

Reference and link:

Joughin, I., Smith, B.E. and Medley, B., 2014. Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science*, 344(6185), pp.735-738. [10.1126/science.1249055](https://doi.org/10.1126/science.1249055)

Modelling West Antarctic ice sheet growth and collapse through the past five million years

Description:

The West Antarctic ice sheet (WAIS) has long been considered capable of past and future catastrophic collapse. Today, the ice sheet is fringed by vulnerable floating ice shelves that buttress the fast flow of inland ice streams. Grounding lines are several hundred metres below sea level and the bed deepens upstream, raising the prospect of runaway retreat. Projections of future WAIS behaviour have been hampered by limited understanding of past variations and their underlying forcing mechanisms^{6,7}. Its variation since the

Last Glacial Maximum is best known, with grounding lines advancing to the continental-shelf edges around ~15 kyr ago before retreating to near-modern locations by ~3 kyr ago. Prior collapses during the warmth of the early Pliocene epoch and some Pleistocene interglacials have been suggested indirectly from records of sea level and deep-sea-core isotopes, and by the discovery of open-ocean diatoms in subglacial sediments. These authors used a combined ice sheet/ice shelf model capable of high-resolution nesting with a new treatment of grounding-line dynamics and iceshelf buttressing to simulate Antarctic ice sheet variations over the past five million years. Modelled WAIS variations range from full glacial extents with grounding lines near the continental shelf break, intermediate states similar to modern, and brief but dramatic retreats, leaving only small, isolated ice caps on West Antarctic islands. Transitions between glacial, intermediate and collapsed states are relatively rapid, taking one to several thousand years. The simulation is in good agreement with a new sediment record (ANDRILL AND-1B) recovered from the western Ross Sea, indicating a long-term trend from more frequently collapsed to more glaciated states, dominant 40-kyr cyclicity in the Pliocene, and major retreats at marine isotope stage 31 (~1.07 Myr ago) and other super-interglacials.

Geographical scope:

Antarctica

Reference and link:

Pollard, D., DeConto, R. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* **458**, 329–332 (2009). <https://doi.org/10.1038/nature07809>

Multimillennial sea-level commitment due to global warming

Description:

Global mean sea level has been steadily rising over the last century, is projected to increase by the end of this century, and will continue to rise beyond the year 2100 unless the current global mean temperature trend is reversed. Inertia in the climate and global carbon system, however, causes the global mean temperature to decline slowly even after greenhouse gas emissions have ceased, raising the question of how much sea-level commitment is expected for different levels of global mean temperature increase above preindustrial levels. Although sea-level rise over the last century has been dominated by ocean warming and loss of glaciers, the sensitivity suggested from records of past sea levels indicates important contributions should also be expected from the Greenland and Antarctic Ice Sheets. Uncertainties in the paleo-reconstructions, however, necessitate additional strategies to better constrain the sea-level commitment. Here we combine paleo-evidence with simulations from physical models to estimate the future sea-level commitment on a multimillennial time scale and compute associated regional sea-level patterns. Oceanic thermal expansion and the Antarctic Ice Sheet contribute quasi-linearly, with $0.4 \text{ m } ^\circ\text{C}^{-1}$ and $1.2 \text{ m } ^\circ\text{C}^{-1}$ of warming, respectively. The saturation of the contribution from glaciers is overcompensated by the nonlinear response of the Greenland Ice Sheet. As a consequence, we are committed to a sea-level rise of approximately $2.3 \text{ m } ^\circ\text{C}^{-1}$ within the next 2,000 y. Considering the lifetime of anthropogenic greenhouse gases, this imposes the need for fundamental adaptation strategies on multicentennial time scales.

Geographical scope:

Greenland and Antarctica

Reference and link:

A. Levermann, P.U. Clark, B. Marzeion, G.A. Milne, D. Pollard, V. Radic, & A. Robinson, The multimillennial sea-level commitment of global warming, *Proc. Natl. Acad. Sci. U.S.A.* **110** (34) 13745-13750, <https://doi.org/10.1073/pnas.1219414110> (2013).

Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites

Description:

This study presents a global set of local sea-level (LSL) projections to inform decisions on timescales ranging from the coming decades through the 22nd century. Between the years 2000 and 2100, they project a *very likely* (90% probability) GSL rise of 0.5–1.2 m under representative concentration pathway (RCP) 8.5, 0.4–0.9 m under RCP 4.5, and 0.3–0.8 m under RCP 2.6. Site-to-site differences in LSL projections are due to varying non-climatic background uplift or subsidence, oceanographic effects, and spatially variable responses of the geoid and the lithosphere to shrinking land ice. The Antarctic ice sheet constitutes a growing share of variance in GSL and LSL projections. In the global average and at many locations, it is the dominant source of variance in late 21st century projections, though at some sites oceanographic processes contribute the largest share throughout the century. LSL rise dramatically reshapes flood risk, greatly increasing the expected number of “1-in-10” and “1-in-100” year events.

Geographical scope:

Global

Reference and link:

Kopp, R. E. et al. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* 2, 383–406 (2014). 10.1002/2014ef000239

Evolution of the Antarctic Ice Sheet Over the Next Three Centuries

Description:

A comparison of 16 leading ice-sheet models highlighted the sharp risk of triggering a large acceleration in Antarctic ice loss rates after 2100 if the world continues on a high emissions pathway. The models suggest that Antarctica alone could contribute up to 28 cm of sea-level rise by 2100 under a high emissions pathway, and up to 1.7 m by 2200 and 6.9 m by 2300 if its peripheral ice shelves collapse. 40% of the models predict that the West Antarctic Ice Sheet will collapse by 2300.

Geographical scope:

Antarctica

Reference and link:

Seroussi, H., Pelle, T., Lipscomb, W. H., Abe-Ouchi, A., Albrecht, T., Alvarez-Solas, J., Asay-Davis, X., Barre, J.-B., Berends, C. J., Bernales, J., Blasco, J., Caillet, J., Chandler, D. M., Coulon, V., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Garbe, J., Gillet-Chaulet, F., Gladstone, R., Goelzer, H., Golledge, N., Greve, R., Gudmundsson, G. H., Han, H. K., Hillebrand, T. R., Hoffman, M. J., Huybrechts, P., Jourdain, N. C., Klose, A. K., Langebroek, P. M., Leguy, G. R., Lowry, D. P., Mathiot, P., Montoya, M., Morlighem, M., Nowicki, S., Pattyn, F., Payne, A. J., Quiquet, A., Reese, R., Robinson, A., Saraste, L., Simon, E. G., Sun, S., Twarog, J. P., Trusel, L. D., Urruty, B., Van Breedam, J., van de Wal, R. S. W., Wang, Y., Zhao, C., and Zwinger, T. (2024). Evolution of the Antarctic Ice Sheet Over the Next Three Centuries From an ISMIP6 Model Ensemble. *Earth's Future*, v. 12, no, 9, e2024EF004561, <https://doi.org/https://doi.org/10.1029/2024EF004561>.

d. Addressing sensitivities of climate simulations to varying scenarios and parameterizations

Summary:

Recent developments in modelling have improved parameterization and representation of key processes in ice sheet models such as coupled ice-ocean interactions, representation of subglacial processes that may accelerate ice retreat, and small-scale processes at ice sheet grounding zones. As a result, improvements have been made in understanding the vulnerability of ice sheets to climate warming and their thresholds for irreversible change.

Present-Day Warming Nearing Critical Threshold for West Antarctic Ice Sheet Stability

Description:

Research analyzing the Antarctic Ice Sheet's behavior over the past 800,000 years finds that a minimal increase in ocean temperatures above today's levels, or even no additional warming at all if today's temperatures continue, could trigger the irreversible collapse of the West Antarctic Ice Sheet (WAIS). Historically, WAIS has oscillated between two stable states for nearly a million years: one where it remains intact, as it is today, and another where it has collapsed entirely. These oscillations are driven by small variations in ocean temperature, which once exceeded past a critical limit, push the ice sheet irreversibly towards disintegration. Once the tipping point is crossed, returning WAIS to a new stable state requires temperatures to stay at or below pre-industrial levels for several thousand years. While ice sheet formation is incredibly slow, its destabilization can happen in just a few decades; once triggered, it sets in motion feedback loops that amplify heat absorption and ice loss, rendering it nearly impossible to halt. A stable WAIS is important not only to maintain global sea levels, but also ocean circulation patterns and weather systems.

Geographical scope:

Antarctica

Reference and link:

Chandler, D.M., Langebroek, P.M., Reese, R. *et al.* Antarctic Ice Sheet tipping in the last 800,000 years warns of future ice loss. *Commun Earth Environ* 6, 420 (2025). <https://doi.org/10.1038/s43247-025-02366-2>

Improved Models of Subglacial Water Show Potential Tripling of Antarctic Ice Loss by 2300

Description:

Subglacial water may play a much larger role in Antarctic ice loss than previously thought, and this study suggests that current models may underestimate future sea-level rise by a factor of three. Vast networks of lakes and streams lie beneath the Antarctic ice sheet. This water can lubricate the ice, allowing it to slide more rapidly toward the ocean. Incorporating the latest understanding of subglacial water processes into projections can increase ice loss threefold, potentially contributing an additional 2.2 meters to global sea-level rise by 2300. The study highlights the importance of accurately modeling subglacial water given its key role in moderating ice sheet flow and increasing melt and related sea-level rise, which could lead to trillions of dollars in earlier and greater economic damage, inundating coastlines and displacing millions of people in coming centuries.

Geographical scope:

Antarctica

Reference and link:

Zhao, C., Gladstone, R., Zwinger, T. *et al.* Subglacial water amplifies Antarctic contributions to sea-level rise. *Nat Commun* 16, 3187 (2025). <https://doi.org/10.1038/s41467-025-58375-4>

Critical thresholds of the Greenland ice sheet**Description:**

This study shows that the Greenland ice sheet is more sensitive to long-term climate change than previously thought. The authors estimate that the warming threshold leading to a monostable, essentially ice-free state is in the range of 0.8–3.2 °C, with a best estimate of 1.6 °C. By testing the ice sheet’s ability to regrow after partial mass loss, they find that at least one intermediate equilibrium state is possible, though for sufficiently high initial temperature anomalies, total loss of the ice sheet becomes irreversible. Crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia). However, the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical threshold.

Geographical scope:

Greenland

Reference and link:

Robinson, A., Calov, R. & Ganopolski, A. Multistability and critical thresholds of the Greenland ice sheet. *Nature Clim Change* 2, 429–432 (2012). <https://doi.org/10.1038/nclimate1449>

Coupled ice–ocean interactions during future retreat of West Antarctic ice streams in the Amundsen Sea sector**Description:**

The Amundsen Sea sector has some of the fastest-thinning ice shelves in Antarctica, caused by high, ocean-driven basal melt rates, which can lead to increased ice streamflow, causing increased sea level rise (SLR) contributions. In this study, we present the results of a new synchronously coupled ice-sheet–ocean model of the Amundsen Sea sector. We use the Wavelet-based, Adaptive-grid, Vertically Integrated ice sheet model (WAVI) to solve for ice velocities and the Massachusetts Institute of Technology general circulation model (MITgcm) to solve for ice thickness and three-dimensional ocean properties, allowing for full mass conservation in the coupled ice–ocean system. The coupled model is initialised in the present day and run forward under idealised warm and cold ocean conditions with a fixed ice front. We find that Thwaites Glacier dominates the future SLR from the Amundsen Sea sector, with a SLR that evolves approximately quadratically over time. The future evolution of Thwaites Glacier depends on the lifespan of small pinning points that form during the retreat. The rate of melting around these pinning points provides the link between future ocean conditions and the SLR from this sector and will be difficult to capture without a coupled ice–ocean model. Grounding-line retreat leads to a progressively larger Thwaites Ice Shelf cavity, leading to a positive trend in total melting, resulting from the increased ice basal surface area. Despite these important sensitivities, Thwaites Glacier retreats even in a scenario with zero ocean-driven melting. This demonstrates that a tipping point may have been passed in these simulations and some SLR from this sector is now committed.

Geographical scope:

Antarctica

Reference and link:

Bett, D. T., Bradley, A. T., Williams, C. R., Holland, P. R., Arthern, R. J., and Goldberg, D. N.: Coupled ice–ocean interactions during future retreat of West Antarctic ice streams in the Amundsen Sea sector, *The Cryosphere*, 18, 2653–2675, <https://doi.org/10.5194/tc-18-2653-2024>, 2024.

e. Addressing uncertainties identified in the Intergovernmental Panel on Climate Change (IPCC) Reports (from the Fourth Assessment Report to date)

Summary:

Research on the cryosphere since IPCC AR4 has included addressing gaps on the inclusion of dynamical ice loss processes (e.g., rapid ice sheet flow, calving, ice shelf collapse) in ice sheet projections, greater understanding of the sensitivity and stability of the West Antarctic Ice Sheet, and improved understanding of ice shelf basal melting and ice sheet wide mass balance trends. Substantial research has also been undertaken on the drivers of emergent phenomena such as the abrupt decline in Antarctic sea ice since 2015. Alongside improvements in model capability and process representation (such as calibration of models with satellite observations) complimentary approaches for predicting the future evolution of the ice sheets and quantifying uncertainties, such as structured elicitation approaches, have also been developed. Improvements have also been made in understanding the future evolution of key elements of the global ocean circulation such as the Atlantic Meridional Overturning Circulation (AMOC) and identifying potential precursors of significant change. Many studies have highlighted the great vulnerability of the Earth's cryosphere to even low levels of warming, with even today's temperature being identified as not safe for the cryosphere.

Ocean Warming Triggered Widespread 2015 Antarctic Sea Ice Loss

Description:

Between 2015 and 2017, Antarctic sea ice underwent a drastic shift from a record high to a record low in sea ice area. Researchers used over 100,000 hydrographic profiles from the Southern Ocean and atmospheric reanalysis data to show that a change in ocean–sea ice state was preconditioned by a thinning of Antarctic Winter Water between 2005 and 2015, while the reservoir of warmer deep water moved closer to the surface and sea ice. Then, in 2015, anomalously strong winds enhanced mixing across the thin Winter Water layer, entraining warm and salty subsurface waters, which broke down upper-ocean stratification. This combination of decadal-scale oceanic preconditions and strong wind-driven mixing in 2015 drove the sea ice loss that marked the regime shift. This regime shift poses a serious risk to polar species, including krill that rely on stable sea ice, and threatens the future stability of Antarctic ice shelves. It could also impact global ocean currents, including the important Atlantic Meridional Overturning Circulation (AMOC), carrying broader implications for global climate and weather.

Geographical scope:

Antarctica

Reference and link:

Spira, T., du Plessis, M., Haumann, F.A. *et al.* Wind-triggered Antarctic sea-ice decline preconditioned by thinning Winter Water. *Nat. Clim. Chang.* (2026). <https://doi.org/10.1038/s41558-026-02601-4>

Returning closer to 1°C or below is essential for reducing ice loss from Polar ice sheets

Description:

A synthesis study presents strong evidence that the Paris Agreement's lower temperature limit of 1.5°C above pre-industrial levels is too high to prevent significant sea-level rise from Antarctica and Greenland. Even current warming levels at 1.2°C, if sustained, will likely lead to several meters of sea-level rise over coming centuries, resulting in extensive loss and damage to coastal populations and challenging the

implementation of adaptation measures. Currently, around 230 million people live within just one meter of sea level; melting ice represents an existential threat to those communities as well as several low-lying nations. To avoid this future, global mean temperature must return closer to 1°C or below as soon as possible through strong and immediate cuts in greenhouse gas pollution to prevent (in IPCC terminology) “slow-onset, high-impact” losses from both polar ice sheets.

Geographical scope:

Polar regions

Reference and link:

Stokes, C.R., Bamber, J.L., Dutton, A. et al. Warming of +1.5 °C is too high for polar ice sheets. *Commun Earth Environ* 6, 351 (2025). <https://doi.org/10.1038/s43247-025-02299-w>

Octopus DNA Shows Past West Antarctic Ice Sheet Collapse with Temperatures Similar to Today

Description:

The West Antarctic Ice Sheet (WAIS) holds enough ice to raise global sea level by 5 meters, with direct consequences that include complete inundation of low-lying countries and global loss of coastal ecosystems. Modelling studies have suggested that WAIS collapse may already be inevitable, or very close to long-term committed collapse; but the harsh environment of Antarctica has made it difficult to gather direct evidence of past collapse patterns during former warm interglacial periods. Using novel genetic analyses, this study shows that octopuses around Antarctica are genetically related in a manner only possible if the WAIS had retreated such as to create a connecting seaway running straight through today’s ice sheet. Their analysis shows for the first time empirically that the WAIS collapsed completely during the Last Interglacial Period (119,000 – 116,000 years ago), when global sea levels were 5 to 10 meters higher than today and global average temperatures between 0.5°-1.5°C warmer than pre-industrial.

Geographical scope:

Antarctica

Reference and link:

[10.1126/science.ade0664](https://doi.org/10.1126/science.ade0664)

Some East Antarctic glaciers Retreating Nearly as Fast as those in West Antarctica

Description:

Latest observations confirm that the Vanderford Glacier in Wilkes Land, East Antarctica, is the third fastest retreating glacier in Antarctica over the past two decades. West Antarctica receives the bulk of attention for ice loss, but this study shows such rapid loss is nearly matched even in parts of East Antarctica, mistakenly thought nearly immune to global warming by much of the public. Conditions on Vanderford mirror those of West Antarctic glaciers, with warm water entering cavities beneath its ice shelf. The study included a detailed assessment of the Vincennes Bay region around Vanderford, recording the warmest water intrusions ever seen in East Antarctica. Deep channels in the bottom of the bay allow warm ocean currents to flow upward onto the continental shelf, eroding the glacier where it meets the water. As the ice shelf supporting the glacier thins, it loses the ability to restrain the immense wall of ice behind it. Wilkes Land overall has been rapidly losing mass for several decades. Recent record-low sea ice trends around Antarctica may further speed ice loss and resulting global sea-level rise from glaciers such as Vanderford, which rely on frozen mixtures of sea ice and icebergs to stabilize the floating edge of the glacier, as well as shield against ice erosion from large ocean swells. If Vanderford’s retreat continues at its present rate, it will move from its position on

stabilizing bedrock, triggering its inevitable loss; similar to the unstable retreat that multiple studies argue may already be underway for the Pine Island and Thwaites glaciers in West Antarctica.

Geographical scope:

Antarctica

Reference and link:

Picton, H. J., Stokes, C. R., Jamieson, S. S. R., Floricioiu, D., and Krieger, L.: Extensive and anomalous grounding line retreat at Vanderford Glacier, Vincennes Bay, Wilkes Land, East Antarctica, *The Cryosphere*, 17, 3593–3616, <https://doi.org/10.5194/tc-17-3593-2023>, 2023.

An expert judgement assessment of future sea level rise from the ice sheets

Description:

A major gap in predictive capability concerning the future evolution of the ice sheets was identified in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change. As a consequence, it has been suggested that the AR4 estimates of future sea-level rise from this source may have been underestimated. Various approaches for addressing this problem have been tried, including semi-empirical models and conceptual studies. Here, we report a formalized pooling of expert views on uncertainties in future ice-sheet contributions using a structured elicitation approach. We find that the median estimate of such contributions is 29 cm—substantially larger than in the AR4—while the upper 95th percentile value is 84 cm, implying a conceivable risk of a sea-level rise of greater than a metre by 2100. On the critical question of whether recent ice-sheet behaviour is due to variability in the ice sheet–climate system or reflects a long-term trend, expert opinion is shown to be both very uncertain and undecided.

Geographical scope:

Antarctica and Greenland

Reference and link:

Bamber, J., Aspinall, W. An expert judgement assessment of future sea level rise from the ice sheets. *Nature Clim Change* 3, 424–427 (2013). <https://doi.org/10.1038/nclimate1778>

Observed fingerprint of a weakening Atlantic Ocean overturning circulation

Description:

The Atlantic meridional overturning circulation (AMOC)—a system of ocean currents in the North Atlantic—has a major impact on climate, yet its evolution during the industrial era is poorly known owing to a lack of direct current measurements. Here we provide evidence for a weakening of the AMOC by about 3 ± 1 sverdrups (around 15 per cent) since the mid-twentieth century. This weakening is revealed by a characteristic spatial and seasonal sea-surface temperature ‘fingerprint’—consisting of a pattern of cooling in the subpolar Atlantic Ocean and warming in the Gulf Stream region—and is calibrated through an ensemble of model simulations from the CMIP5 project. We find this fingerprint both in a high-resolution climate model in response to increasing atmospheric carbon dioxide concentrations, and in the temperature trends observed since the late nineteenth century. The pattern can be explained by a slowdown in the AMOC and reduced northward heat transport, as well as an associated northward shift of the Gulf Stream. Comparisons with recent direct measurements from the RAPID project and several other studies provide a consistent depiction of record-low AMOC values in recent years.

Geographical scope:

North Atlantic

Reference and link:

Caesar, L., Rahmstorf, S., Robinson, A. *et al.* Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* **556**, 191–196 (2018). <https://doi.org/10.1038/s41586-018-0006-5>

Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting

Description:

The AR5 of the Intergovernmental Panel on Climate Change concludes that the Atlantic Meridional Overturning Circulation (AMOC) could weaken substantially but is very unlikely to collapse in the 21st century. However, the assessment largely neglected Greenland Ice Sheet (GrIS) mass loss, lacked a comprehensive uncertainty analysis, and was limited to the 21st century. Here in a community effort, improved estimates of GrIS mass loss are included in multicentennial projections using eight state-of-the-science climate models, and an AMOC emulator is used to provide a probabilistic uncertainty assessment. We find that GrIS melting affects AMOC projections, even though it is of secondary importance. By years 2090–2100, the AMOC weakens by 18% [–3%, –34%; 90% probability] in an intermediate greenhouse-gas mitigation scenario and by 37% [–15%, –65%] under continued high emissions. Afterward, it stabilizes in the former but continues to decline in the latter to –74% [+4%, –100%] by 2290–2300, with a 44% likelihood of an AMOC collapse. This result suggests that an AMOC collapse can be avoided by CO₂ mitigation.

Geographical scope:

North Atlantic

Reference and link:

Bakker, P., et al. (2016), Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting, *Geophys. Res. Lett.*, 43, 12,252–12,260, doi:10.1002/2016GL070457.

Increased sea-level contribution from northwestern Greenland for models that reproduce observation

Description:

A new model of northwestern Greenland calibrated with satellite observations was able to correct a long-standing bias in the models previously used to inform the IPCC which tend to underestimate the observed mass loss from the Greenland Ice Sheet. The revised model leads to an 8 to 17% greater sea-level rise contribution from this region by 2100

Geographical scope:

Greenland

Reference and link:

Badgeley, J. A., Morlighem, M., and Seroussi, H. (2025). Increased sea-level contribution from northwestern Greenland for models that reproduce observations. *Proceedings of the National Academy of Sciences*, v. 122, no, 25, e2411904122, <https://doi.org/doi:10.1073/pnas.2411904122>.

f. High resolution local and regional climate information, as well as improving the development and application of downscaled regional and sub regional climate models, for understanding risks and implementing climate actions

Summary:

Substantial effort has gone into improving regional information used to feed into models of cryosphere change. In addition, one particularly notable study recently highlighted a methodological blindspot present in most coastal hazard studies used to inform previous IPCC assessments which may suggest that existing coastal hazard assessments may underestimate exposure to sea-level risks.

Sea level much higher than assumed in most coastal hazard assessments

Description:

A review of 385 coastal hazard studies published between 2009 and 2025 found that more than 99% of them inadequately integrate sea levels with land elevation data, often underrepresenting coastal risk. About 90% of studies relied on “zero elevation geoid models” rather than measured sea-level data, which led to systematic errors. Researchers found that measured coastal sea level is about 0.25 meters higher on average than commonly used in risk estimates, with some errors however exceeding 1 meter in parts of the Global South, particularly in the Indo-Pacific. When coastal elevation is correctly aligned with measured sea level, global land area falling below 1 meter of relative sea-level rise increases by 31-37%, placing 77-132 million people residing in these areas at risk. This indicates that many existing coastal hazard assessments may underestimate exposure, with major implications for coastal populations.

Geographical scope:

Global, with particular emphasis on the Global South

Reference and link:

Seeger, K., Minderhoud, P.S.J. Sea level much higher than assumed in most coastal hazard assessments. *Nature* (2026). <https://doi.org/10.1038/s41586-026-10196-1>

Rapid Grounding Line Retreat in Key Regions of Antarctica

Description:

Satellite radar observations from 1992-2025 show concentrated areas of rapid retreat of the “grounding line,” where this massive ice sheet meets the ocean floor. These regions include Wilkes and George V Lands in East Antarctica; the Bellingshausen Sea, Amundsen Sea, and Getz Ice Shelf sectors of West Antarctica, and the northeast and southwest Antarctic Peninsula. The most extreme retreat occurred in West Antarctica’s Amundsen and Getz sectors, where grounding lines retreated up to 42 kilometres at Smith Glacier, 33 kilometres at Pine Island Glacier, and 26 kilometres at Thwaites Glacier. Areas experiencing the greatest retreat have deep seafloor troughs that channel warm ocean water toward grounding zones, particularly where the bed slopes downward inland; raising concerns for more rapid future ice loss. As a whole, Antarctica lost over 12,000 square kilometres of grounded ice between 1996 and 2025, with 62% of the loss occurring in West Antarctica and 28% in East Antarctica. About 77% of the Antarctic grounding line otherwise has remained stable over this period.

Geographical scope:

Antarctica

Reference and link:

Rignot, E., Scheuchl, B., Barre, J.B., Brancato, V., Charrier, L., Chen, H., Ciraci, E., Dinh, A., Herreid, S., Jeong, S. and Li, X., 2026. Thirty years of glacier grounding line retreat in Antarctica. *Proceedings of the National Academy of Sciences*, 123(10), p.e2524380123. <https://doi.org/10.1073/pnas.2524380123>

g. Advances and gaps in attribution science, including at regional and national scale, as well as attribution of monsoon pattern changes.

Summary:

Advances have and are being made in attributing the role of anthropogenic climate change to extreme events in Antarctica.

Human Emissions Exacerbate Record-Breaking Heatwaves in Antarctica

Description:

Long-term summer warming in the Antarctic Peninsula has increased the severity of Antarctic heatwaves by 25% over the past century, largely as a result of rising human emissions. During February 2020, the Antarctic Peninsula experienced one of the most intense heatwaves ever recorded in Western Antarctica, with temperatures reaching an unprecedented 18.3°C at the Esperanza base. A high-pressure system pushed warm and moist air from the Pacific Ocean over the Antarctic Peninsula, triggering this heatwave. The rapid movement of these air currents through the mountains further intensified local warming. This study underscores that changes in air circulation alone cannot explain the extreme temperature rise during such heatwaves. Rising global temperatures have multiplied the likelihood of Antarctica experiencing intense week-long heatwaves – such as the one observed in February 2020 – by tenfold since the 1950s. These findings suggest that human activity increases the severity of temperature and weather extremes in Antarctica.

Geographical scope:

Antarctica

Reference and link:

González-Herrero, S., Barriopedro, D., Trigo, R.M. *et al.* Climate warming amplified the 2020 record-breaking heatwave in the Antarctic Peninsula. *Commun Earth Environ* **3**, 122 (2022).
<https://doi.org/10.1038/s43247-022-00450-5>

B. Adaptation, loss and damage and extreme events:

a. The evolution and dynamics of extreme events, and early warning systems and climate services

Summary:

Extreme melt events have been increasingly documented in Greenland, Svalbard and in the European Alps. In Antarctica, alarming increases in extreme heatwaves, all-time low sea ice conditions, ice shelf collapse and species population crashes have occurred which risk triggering cascading impacts across the rest of the planet.

Increasing extreme melt events in Greenland

Description:

The Greenland Ice Sheet has seen an increase in extreme summer melting since the 1950s, with melt events becoming more frequent, widespread, and severe. Seven of the ten most extreme melt events have occurred since 2000, with meltwater up to three times higher than the average. Rising temperatures have increased Greenland's meltwater production by approximately 25% during these more recent extreme events relative to 1950-1975. When compared with past melt events under the same large-scale atmospheric circulation patterns, present-day meltwater production is about 63% higher than mid-20th century levels, with the strongest increase observed in northern Greenland. Major record-breaking events in August 2012, July 2019, and July 2021 had no historical precedent in the satellite record. Under a high emissions scenario (SSP5-8.5), extreme meltwater events are projected to rise by as much as 370% by 2100.

Geographical scope:

Greenland

Reference and link:

Bonsoms, J., González-Herrero, S., Fettweis, X. *et al.* Record-breaking Greenland ice sheet melt events under recent and future climate. *Nat Commun* (2026). <https://doi.org/10.1038/s41467-026-69543-5>

Abrupt Changes in Antarctic Ice, Ocean, Ecosystems Trigger Cascading Impacts

Description:

Rapid changes unfolding across the Antarctic Ice Sheet and Southern Ocean are more interconnected than previously understood, with shrinking sea ice, fast-melting glaciers, slowing ocean currents, and habitat loss increasingly pushing each other out of balance. This study draws connections between multiple abrupt changes that began to occur in Antarctica over the past decade. For example: not only did sea ice shrink to record-breaking lows during this period, but this loss increased ocean heat absorption, exposed the edges of ice shelves to stronger waves, altered the flow of deep ocean currents, and reduced the breeding habitat available to species such as penguins. Rising temperatures and unreliable ice conditions reshape Antarctic land and marine environments, increasing the risk of major biodiversity loss and rapid global sea-level rise. Stabilizing Earth's climate with minimal overshoot of 1.5°C will be imperative alongside global adaptation measures to minimize and prepare for the far-reaching impacts of Antarctic and Southern Ocean abrupt changes.

Geographical scope:

Antarctica

Reference and link:

Abram, N.J., Purich, A., England, M.H. *et al.* Emerging evidence of abrupt changes in the Antarctic environment. *Nature* **644**, 621–633 (2025). <https://doi.org/10.1038/s41586-025-09349-5>

Sharp Rise in Greenland and Antarctic Surface Melt Since the 1990s

Description:

Daily observations of surface melt over the past three decades show that overall melting of Greenland’s surface has significantly increased each year, and East Antarctica has also registered significant surface melting. These spikes in surface melt are driven by a wide range of factors, worsened by rising global temperatures. Greenland’s northern basins have suffered intensified melt due to North Atlantic atmospheric patterns that have resulted in changing temperature, precipitation, and wind over the ice; while its western basins endured high surface temperatures intensified by Arctic sea ice loss and ocean warming. At the opposite pole, pockets of warm air intruding over the surface of East Antarctica have led to hotspots of greater loss, which have significantly increased since the turn of the century. Surface meltwater ponds formed more frequently, a critical precursor to ice shelf destabilization. These findings highlight interconnections between ice sheet stability and sea ice extent, atmospheric circulation patterns and surface meltwater ponds, and should aid in forecasting extreme melt seasons and ice loss.

Geographical scope:

Polar regions

Reference and link:

Zheng, L., Shang, X., van den Broeke, M.R. *et al.* Rapid increases in satellite-observed ice sheet surface meltwater production. *Nat. Clim. Chang.* **15**, 769–774 (2025). <https://doi.org/10.1038/s41558-025-02364-4>

Extreme Summer Heat Melted 1% of Svalbard’s Glacier Ice in 6 Weeks

Description:

A 6-week period of record-high air temperatures during summer 2024 left a serious dent on Svalbard’s glaciers, resulting in 1% of this region’s total ice volume lost. This rapid melt from Svalbard actually exceeded that of the Greenland Ice Sheet – which is 50 times larger – during this period. Persistent atmospheric circulation patterns contributed to these extremely warm conditions, exceeding any past observations and nearly doubling the previous melt record. Four of the past five years have set new records for summer ice loss in Svalbard. Future climate projections suggest that such temperature levels will become increasingly frequent and even more intense by the end of the century under current emissions. Svalbard ice loss during 2024 therefore serves as a forecast for future glacier meltdown in the Arctic.

Geographical scope:

The Arctic

Reference and link:

T.V. Schuler, R.E. Benestad, K. Isaksen, H.P. Kierulf, J. Kohler, G. Moholdt, & L.S. Schmidt, Svalbard’s 2024 record summer: An early view of Arctic glacier meltdown?, *Proc. Natl. Acad. Sci. U.S.A.* **122** (34) e2503806122, <https://doi.org/10.1073/pnas.2503806122> (2025).

10% of Swiss Glacier Ice Lost in 2022-2023

Description:

High summer heat and low winter snowfall have created the perfect storm for extreme ice loss in the European Alps. The Swiss Academy of Sciences reported that 2023 saw a 4% reduction in the volume of Swiss glaciers, adding to all-time high loss of 6% in 2022. These updated measurements show that 10% of the ice volume in the Swiss Alps has disappeared in the last two years with the rapid acceleration in global temperature rise caused by unrelenting fossil fuel emissions. As a comparison, the amount of ice lost in the last two years is the same amount that took three decades to melt between 1960 and 1990. These high losses, which have already decreased the thickness of glaciers in southeast Switzerland by 3 meters on average, increase as summer air temperatures rise. Very low volumes of snow in the winter expose the ice to the sun for extended periods and exacerbate melting, preventing the glaciers from recovering after warm summer months.

Geographical scope:

Switzerland

Reference and link:

<https://www.glamos.ch/>

Antarctic extreme events

Description:

Extreme events in Antarctica will become more frequent and pronounced unless drastic action is taken to reduce greenhouse gas emissions to net zero by 2050. This study documents the alarming increase in extreme heatwaves, all-time low sea ice conditions, ice shelf collapse and species population crashes that are threatening the delicate and globally important Antarctic environment, including its massive ice sheet holding more than 50 meters of sea-level rise. Due to fossil fuel burning, Antarctic ice losses today are now six times greater than just 30 years ago. If current high levels of greenhouse gas emissions continue unabated, extreme events could contribute to pushing Antarctica past thresholds that lock in multiple meters of unstoppable sea level rise for centuries. Only immediate and far-reaching climate action can prevent the impacts of Antarctic extreme events from escalating into more frequent, widespread and larger hazards in coming decades.

Geographical scope:

Antarctica

Reference and link:

Siegert, M.J., Bentley, M.J., Atkinson, A., Bracegirdle, T.J., Convey, P., Davies, B., Downie, R., Hogg, A.E., Holmes, C., Hughes, K.A. and Meredith, M.P., 2023. Antarctic extreme events. *Frontiers in Environmental Science*, 11, p.1229283. <https://www.frontiersin.org/articles/10.3389/fenvs.2023.1229283/full>

b. Assessing adaptation progress, and the impact of adaptation actions on reducing risks, to inform adaptation planning and action

Summary:

Research has highlighted the risks to adaptation efforts associated with cryosphere loss, with some studies highlighting that current coastal adaptation measures are designed largely based on past and current experiences of hazards, exposure and vulnerability, rather than on future projections that take into account emissions pathways. If cryosphere loss becomes too severe, the limits of many adaptation measures are likely to be exceeded, leading to loss and damage.

Adaptation Plans for Coastal Cities Inadequate in Face of Increasing Cryosphere Loss

Description:

Current measures taken by most coastal cities to adapt to climate change, especially in light of cryosphere-related impacts such as rising seas, extreme weather and flooding, are presently inadequate, according to this new study published in advance of the upcoming IPCC Special Report on Cities. Authors systematically evaluated the strategies of 199 coastal cities worldwide, and found that current adaptation efforts in coastal cities are generally slow, narrow in scope, and not sufficiently transformative. Current adaptation measures are designed largely based on past and current experiences of hazards, exposure and vulnerability, rather than on future projections that take into account emissions pathways (and the near-term and long-term cryosphere response). Such measures therefore may not be sufficient to address the challenges cities will face in a warmer world — especially in light of fundamental state changes in the cryosphere, such as glacier and ice sheet loss. While an increasing range of adaptation planning in coastal cities is underway, a fundamental re-think of risk management is needed to adequately address future risks from climate change, especially without adequate course-correction on emissions reductions congruent with the lower Paris Agreement 1.5C temperature limit.

Geographical scope:

Global

Reference and link:

Wannewitz, M., Ajibade, I., Mach, K.J. *et al.* Progress and gaps in climate change adaptation in coastal cities across the globe. *Nat Cities* 1, 610–619 (2024). <https://doi.org/10.1038/s44284-024-00106-9>

Coastal flood damage and adaptation costs under 21st century sea-level rise

Description:

Coastal flood damage and adaptation costs under 21st century sea-level rise are assessed on a global scale taking into account a wide range of uncertainties in continental topography data, population data, protection strategies, socioeconomic development and sea-level rise. Uncertainty in global mean and regional sea level was derived from four different climate models from the Coupled Model Intercomparison Project Phase 5, each combined with three land-ice scenarios based on the published range of contributions from ice sheets and glaciers. Without adaptation, 0.2–4.6% of global population is expected to be flooded annually in 2100 under 25–123 cm of global mean sea-level rise, with expected annual losses of 0.3–9.3% of global gross domestic product. Damages of this magnitude are very unlikely to be tolerated by society and adaptation will be widespread. The global costs of protecting the coast with dikes are significant with annual investment and maintenance costs of US\$ 12–71 billion in 2100, but much smaller than the global cost of avoided damages even without accounting for indirect costs of damage to regional production supply. Flood damages by the end of this century are much more sensitive to the applied protection strategy than to variations in climate

and socioeconomic scenarios as well as in physical data sources (topography and climate model). Our results emphasize the central role of long-term coastal adaptation strategies. These should also take into account that protecting large parts of the developed coast increases the risk of catastrophic consequences in the case of defense failure.

Geographical scope:

Global

Reference and link:

J. Hinkel, D. Lincke, A.T. Vafeidis, M. Perrette, R.J. Nicholls, R.S.J. Tol, B. Marzeion, X. Fettweis, C. Ionescu, & A. Levermann, Coastal flood damage and adaptation costs under 21st century sea-level rise, *Proc. Natl. Acad. Sci. U.S.A.* 111 (9) 3292-3297, <https://doi.org/10.1073/pnas.1222469111> (2014).

Sea level much higher than assumed in most coastal hazard assessments

Description:

A review of 385 coastal hazard studies published between 2009 and 2025 found that more than 99% of them inadequately integrate sea levels with land elevation data, often underrepresenting coastal risk. About 90% of studies relied on “zero elevation geoid models” rather than measured sea-level data, which led to systematic errors. Researchers found that measured coastal sea level is about 0.25 meters higher on average than commonly used in risk estimates, with some errors however exceeding 1 meter in parts of the Global South, particularly in the Indo-Pacific. When coastal elevation is correctly aligned with measured sea level, global land area falling below 1 meter of relative sea-level rise increases by 31-37%, placing 77-132 million people residing in these areas at risk. This indicates that many existing coastal hazard assessments may underestimate exposure, with major implications for coastal populations.

Geographical scope:

Global, with particular emphasis on the Global South

Reference and link:

Seeger, K., Minderhoud, P.S.J. Sea level much higher than assumed in most coastal hazard assessments. *Nature* (2026). <https://doi.org/10.1038/s41586-026-10196-1>

c. Climate impacts across 1.5 °C warming scenarios at local and regional levels

Summary:

Research published over the last two decades has made abundantly clear the importance of limiting global warming to 1.5°C for preserving the cryosphere and limiting the extent of its global impacts. Limiting warming to 1.5°C is predicted to halve glacier extinction rates in the coming decades; globally, nearly 50% of today's glaciers could still exist by 2100 under 1.5°C warming, whereas only 20% will still exist under current policies (2.7°C). These projections have serious consequences for regional water management and mountain communities. Additional work has also examined the impact of temporarily overshooting and then returning to below 1.5 °C. Research has found that overshoot will have irreversible consequences for glacier mass and runoff over centuries, potentially leading to 11% more global glacier mass loss by 2500 in a 3.0 °C peak-and-decline scenario compared with limiting warming to 1.5 °C without overshooting. However, recent research also consistently demonstrates that even 1.5°C will lead to substantial cryosphere losses and impacts globally. In one recent synthesis, researchers have argued that even current warming levels at 1.2°C, if sustained, will likely lead to several meters of sea-level rise over coming centuries, resulting in extensive loss and damage to coastal populations and challenging the implementation of adaptation measures. To limit loss and damage associated with cryosphere loss, global mean temperature must return closer to 1°C or below as soon as possible through strong and immediate cuts in greenhouse gas emissions.

Limiting Warming to 1.5°C Could Halve Glacier “Extinction” in Coming Decades

Description:

Glacier loss is projected to rapidly increase this century, peaking between 2040 and 2055, when up to 2,000 glaciers per year could disappear even if warming is limited to 1.5°C. However, up to 4,000 glaciers per year could disappear under 4.0°C warming. This peak rate under high emissions is three to five times higher than today's losses of roughly 750-800 glaciers annually. Globally, nearly 50% of today's glaciers could still exist by 2100 under 1.5°C warming, compared to around only 20% under current policies (2.7°C), and fewer than 10% at 4.0°C. Many regions therefore face near-total loss under high emissions, including Central Europe, Western Canada and the U.S., with Central Asia also facing a steep decline. These findings highlight the importance of mitigation: limiting warming to 1.5°C could more than double the number of glaciers surviving by 2100 compared with 2.7°C and prevent the near-complete loss expected under 4.0°C warming.

Geographical scope:

Global

Reference and link:

Van Tricht, L., Zekollari, H., Huss, M. *et al.* Peak glacier extinction in the mid-twenty-first century. *Nat. Clim. Chang.* **16**, 143–147 (2026). <https://doi.org/10.1038/s41558-025-02513-9>

Irreversible glacier change and trough water for centuries after overshooting 1.5 °C

Description:

Exceeding and then returning to below 1.5 °C will have irreversible consequences for glacier mass and runoff over centuries. Global climate and glacier simulations project that a 3.0 °C peak-and-decline scenario will lead to 11% more global glacier mass loss by 2500 compared with limiting warming to 1.5 °C without overshooting. In basins where glaciers regrow after peak temperature, glacier runoff reduces further than if the glaciers stabilize. Half the studied glaciated basins show reduced glacier runoff with overshoot compared with without for decades to centuries after peak warming. These findings underscore the urgency of near-term emissions reductions and limiting temperature overshoot.

Geographical scope:

Global

Reference and link:

Schuster, L., Maussion, F., Rounce, D.R. *et al.* Irreversible glacier change and trough water for centuries after overshooting 1.5 °C. *Nat. Clim. Chang.* 15, 634–641 (2025). <https://doi.org/10.1038/s41558-025-02318-w>

Confirmation that NW Greenland was Ice-Free During Sustained 1-2°C Warming in Earth's Past**Description:**

Ancient sediments trapped beneath the northwestern portion of Greenland's ice sheet confirm ice-free conditions existed for around 16,000 years there, during a period of only 1-2°C of warming. That sustained warmer period occurred 400,000 years ago, for about 30,000 years total, when sea levels were 6-13 meters higher than today. Modeling of these conditions in this study show that Greenland would have contributed at least 1.4 meters of that global sea-level rise; and perhaps as much as 6 meters, meaning that nearly the entire ice sheet had melted. The site of the ice and sediment core used in this study is today buried beneath nearly 2km of ice. These findings make clear the danger of exposing Earth's ice sheets to sustained warming even below the 2°C Paris Agreement limit, with temperature of 1.5°C or lower carrying far less risk to low-lying coastal communities. It stresses the importance of urgent emissions reductions consistent with the lower 1.5°C Paris limit, such as the "very low" (SSP1) emissions pathway outlined by the IPCC in its Sixth Assessment earlier this year.

Geographical scope:

Greenland

Reference and link:

Christ, A.J., Rittenour, T.M., Bierman, P.R., Keisling, B.A., Knutz, P.C., Thomsen, T.B., Keulen, N., Fosdick, J.C., Hemming, S.R., Tison, J.L. and Blard, P.H., 2023. Deglaciation of northwestern Greenland during marine isotope stage 11. *Science*, 381(6655), pp.330-335. <https://www.science.org/doi/10.1126/science.ade4248>

Landmark Report: Water, ice, society, and ecosystems in the Hindu Kush Himalaya**Description:**

Building on the [2019](#) Hindu Kush Himalaya (HKH) assessment report, a major study from the International Centre for Integrated Mountain Development ([ICIMOD](#)) provides the most complete assessment of snow, ice, and permafrost in the Himalayas to date. The report draws on recent scientific advances to map the extensive links between cryosphere, water, ecosystems, and society in the HKH region.

ICIMOD finds that 70-80% of current glacier volume in this region will disappear by 2100 under a high emission scenario, but keeping the global temperature average to 1.5°C could limit glacier loss to 30%, and also help preserve the region's essential snow cover. Snowmelt provides freshwater for major rivers such as the Amu Darya (supporting up to 79% of its flow), the Indus (40%), and Helmand (77%). Over 120 million farmers in the Indus, Ganges and Brahmaputra basins depend on this snowmelt for their livelihoods.

Even with very low emissions and 1.5°C however, the HKH will face serious impacts in terms of species loss, ecosystem structure and productivity. HKH ecosystem services directly support 240 million people in the high altitude regions, and aid a further 1.65 billion people downstream. Species decline and extinction

has already been observed at today's temperatures, and further habitat degradation will dramatically increase as glaciers retreat, snow melts and permafrost thaws.

The HKH has warmed by +0.28°C on average per decade since the 1950s, rendering it highly vulnerable to rapid ice loss, with irreversible changes occurring to downstream water supplies as temperatures rise. Melting glaciers also increase the risk of hazards such as glacial lake outburst floods (GLOFs) and landslides, both of which are projected to increase over coming decades. 200 glacier lakes across the HKH region currently pose a dangerous risk to downstream communities, and researchers anticipate that the risk of GLOFs could spike by the end of the century unless rapid and far-reaching emissions reductions keep peak temperatures close to 1.5°C, a hard adaptation limit for millions of people across Asia.

Two billion people living within these mountains and downstream river valleys depend on melting ice and snow for freshwater resources, and the availability of this water is expected to peak mid-century and then decline as rising temperatures shrink both glaciers and snowpack. Cryosphere plays an essential role in the livelihoods, agriculture, hydropower and infrastructure underpinning societies across the Hindu Kush Himalaya. The report makes clear that urgent policy action is needed to enhance adaptation measures, support those already affected by cryosphere loss; and not least, mitigate global emissions to uphold 1.5°C as a guardrail for the billions reliant on the HKH region.

Geographical scope:

High Mountain Asia

Reference and link:

<https://hkh.icimod.org/hi-wise/hi-wise-report/>

The Ronne Ice Shelf survived the last interglacial

Description:

Ice core data from West Antarctica suggest that the Ronne Ice Shelf persisted throughout a substantial portion of the Last Interglacial period (around 125,000 years ago), when global average temperatures were 0.5°C to 1.5°C warmer than preindustrial levels and sea levels were 2 to 9 meters higher than present. The data suggest that most West Antarctic ice loss occurred in the Amundsen Sea sector (the most rapidly changing region of Antarctica today).

Geographic scope:

Antarctica

Reference and link:

Wolff, E.W., Mulvaney, R., Grieman, M.M. *et al.* The Ronne Ice Shelf survived the last interglacial. *Nature* **638**, 133–137 (2025). <https://doi.org/10.1038/s41586-024-08394-w>

Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers

Description:

Glaciers in the high mountains of Asia (HMA) make a substantial contribution to the water supply of millions of people, and they are retreating and losing mass as a result of anthropogenic climate change. However, it is not known what an increase of 1.5 °C would mean for the glaciers in HMA. Here we show that a global temperature rise of 1.5 °C will lead to a warming of 2.1 ± 0.1 °C in HMA, and that 64 ± 7 per

cent of the present-day ice mass stored in the HMA glaciers will remain by the end of the century. The 1.5 °C goal is extremely ambitious and is projected by only a small number of climate models of the conservative IPCC's Representative Concentration Pathway (RCP)2.6 ensemble. Projections for RCP4.5, RCP6.0 and RCP8.5 reveal that much of the glacier ice is likely to disappear, with projected mass losses of 49 ± 7 per cent, 51 ± 6 per cent and 64 ± 5 per cent, respectively, by the end of the century; these projections have potentially serious consequences for regional water management and mountain communities.

Geographical scope:

Asia

Reference and link:

Kraaijenbrink, P., Bierkens, M., Lutz, A. *et al.* Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature* **549**, 257–260 (2017). <https://doi.org/10.1038/nature23878>

1.5°C is too high for polar ice sheets

Description:

A synthesis study presents strong evidence that the Paris Agreement's lower temperature limit of 1.5°C above pre-industrial levels is too high to prevent significant sea-level rise from Antarctica and Greenland. Even current warming levels at 1.2°C, if sustained, will likely lead to several meters of sea-level rise over coming centuries, resulting in extensive loss and damage to coastal populations and challenging the implementation of adaptation measures. Currently, around 230 million people live within just one meter of sea level; melting ice represents an existential threat to those communities as well as several low-lying nations. To avoid this future, global mean temperature must return closer to 1°C or below as soon as possible through strong and immediate cuts in greenhouse gas pollution to prevent (in IPCC terminology) “slow-onset, high-impact” losses from both polar ice sheets.

Geographical scope:

Polar regions

Reference and link:

Stokes, C.R., Bamber, J.L., Dutton, A. *et al.* Warming of +1.5 °C is too high for polar ice sheets. *Commun Earth Environ* **6**, 351 (2025). <https://doi.org/10.1038/s43247-025-02299-w>

d. Understanding of complex, cascading and transboundary risks

Summary:

Research has shed greater light on the complex, cascading and transboundary risks stemming from cryosphere loss. Risks to human lives, agriculture, within watersheds and on world heritage sites and infrastructure have been elucidated for populations ranging from local communities to billions across the world. Many impacts of cryosphere loss also carry the risk of cascading into other areas, emphasising the wide range of indirect and multisystem impacts stemming from changes to the cryosphere.

Greater Snow Drought Increasing the Vulnerability of Winter Wheat Yields

Description:

Winter wheat regions across the Northern Hemisphere have experienced a steady rise in snow drought, with frequency increasing around 5-6% per decade from 1960 to 2020. In addition, crop yield sensitivity to snowpack water levels has significantly increased across more than 25% of winter wheat croplands. These snow droughts reduce yields by increasing freeze stress, lowering soil moisture during key growth stages, worsening the effects of hotter and drier conditions, and limiting nitrogen replenishment in soils. Snow droughts are projected to become increasingly frequent as winters warm, posing escalating risks to winter wheat productivity and challenging regional food security, in particular if these difficulties hit other major crops as well.

Geographical scope:

Global

Reference and link:

Chen, H., Wang, S., Zhu, P. *et al.* Winter wheat yield sensitivity to snow drought is increasing across the Northern Hemisphere. *Nat Food* 7, 174–184 (2026). <https://doi.org/10.1038/s43016-026-01302-7>

Mountain Water Loss Threatens Downstream Supply for Billions

Description:

This study addresses emerging and cascading changes facing global mountain ecosystems from glacier loss, highlighting the damaging impact of such loss on diverse socio-ecological sectors and adaptation needs. Mountains provide both surface water and groundwater critical for downstream regions, especially in dry and semi-arid regions where billions of people rely on seasonal upstream flows. Rising temperatures increase glacier mass loss, initially triggering faster meltwater runoff but gradually reducing it over time as the ice volume shrinks. This shift causes runoff to peak earlier in the year and diminishes late-summer flows, weakening the natural buffering that sustains rivers during dry periods. Snow is also increasingly falling as rain in many regions, leading to earlier and more unpredictable runoff. At the same time, groundwater levels in several major mountain ranges are projected to decline, further reducing base flow and the resilience of river systems. These changes have direct consequences for downstream water availability, heightening competition for natural resources, intensifying drought impacts, and reducing low streamflows. Collectively, these trends underscore the far-reaching consequences of changing mountain water systems for downstream populations, reinforcing the urgency of transition from fossil fuel use.

Geographical scope:

Global

Reference and link:

Viviroli, D., Drenkhan, F., Scott, C.A. *et al.* Cascading downstream impacts of water cycle changes in mountain regions. *Nat. Clim. Chang.* **16**, 129–142 (2026). <https://doi.org/10.1038/s41558-025-02552-2>

Thawing Permafrost Directly Increases Wildfire Risk and Carbon Emissions**Description:**

As frozen permafrost thaws and the seasonally thawed layer deepens, summers become hotter and drier, vegetation and burnable soils increase, and wildfires grow larger and more intense across the Arctic and boreal (sub-Arctic) zones. Field observations paired with satellite data from 1997-2018 show that this thaw is a direct driver of drier conditions, higher fire danger, and fuel buildup. Satellite and ground data during this two-decade period show that this thaw is a direct driver of drier conditions and fuel buildup, leading to a 16.1% increase in the summer fire weather index. Permafrost thaw and wildfires therefore create a self-reinforcing cycle in which thaw promotes fires, fires release more carbon and further damage permafrost, and warming increases exponentially.

Geographical scope:

The Arctic

Reference and link:

Li, J., Lai, G., Meng, L. *et al.* Amplified Arctic–boreal fire regimes from permafrost thaw feedbacks. *Nat. Geosci.* **19**, 279–290 (2026). <https://doi.org/10.1038/s41561-025-01894-y>

Rising Seas Could Threaten Half of Arctic Communities by 2100**Description:**

This interdisciplinary risk assessment of coastal threats consolidated data on erosion, sea-level rise, and permafrost thaw across the Arctic to produce the first comprehensive map illustrating the vulnerability of coastal communities and infrastructure to climate change. Results show that by 2100, 45% of coastal settlements will be impacted by sea-level rise and 21% by coastal erosion, endangering both these communities and nearby wildlife. The study also shows permafrost is thawing quickly, with potentially 77% of current Arctic infrastructure resting on ground that is no longer frozen solid but crumbling and subsiding by 2100. This thaw, in addition to the sea-level rise and erosion, will greatly threaten Arctic settlements. The research emphasizes the need for action, resources, and adaptation strategies to protect these communities.

Geographical scope:

Arctic

Reference and link:

Tanguy, R., Bartsch, A., Nitze, I., Irrgang, A., Petzold, P., Widhalm, B., et al. (2024). Pan-Arctic assessment of coastal settlements and infrastructure vulnerable to coastal erosion, sea-level rise, and permafrost thaw. *Earth's Future*, 12, e2024EF005013. <https://doi.org/10.1029/2024EF005013>

Salinization Intensified by Sea-level Rise Will Damage Coastal Watersheds by 2100**Description:**

Saltwater intrusion into fresh groundwater aquifers is increasingly damaging freshwater agriculture and ecosystems, and corroding underground urban infrastructure along coastal zones. State-of-the art projections of future sea-level rise and changes to groundwater recharge reveal that seawater will infiltrate underground freshwater supplies in about three of every four coastal areas around the world by the year 2100. The level of emissions reductions, or lack thereof will determine the degree of damage to coastal freshwater systems. The distance that saltwater intrudes inland will be driven largely by climate-dependent changes to subsurface water replenishment, whereas the amount of sea-level rise will drive the degree of salinization around global coasts.

Geographical scope:

Global

Reference and link:

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024GL110359>

15 Million Face Threat of Sudden Glacial Lake Outburst Floods (GLOFs)

Description:

Fifteen million people around the world are at risk from flooding caused by glacial lakes, with more than half of these people living in just four countries: Pakistan, China, India, and Peru. This study provides the first global assessment of the most vulnerable regions to glacial lake outburst floods (GLOFs); factoring in not just physical lake conditions, but also the proximity of downstream communities and their capacity to efficiently cope with flooding. GLOFs occur when streams of meltwater pool into large lakes at the base of rapidly melting glaciers. These lakes are growing in many regions, and can burst with little advanced warning, with floods that damage property, infrastructure, and agriculture as much as 120 kilometers downstream. A single flooding event can lead to thousands of lives lost. Authors determined that communities living in High Mountain Asia are the most vulnerable to GLOFs, with 9.3 million people at risk. They ranked Pakistan and China as the two countries with populations most in danger: Pakistan has 2.1 million people living near glacial lakes at risk of overflowing, and China has some of the largest and most numerous glacial lakes, which places it at high risk of extensive infrastructure damage. Glacial lakes across the world have, over the past three decades of rapid global warming, become increasingly dangerous and unstable. Understanding which areas face the greatest danger from glacial flooding will allow for more targeted and effective risk management actions, which help minimize loss of life and protect communities downstream.

Geographical scope:

Global

Reference and link:

Taylor, C., Robinson, T.R., Dunning, S. *et al.* Glacial lake outburst floods threaten millions globally. *Nat Commun* **14**, 487 (2023). <https://doi.org/10.1038/s41467-023-36033-x>

Teleconnections among tipping elements in the Earth system

Description:

Rising temperatures can push parts of the climate system across “thresholds” that trigger abrupt or irreversible changes in other regions of the world, even tens of thousands of kilometers apart. In this study, an international team of climate researchers investigate the long-range impacts of deforestation of the Amazon rainforest on other regions. As logging, road construction and warming increase, this South

American ecosystem edges closer to a threshold at which point the rainforest cannot be sustained, drastically altering moisture and weather patterns. Authors consolidate fifty years of climate data to reveal that if the Amazon crosses this threshold, it could permanently increase temperatures and decrease snowfall in both the Tibetan Plateau and West Antarctica by altering global atmospheric circulation patterns. The Tibetan Plateau provides frozen freshwater resources for millions of downstream communities. Over the past few decades, rising temperatures have been accelerating glacier retreat across the region. These findings confirm that crossing one threshold could trigger a cascade of others, even reaching the opposite side of the world. Reducing emissions is the most effective way to minimize present and future disaster phenomena such as floods, droughts and sea level rise on a global scale.

Geographical scope:

Global

Reference and link:

Liu, T., Chen, D., Yang, L. *et al.* Teleconnections among tipping elements in the Earth system. *Nat. Clim. Chang.* **13**, 67–74 (2023). <https://doi.org/10.1038/s41558-022-01558-4>

High Mountain Asia hydropower systems threatened by climate-driven landscape instability

Description:

The accelerated retreat of glaciers in the Himalayas and other high mountain regions of Asia is posing deadly risks to local communities, destabilizing the landscape and threatening to overwhelm numerous hydropower projects. As temperatures rise further, the snow and ice resources in high-altitude regions experience warming two to three times stronger than the global average. Such high temperatures increase the risk of glaciers and permafrost to extreme retreat and collapse, producing outburst floods, rock-ice avalanches, and debris flows that devastate downstream communities. These events also cause the release of large amounts of sediment, which can flow great distances in water currents. The accumulation of sediments in downstream reservoirs degrades power turbines and ultimately can result in dam failure, posing risks to billions of downstream populations in Asia that rely on the stability of these freshwater resources. High Mountain Asia contains the largest frozen water reservoirs outside of the polar regions, with numerous new hydropower projects under construction or planning. This study emphasizes the necessity of monitoring and predicting glacial hazards to enable the sustainable development of climate change-resilient dams and reservoirs in High Mountain Asia, even as mitigation is needed to preserve sustainable conditions for their future operation.

Geographical scope:

Asia

Reference and link:

Li, D., Lu, X., Walling, D.E. *et al.* High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nat. Geosci.* **15**, 520–530 (2022). <https://doi.org/10.1038/s41561-022-00953-y>

Global environmental consequences of twenty-first-century ice-sheet melt

Description:

Ice-sheet discharge was not explicitly included in Coupled Model Intercomparison Project phase 5, so effects on climate from this melt are not currently captured in the simulations most commonly used to inform governmental policy. This study used simulations of the Greenland and Antarctic ice sheets constrained by satellite-based measurements of recent changes in ice mass, to show that increasing meltwater from

Greenland will lead to substantial slowing of the Atlantic overturning circulation, and that meltwater from Antarctica will trap warm water below the sea surface, creating positive feedback that increases Antarctic ice loss. In the simulations, future ice-sheet melt enhances global temperature variability and contributes up to 25 centimetres to sea level by 2100. However, uncertainties in the way in which future changes in ice dynamics are modelled remain, underlining the need for continued observations and comprehensive multi-model assessments.

Geographical scope:

Greenland and Antarctica

Reference and link:

Golledge, N.R., Keller, E.D., Gomez, N. *et al.* Global environmental consequences of twenty-first-century ice-sheet melt. *Nature* **566**, 65–72 (2019). <https://doi.org/10.1038/s41586-019-0889-9>

Loss of cultural world heritage and currently inhabited places to sea-level rise

Description:

The world population is concentrated near the coasts, as are a large number of Cultural World Heritage sites, defined by the UNESCO. Using spatially explicit sea-level estimates for the next 2000 years and high-resolution topography data, we compute which current cultural heritage sites will be affected by sea-level rise at different levels of sustained future warming. As indicators for the pressure on future cultural heritage we estimate the percentage of each country's area loss, and the percentage of current population living in regions that will be permanently below sea level, for different temperature levels. If the current global mean temperature was sustained for the next two millennia, about 6% (40 sites) of the UNESCO sites will be affected, and 0.7% of global land area will be below mean sea level. These numbers increase to 19% (136 sites) and 1.1% for a warming of 3 K. At this warming level, 3–12 countries will experience a loss of more than half of their current land surface, 25–36 countries lose at least 10% of their territory, and 7% of the global population currently lives in regions that will be below local sea level. Given the millennial scale lifetime of carbon dioxide in the atmosphere, our results indicate that fundamental decisions with regard to mankind's cultural heritage are required.

Geographical scope:

Global

Reference and link:

Marzeion, B. & Levermann, A. Loss of cultural world heritage and currently inhabited places to sea-level rise. *Environ. Res. Lett.* **9**, 034001 (2014). [10.1088/1748-9326/9/3/034001](https://doi.org/10.1088/1748-9326/9/3/034001)

Asia's shrinking glaciers protect large populations from drought stress

Description:

About 800 million people depend in part on meltwater from the thousands of glaciers in the high mountains of Asia. Water stress makes this region vulnerable to drought, but glaciers are a uniquely drought-resilient source of water. This study shows that seasonal glacier meltwater is equivalent to the basic needs of 221 ± 59 million people, or most of the annual municipal and industrial needs of Pakistan, Afghanistan, Tajikistan, Turkmenistan, Uzbekistan and Kyrgyzstan. During drought summers, meltwater dominates water inputs to the upper Indus, Aral and Chu/Issyk-Kul river basins. This reduces the risk of social instability, conflict and sudden migrations triggered by water scarcity, which is already associated with the large, rapidly growing populations and hydro-economies of these basins. Regional meltwater production is, however, unsustainably

high—at 1.6 times the balance rate—and is expected to increase in future decades before ultimately declining.

Geographical scope:

Asia

Reference and link:

Pritchard, H.D. Asia's shrinking glaciers protect large populations from drought stress. *Nature* **569**, 649–654 (2019). <https://doi.org/10.1038/s41586-019-1240-1>

Importance and vulnerability of the world's water towers

Description:

Mountains are the water towers of the world, supplying a substantial part of both natural and anthropogenic water demands. This study presents a global water tower index (WTI), which ranks all water towers in terms of their water-supplying role and the downstream dependence of ecosystems and society. For each water tower, we assess its vulnerability related to water stress, governance, hydro-political tension and future climatic and socio-economic changes. They conclude that the most important (highest WTI) water towers are also among the most vulnerable, and that climatic and socio-economic changes will affect them profoundly. This could negatively impact 1.9 billion people living in (0.3 billion) or directly downstream of (1.6 billion) mountainous areas. Immediate action is required to safeguard the future of the world's most important and vulnerable water towers.

Geographical scope:

Global

Reference and link:

Immerzeel, W.W., Lutz, A.F., Andrade, M. *et al.* Importance and vulnerability of the world's water towers. *Nature* **577**, 364–369 (2020). <https://doi.org/10.1038/s41586-019-1822-y>

C. Ecosystems and nature-based solutions:

a. Opportunities and challenges of implementing nature-based solutions in land and ocean systems in support of climate adaptation and mitigation

Summary:

Research has outlined the risk that escalating cryosphere loss will pose to nature-based solutions in coastal environments. Many coastal ecosystems used to stabilise coastal margins will face retreat under rates of relative sea-level rise faster than 7 mm yr^{-1} , which is a rate of sea-level rise that would affect nearly all the world's mangrove forests and coral reef islands and almost 40% of mapped tidal marshes if $3 \text{ }^{\circ}\text{C}$ of warming is reached. Such high rates of sea-level rise may be realised shortly after 2050 if the currently observed acceleration in sea-level rise continues.

Widespread retreat of coastal habitat is likely at warming levels above 1.5°C

Description:

Coastal ecosystems—most notably mangroves and tidal marshes—exhibit biogenic feedbacks that are facilitating adjustment to relative sea-level rise, including the sequestration of carbon and the trapping of mineral sediment. If rates of relative sea-level rise grow too large, the stability of these coastal ecosystems may be compromised leading to habitat retreat. This study shows that tide marshes and mangroves will undergo retreat under relative sea-level rise rates of 4 mm yr^{-1} (likely) and 7 mm yr^{-1} (highly likely). If rates of relative sea-level rise exceed 7 mm yr^{-1} , reef islands may destabilize through increased shoreline erosion and wave over-topping. Increased global warming from $1.5 \text{ }^{\circ}\text{C}$ to $2.0 \text{ }^{\circ}\text{C}$ doubles the area of mapped tidal marsh exposed to 4 mm yr^{-1} of relative sea-level rise by between 2080 and 2100. With $3 \text{ }^{\circ}\text{C}$ of warming, nearly all the world's mangrove forests and coral reef islands and almost 40% of mapped tidal marshes are estimated to be exposed to relative sea-level rise of at least 7 mm yr^{-1} . Meeting the Paris agreement targets would minimize disruption to coastal ecosystems.

Geographical scope: Global

Reference and link:

Saintilan, N., Horton, B., Törnqvist, T.E. *et al.* Widespread retreat of coastal habitat is likely at warming levels above $1.5 \text{ }^{\circ}\text{C}$. *Nature* **621**, 112–119 (2023). <https://doi.org/10.1038/s41586-023-06448-z>

The rate of sea-level rise has doubled in the last 30 years, and is accelerating towards rates that may be difficult to adapt to by 2100.

Description:

The global rate of sea-level rise has doubled in the last 30 years. Between 1993 and 2024, sea levels rose by over 11 cm at an accelerating rate of 2.1 mm/year in 1993 to 4.5 mm/year in 2023. Rates are expected to increase to 5.0 mm/year by 2030, 5.8 mm/year by 2040 and 6.5 mm/year by 2050, presenting a widespread challenge for adaptation efforts along coastlines worldwide.

Geographical scope: Global

Reference and link:

Hamlington, B.D., Bellas-Manley, A., Willis, J.K. *et al.* The rate of global sea level rise doubled during the past three decades. *Commun Earth Environ* **5**, 601 (2024). <https://doi.org/10.1038/s43247-024-01761-5>

b. Climate change impacts and risks for the ocean and cryosphere and related ecosystems

Summary:

There is an enormous body of literature (including all of the studies detailed in other sections) that has improved understanding of the impacts and risks of climate change on the cryosphere. Headline messages from the IPCC AR6 outline the increasing hazards from glacier retreat and snow loss, increasing weather extremes and ocean acidification that threatens communities and ecosystems, and escalating rates of sea-level rise from increasing ice losses. In addition, major findings published since AR6 reveal that glaciers globally are losing ice at an alarming rate, averaging 270 billion tonnes annually from 2000 to 2023, with a significant acceleration in recent years. Central Europe and other regions with smaller glaciated areas have experienced disproportionately larger losses, up to 40% of glacier ice during this period. Climate change is also affecting Arctic shorelines, with thawing permafrost enhancing coastal erosion, particularly as storms intensify and coastal sea ice thins. Increasingly early Antarctic sea ice breakup has led to catastrophic die-off events of emperor penguin chicks in several breeding seasons.

Key Cryosphere Messages from the IPCC AR6 Synthesis Report: Climate Change 2023

Description:

The IPCC AR6 Synthesis Report takes note of the global and intergenerational implications of cryosphere loss throughout the Report. Communities living near mountain glaciers, permafrost, and Arctic sea ice experience increasing hazards from cryosphere loss almost immediately as the ice melts, but larger frozen regions such as the Greenland and Antarctic ice sheets respond over centuries, with future sea levels increasing as global temperatures rise.

Increasing Hazards from Glacier Retreat and Snow Loss

Every increment of warming will multiply and intensify future hazards from cryosphere regions. Floods, landslides, and freshwater shortages from glacier retreat and snow loss pose a serious threat to mountain regions across the world (B.2.1). These climate hazards have the potential to cause irrevocable damage to communities and ecosystems, and they will only become more widespread and pronounced if temperatures exceed 1.5°C.

Nearly half of the world's population lives in regions that are "highly vulnerable" to climate change, with more intense heatwaves and weather extremes increasing risk to human health if temperatures continue to rise (A.2.2). In the last decade, deaths from floods, droughts and storms were 15 times higher in highly vulnerable regions compared to those in most resilient areas (A.2.2).

If warming goes beyond 1.5°C, limited freshwater resources will pose hard adaptation limits for small islands, high mountain regions, and downstream communities dependent on glacier and snow melt (B.4.2). The growing impact of climate change on cryosphere regions is already approaching irreversibility, such as with glacier retreat limiting freshwater availability in high mountain areas and permafrost thaw destabilizing land in the Arctic (A.2.3). Approximately 3.5 billion people currently experience severe water scarcity for at least part of the year (A.2.4), which will increase as retreating glaciers decrease seasonal freshwater supplies, and as droughts occur more frequently.

Weather Extremes and Ocean Acidification Threaten Communities and Ecosystems

With further warming, every region will experience stronger and more prolonged climate and weather extremes. Heatwaves and droughts become more frequent, tropical cyclones and storms more intense, and dry landscapes more vulnerable to wildfires (B.1.4). Heavier precipitation will intensify local flooding (B.2.1). In some coastal regions, extreme sea level events that currently occur only once per century will happen annually by 2100 (B.1.4). Rising temperatures pose an increasing risk to local transportation, water, sanitation and energy systems; thereby jeopardizing human health, with the most harmful impacts concentrated amongst economically and socially marginalized communities (A.2.7).

Climate change has already caused substantial damages and irreversible losses in freshwater, cryosphere, and ocean ecosystems (A.2.3). Over recent decades, heat extremes have also led to mass mortality events that jeopardize local biodiversity, with hundreds of species unable to survive in their current environments (A.2.3). With every increase in warming, oceans become more acidic and deoxygenated, which dissolves the shells of marine species and prevents larger organisms from drawing enough oxygen into their tissues (B.1.3). These increasingly hostile marine environments will cause reduced catches for fisheries and collapse of regional stocks, especially in polar and near-polar ecosystems.

Exceeding 1.5°C Increases Likelihood of Irreversible Cryosphere Impacts

Earth's cryosphere directly reacts to peaks in temperature and CO₂ emissions. Even temporarily passing 1.5°C will result in "irreversible" impacts on polar, mountain and coastal communities by increasing glacier melt and sea level rise from ice sheets (B.7.2). The higher temperatures rise, and the longer they remain above 1.5°C, the more societies will be exposed to greater risks; including freshwater scarcity and sudden flooding, heatwaves, and droughts (B.7.2). Surpassing this temperature threshold will increase damage to infrastructure, threaten livelihoods, diminish agricultural productivity, and force low-lying coastal settlements to either adapt or move inland.

Any period of overshoot will increase warming through positive feedbacks, such as increased wildfires, drying of peatlands, permafrost thawing with related emissions, and weakening natural land carbon sinks (B.7.1). Already today, permafrost releases large amounts of greenhouse gases into the atmosphere on the same level as some top-20 national emitters. These feedbacks will make the return below 1.5°C even more challenging. The larger the overshoot, the more net negative CO₂ emissions would be needed to return to 1.5°C.

Extreme Sea Level Rise from Ice Sheets Under High Emissions

Rising global temperatures increase the likelihood of crossing major cryosphere thresholds, which can trigger abrupt and irreversible changes in Earth's climate system. These thresholds elevate the risks of species extinction or permanent biodiversity loss, especially in oceans and Arctic regions (B.3.2).

Even at today's temperatures, the world is committed to unavoidable sea level rise for several centuries to millennia due to deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (B.3.1). Risks for coastal ecosystems, people and infrastructure will continue to increase beyond 2100 (B.2.2). However, low and very-low emissions pathways would slow the acceleration of further ice loss, and limit our commitment to future sea level rise.

Over the next 2000 years, global mean sea levels will rise by 2–3m even if warming is limited to 1.5°C (B.3.1). If warming levels fall between a sustained 2°C and 3°C, the Greenland and West Antarctic ice sheets will be lost almost completely and irreversibly (B.3.2). These two ice sheets alone hold 9-11 meters of sea-level rise. The speed of ice loss, and related sea-level rise will increase with higher temperatures. With very high emissions and taking into account instability processes, the IPCC AR6 cannot rule out that 2 m may occur already by 2100, and 15 m by 2300, continuing to rise further over subsequent millennia (B.3.3). The probability of ice sheet instability processes triggering very large future sea level rise increases with higher global warming levels (B.3.3).

Geographical scope:

Global

Reference and link:

<https://www.ipcc.ch/report/ar6/syr/>

Description:

A comprehensive analysis from the Glacier Mass Balance Intercomparison Exercise, or GlaMBIE, reveals global glaciers are losing ice at an alarming rate, averaging 270 billion tonnes annually from 2000 to 2023, with a significant acceleration in recent years. This mass loss, surpassing both Greenland and Antarctic ice sheet contributions, made glaciers a major driver of sea-level rise during these two decades. Central Europe and other regions with smaller glaciated areas have experienced disproportionately larger losses, up to 40% of glacier ice during this period. While overall ice loss aligns with previous projections, some regions, like the Southern Andes and New Zealand, are already passing predicted rates. Overall, this study paints a sobering picture of the world's glaciers, which face continued and possibly accelerated mass loss until the end of this century unless ambition for climate action is dramatically improved.

Geographical scope:

Global

Reference and link:

The GlaMBIE Team. Community estimate of global glacier mass changes from 2000 to 2023. *Nature* **639**, 382–388 (2025). <https://doi.org/10.1038/s41586-024-08545-z>

Sea-level Rise and Permafrost Thaw Substantially Increases Arctic Coastal Erosion Rates**Description:**

Climate change is affecting Arctic shoreline sea-level rise and permafrost thaw, as storms intensify and coastal sea ice thins. Coastal erosion is an increasing Arctic hazard as a result, yet the combined impact of sea-level rise and permafrost thaw subsidence on future Arctic coastal erosion has been difficult to assess. In this new study, scientists project how sea-level rise and permafrost thaw combined will affect Alaska's Arctic Coastal Plain over the coming century. They found that the combined effect will lead to up to 8x more land lost by 2100 than in models that only account for coastal erosion. Without strong adaptation measures, the authors show that coastal losses could damage 40-65% of infrastructure in villages along the Alaskan Arctic Coastal Plain, including 10-20% of oilfield infrastructure, by 2100.

Geographical scope:

Arctic

Reference and link:

R. Creel, J. Guimond, B.M. Jones, D.M. Nielsen, E. Bristol, C.E. Tweedie, & P.P. Overduin, Permafrost thaw subsidence, sea-level rise, and erosion are transforming Alaska's Arctic coastal zone, *Proc. Natl. Acad. Sci. U.S.A.* **121** (50) e2409411121, <https://doi.org/10.1073/pnas.2409411121> (2024).

Catastrophic Penguin Die-off Caused by Antarctica Sea Ice Decline**Description:**

Researchers have confirmed that an extremely early Antarctic sea ice breakup led to the catastrophic die-off of emperor penguin chicks in the last breeding season, in November 2022. The event, which killed up to 10,000 young birds, is the highest rate of emperor penguin breeding failure ever recorded. The sea ice underneath the chicks broke apart before they could develop the waterproof feathers needed to swim, causing them to drown or freeze to death. Since 2016, Antarctic sea ice extent has undergone a significant decline: the years 2021/22 and 2022/23 have experienced the lowest sea ice extents observed since observations began 45 years ago. Currently, an area of sea ice the size of Greenland is missing from this periphery of the Antarctic Ice Sheet. In the Bellingshausen Sea of West Antarctica where the penguin study focussed, many

regions have experienced a 100% loss in sea ice cover. With more than 90% of emperor penguin colonies predicted to be extinct by the end of the century because of current fossil fuel warming, only rapid emissions cuts can safeguard this iconic species.

Geographical scope:

Antarctica

Reference and link:

Fretwell, P.T., Boutet, A. & Ratcliffe, N. Record low 2022 Antarctic sea ice led to catastrophic breeding failure of emperor penguins. *Commun Earth Environ* **4**, 273 (2023). <https://doi.org/10.1038/s43247-023-00927-x>

Melting Glaciers Expose Vulnerable New Ecosystems in Need of Protection

Description:

An international team of glaciologists has created the first assessment of new ecosystems that will emerge due to future glacier retreat. Under a high emission scenario, half of the area covered by mountain glaciers could disappear by 2100. Rapidly curbing emissions to remain within 1.5°C could limit that loss to one-fifth, reducing damage to ecosystems and downstream human communities. Glacier retreat of any scale however will expose large land areas to the atmosphere for the first time in thousands of years, opening a vulnerable space for new habitats. Researchers estimate that around 80% of newly exposed terrain would be on land, while the remaining 20% would support marine and freshwater species in termination lakes and coves. These regions could provide refuge for cold-adapted species displaced by warming. However, less than half of these areas are currently located in parks or other protected regions. These rapidly evolving areas contain some of the fastest growing ecosystems in the world. Authors make clear the urgent need for enhanced mitigation and conservation measures, underscoring the importance of glaciers in the face of climate change, biodiversity loss and freshwater security.

Geographical scope:

Global

Reference and link:

Bosson, J.B., Huss, M., Cauvy-Fraunié, S. *et al.* Future emergence of new ecosystems caused by glacial retreat. *Nature* **620**, 562–569 (2023). <https://doi.org/10.1038/s41586-023-06302-2>

Latest IMBIE Assessment: Five-fold Increase in Ice Loss from Greenland and Antarctica since the 1990s

Description:

The latest IMBIE (the Ice Sheet Mass Balance Inter-comparison Exercise) assessment report on the state of the planet's ice sheets found that polar ice sheets have lost ice every year since the satellite record began in 1992, and that the seven years with highest melting all occurred in the past decade. The most intense melting to-date took place in 2019, when the Greenland and Antarctic ice sheets together lost 612 billion tons of ice due to a summer heatwave in the Arctic. They also found that the melting of polar ice sheets has released more than 7,500 billion tons of ice into global oceans over the past three decades, with two-thirds from Greenland and one-third from Antarctica. More recently, Antarctica has been closing the gap on Greenland. Most notably, combined ice loss from Greenland and Antarctica has increased five-fold since the 1990s, and now accounts for more than a quarter of all sea level rise.

Geographical scope:

Reference and link:

Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., van den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., A, G., Agosta, C., Ahlstrøm, A. P., Blazquez, A., Colgan, W., Engdahl, M. E., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B. C., Harig, C., Helm, V., Khan, S. A., Kittel, C., Konrad, H., Langen, P. L., Lecavalier, B. S., Liang, C.-C., Loomis, B. D., McMillan, M., Melini, D., Mernild, S. H., Mottram, R., Mougnot, J., Nilsson, J., Noël, B., Pattle, M. E., Peltier, W. R., Pie, N., Roca, M., Sasgen, I., Save, H. V., Seo, K.-W., Scheuchl, B., Schrama, E. J. O., Schröder, L., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T. C., Vishwakarma, B. D., van Wessem, J. M., Wiese, D., van der Wal, W., and Wouters, B.: Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, *Earth Syst. Sci. Data*, 15, 1597–1616, <https://doi.org/10.5194/essd-15-1597-2023>, 2023.

East Antarctica Vulnerable to High Emissions: Could Add Up to Five Meters Sea-Level Rise by 2300

Description:

This comprehensive review found that in recent decades, glaciers are rapidly thinning across several regions of East Antarctica due to increasingly warm ocean currents eroding the base of the ice sheet. In particular, ice loss has likely accelerated by a factor of ten in the massive Wilkes Land region of East Antarctica over the past decade; and the huge Denman Glacier is now experiencing ice shelf melt rates comparable to the highest rates in West Antarctica.

Evidence from the paleo record highlights the sensitivity of East Antarctica's three main subglacial basins (Aurora, Wilkes, and Recovery) to previous warm periods, which had climate conditions similar to today. During the early to mid-Miocene (24-14 million years ago), the East Antarctic Ice Sheet experienced its largest ice loss as sea surface temperatures peaked around 11-17°C above present, and produced tens of meters of sea-level rise from these three main basins, which are much larger than those in West Antarctica. With current emission trends, average mid-Miocene atmospheric CO₂ concentrations could be reached by 2100. The most recent period when CO₂ concentrations last exceeded today's current levels around 400 ppm was the Mid-Pliocene (3.5-3 million years ago). Mid-Pliocene atmospheric temperatures were about 2-4°C warmer than present, and the Aurora and Wilkes basins both substantially retreated, resulting in several meters of sea-level rise above today.

Climate projections indicate surface melt and rainfall on East Antarctic ice shelves will increase over the next century, further increasing the vulnerability of this region to rapid thinning. If temperatures remain well below 2°C however, East Antarctica might only contribute 0.6 meters to global sea-level rise by 2300, slowing to 0.7 meters by 2500. Under a high-emissions scenario, East Antarctica could contribute 3 meters of sea-level rise by 2300 and nearly 5.5 meters by 2500.

Geographical scope:

East Antarctica

Reference and link:

Stokes, C.R., Abram, N.J., Bentley, M.J. *et al.* Response of the East Antarctic Ice Sheet to past and future climate change. *Nature* **608**, 275–286 (2022). <https://doi.org/10.1038/s41586-022-04946-0>

Arctic Ocean Acidifying Three to Four Times Faster Than Other Oceans

Description:

The Arctic is warming at a rate faster than any comparable region on Earth, with a consequently rapid loss of sea ice there. This study found that sea ice loss is causing more uptake of atmospheric carbon dioxide by surface water and driving rapid acidification of the western Arctic Ocean, at a rate three to four times higher than that of the other ocean basins. They attribute this finding to melt-driven addition of freshwater and the resulting changes in seawater chemistry.

Geographical scope:

The Arctic

Reference and link:

Qi, D., Ouyang, Z., Chen, L., Wu, Y., Lei, R., Chen, B., Feely, R.A., Anderson, L.G., Zhong, W., Lin, H. and Polukhin, A., 2022. Climate change drives rapid decadal acidification in the Arctic Ocean from 1994 to 2020. *Science*, 377(6614), pp.1544-1550. [10.1126/science.abo0383](https://doi.org/10.1126/science.abo0383)

Projected land ice contributions to twenty-first-century sea level rise

Description:

This study uses statistical emulation of the ice sheet and glacier models to predict future sea-level rise. They find that limiting global warming to 1.5 degrees Celsius would halve the land ice contribution to twenty-first-century sea level rise, relative to current emissions pledges. The median decreases from 25 to 13 centimetres sea level equivalent (SLE) by 2100, with glaciers responsible for half the sea level contribution.

The projected Antarctic contribution does not show a clear response to the emissions scenario, owing to uncertainties in the competing processes of increasing ice loss and snowfall accumulation in a warming climate. However, under risk-averse (pessimistic) assumptions, Antarctic ice loss could be five times higher, increasing the median land ice contribution to 42 centimetres SLE under current policies and pledges, with the 95th percentile projection exceeding half a metre even under 1.5 degrees Celsius warming. This would severely limit the possibility of mitigating future coastal flooding. Given this large range (between 13 centimetres SLE using the main projections under 1.5 degrees Celsius warming and 42 centimetres SLE using risk-averse projections under current pledges), adaptation planning for twenty-first-century sea level rise must account for a factor-of-three uncertainty in the land ice contribution until climate policies and the Antarctic response are further constrained.

Geographical scope:

Global

Reference and link:

Edwards, T.L., Nowicki, S., Marzeion, B. *et al.* Projected land ice contributions to twenty-first-century sea level rise. *Nature* **593**, 74–82 (2021). <https://doi.org/10.1038/s41586-021-03302-y>

The Paris Climate Agreement and future sea-level rise from Antarctica

Description:

The Antarctic Ice Sheet is Earth's largest land ice reservoir and extensive regions of it are grounded below sea level and susceptible to dynamical instabilities that are capable of producing very rapid retreat. This study used an observationally calibrated ice sheet–shelf model to show that with global warming limited to 2 degrees Celsius or less, Antarctic ice loss will continue at a pace similar to today's throughout the twenty-first century. However, scenarios more consistent with current policies (allowing 3 degrees Celsius of warming) give an abrupt jump in the pace of Antarctic ice loss after around 2060, contributing about 0.5 centimetres GMSL rise per year by 2100—an order of magnitude faster than today. These results

demonstrate the possibility that rapid and unstoppable sea-level rise from Antarctica will be triggered if Paris Agreement targets are exceeded.

Geographical scope:

Antarctica

Reference and link:

DeConto, R.M., Pollard, D., Alley, R.B. *et al.* The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* **593**, 83–89 (2021). <https://doi.org/10.1038/s41586-021-03427-0>

D. Mitigation and related technologies, and greenhouse gas (GHG) emissions and reporting:

a. GHG emissions by sources, removals by source and all reservoirs

Summary:

Arctic permafrost represents a substantial component of the Earth's carbon system. The thawing of permafrost contributes additional greenhouse gas emissions. Some of this thaw occurs gradually, but some occurs in "abrupt thaw" events, for example in association with wildfires, or when a hillside collapses and leads to exposure of permafrost soils. Many global models however only include gradual permafrost thaw in their emissions estimates, overlooking abrupt thaw processes as well as emissions from increasing wildfires in permafrost regions. At least 30% of the boreal zone of Arctic permafrost is now releasing more carbon than it takes up during the growing season, which will increasingly contribute to global warming as more permafrost thaws.

Abrupt Permafrost Thaw and Wildfire Carbon Emissions Shrinking the Carbon Budget

Description:

Arctic warming is thawing carbon-rich permafrost, which contributes additional greenhouse gas emissions. Some of this thaw occurs gradually, but some occurs in "abrupt thaw" events, for example in association with wildfires, or when a hillside collapses and leads to exposure of permafrost soils. Many global models however only include gradual permafrost thaw in their emissions estimates, overlooking abrupt thaw processes as well as emissions from increasing wildfires in permafrost regions. Wildfires release carbon emissions during combustion, but also remove the insulating organic layer at the soil surface, increasing permafrost thaw and leading to additional post-fire emissions. When abrupt thaw, wildfires, and fire-driven thaw are included in models alongside gradual thaw, these combined processes reduce the remaining allowable carbon budget from 2025 onward by 25% when aiming for 1.5°C warming, and 17% at 2.0°C. This highlights the importance of including abrupt thaw and wildfire-related emissions when setting future human emissions reduction targets.

Geographical scope:

Global, the Arctic

Reference and link:

Schädel, C., Gasser, T., Rogers, B.M. *et al.* Permafrost and wildfire carbon emissions indicate need for additional action to keep Paris Agreement temperature goals within reach. *Commun Earth Environ* 7, 306 (2026). <https://doi.org/10.1038/s43247-026-03189-5>

Increasing Methane Emissions From Northern Arctic Wetlands and Lakes

Description:

Methane emissions from boreal-Arctic wetlands and lakes will increase by one third by 2100 with even moderate warming, with small and mid-sized peatland lakes the largest contributors. Rising temperatures and resulting permafrost thaw will drive this spike in methane released into the atmosphere, which occurs when thawing occurs under wet conditions (CO₂ is released by thawed permafrost under dry conditions). Warming lengthens the growing season and boosts wetland emissions by 12%, while permafrost thaw also reshapes wetland and lake areas, increasing their permeability to water; leading to additional thaw and methane release. In some coastal tundra regions, permafrost thaw can reduce methane emissions as they transition into

permafrost bogs, which hold carbon. At the same time however, the loss of permafrost bogs in boreal regions results in higher emissions. Under high emissions, permafrost thaw also favors lake expansion, further increasing the amount of methane released and highlighting the importance of emissions reductions to limit cascading changes across the Arctic landscape.

Geographical scope:

Arctic

Reference and link:

Kuhn, M., Olefeldt, D., Arndt, K.A. *et al.* Current and future methane emissions from boreal-Arctic wetlands and lakes. *Nat. Clim. Chang.* **15**, 986–991 (2025). <https://doi.org/10.1038/s41558-025-02413-y>

30-40% of Arctic Permafrost Now a Net Source of Emissions

Description:

Arctic tundra, forests, wetlands and permafrost store large quantities of carbon emissions, but new data indicates that at least 30% of this “boreal” zone is now releasing more carbon than it takes up during the growing season. Rising temperatures have transformed this frozen landscape into a net source of carbon emissions, either as CO₂ or methane (CH₄), which will increasingly contribute to global warming as more permafrost thaws. Researchers found that over 30% of the region has become a net source of carbon, or 40% if wildfire emissions are included. This work highlights the need to sustain long-term research focused on carbon dynamics in Arctic tundra regions, in order to accurately track which areas are net carbon sources. Natural carbon sequestration through global oceans, forest, and soils currently absorb roughly half of all human emissions, and this study raises a warning flag that these sinks are becoming strained at current levels of warming.

Geographical scope:

Arctic

Reference and link:

Virkkala, AM., Rogers, B.M., Watts, J.D. *et al.* Wildfires offset the increasing but spatially heterogeneous Arctic–boreal CO₂ uptake. *Nat. Clim. Chang.* **15**, 188–195 (2025). <https://doi.org/10.1038/s41558-024-02234-5>

IIASA Contributions addressing research gaps and needs identified under UNFCCC Research and Systematic Observations (RSO) since SBSTA 22 (2005)

Organization: International Institute for Applied Systems Analysis (IIASA)

Address: Schlossplatz 1, A-2361 Laxenburg, Austria

Website: <https://iiasa.ac.at>

Publications repository: <https://pure.iiasa.ac.at/view/year/>

Period covered: June 2005 – April 2026

About IIASA

The International Institute for Applied Systems Analysis (IIASA) is an independent, international research institution based in Laxenburg, Austria, with national member organizations in 22 countries. Its mission is systems analysis research that provides scientific insight and guidance for decision-makers facing global environmental, energy, and sustainability challenges. IIASA researchers have contributed to IPCC assessment processes since the First Assessment Report, and more recently served as Lead and Coordinating Lead Authors from AR4 through AR6, including the Special Reports on 1.5°C (SR15) and on Climate Change and Land (SRCCL), and contribute annually to the UNEP Emissions Gap Reports.

IIASA conducts research across a wide portfolio spanning integrated assessment modelling, physical climate science and impacts, mitigation and adaptation research, land use and biodiversity, water, risk and resilience, demography, and governance. A central and enduring contribution has been the development and stewardship of global climate scenario infrastructure underpinning IPCC assessments — including the SSP database, the IPCC SR15 Scenario Explorer. IIASA hosts key global scenario platforms, including the NGFS climate scenarios used by 138 central banks and supervisors worldwide (<https://www.ngfs.net/ngfs-scenarios-portal/>). It also co-leads the **Scenario Compass Initiative (SCI)**—a grass-roots community effort that continuously compiles scientific scenarios and provides **near-term, policy-relevant benchmarks** independent of IPCC assessment cycles—made accessible through the open Scenario Compass platform (scenariocompass.org). In 2024, IIASA established the **Integrated Climate Impacts (ICI)** group within Energy, Climate, and Environment (ECE) Program, conducting cutting-edge **research linking physical climate science** — sea-level commitments, regional extremes attribution, heatwave dynamics, tipping risks, and carbon budgets — directly to societal and policy implications.

Through model intercomparison projects such as ENGAGE and community-driven efforts such as **JustMIP** (Justice Model Intercomparison Project), IIASA is advancing the representation of regional differentiation and justice considerations in Integrated Assessment Models, incorporating differentiated effort-sharing, minimum development thresholds, and broader wellbeing and equity metrics.

Concrete outputs include the **DESIRE framework** (Kikstra et al. 2025, *Environmental Research Letters*), enables the assessment of decent living standards in global mitigation scenarios, ensuring low-carbon pathways do not leave behind those currently lacking access to basic services. Pelz et al. (2025, *PNAS*) introduced the **net-zero carbon debt framework**, the first operational mechanism for tracking "fair shares" post-net-zero and quantifying regional responsibilities for overshoot. The accompanying **Carbon Debt Explorer** and earlier **Fair Mitigation Finance Explorer** (Pachauri et al. 2022, *Science*) make these calculations accessible to policymakers, providing a rigorous quantitative foundation for equity-focused IPCC AR7 preparation. Complementing these, **DSCALE**

(Sferra 2025, IIASA) downscales global IAM outputs into country-level energy and emissions pathways, improving scenario relevance for NDC and Long-Term Strategy design.

Capacity development is a core pillar of IIASA's mission, sustained across more than five decades. The Young Scientists Summer Program, running annually since 1977, has trained over 2,600 early-career researchers from more than 90 countries, complemented by summer schools, postdoctoral fellowships, and targeted workshops such as the 2023 water-energy-land nexus training co-organized with WRI in Addis Ababa for 14 African countries. Beyond individual training, IIASA embeds integrated assessment and scenario methods directly into partner research systems through national modelling partnerships — from NITI Aayog's energy model in India and MESSAGEix-CAEP in China to MESSAGEix-Canada and the Archimedes Centre in Israel. This is reinforced by a deep open-science commitment: IIASA's flagship modelling frameworks and scenario databases are released under open-source licenses with full documentation, enabling partners to independently run, adapt, and extend the tools.

The contributions described in this document are organised to match precisely the research needs and gap categories identified under UNFCCC RSO since SBSTA 22 (A through E, and their sub-categories).

IIASA-Coordinated Community Efforts in Support of UNFCCC RSO

Beyond its own research outputs, IIASA convenes and coordinates four major international community efforts that are directly relevant to the UNFCCC RSO process, including its Research Dialogue. These are listed here as a collective overview; each is also referenced in the relevant thematic sections below.

1. Scenario Compass Initiative (SCI) — Annually Updated, Near-Term, Policy-Relevant Scenario Benchmark

The Scenario Compass Initiative (SCI) is a grass-roots community effort, co-led by IIASA, that continuously collects scientific scenarios and produces near-term, policy-relevant scenario benchmarks independent of IPCC assessment cycles. This directly addresses a critical gap repeatedly flagged under UNFCCC RSO: IPCC assessment timelines are too slow to track rapidly evolving emission trajectories and NDC ambition, while the UNEP Emissions Gap Report does not itself collect and harmonise scenario data. SCI provides member states and the broader research community with a living reference for where the world stands, what additional action is needed, and how individual countries can set on-track trajectories. The first SCI community paper is currently in review.

Publications & links:

- [Scenario Compass platform: scenariocompass.org](https://scenariocompass.org)
- [First SCI community paper in review.](#)

2. Multi-Model Scenario Intercomparison Coordination – IAMC/ICONICS/Scenarios Forum

IIASA plays a central coordinating and enabling role in global multi-model scenario intercomparison efforts, in close collaboration with the Integrated Assessment Modeling Consortium (IAMC) and under the umbrella of International Committee on New Integrated Climate Change Assessment Scenarios (ICONICS).

IIASA provides the core data infrastructure used in Intergovernmental Panel on Climate Change Working Group III assessments (AR5, SR1.5, AR6), enabling systematic comparison across global modeling teams.

Beyond maintaining core SSP databases, IIASA also hosts the **SSP Extensions Explorer**, which expand the framework with additional **socioeconomic dimensions**. At the same

time, the community, coordinated through IAMC and ICONICS, is advancing a more **inclusive scenario development process** to update and evolve the SSP framework with broader stakeholder input for applications in the 2030s.

These efforts are further supported by initiatives such as the Scenarios Forum, which brings together researchers and stakeholders to exchange knowledge, foster collaboration, and shape the future of scenario development.

This ecosystem serves as a key access point for the research community and supports international policy processes.

Resources & links:

- [IIASA SSP Scenario Explorer](#)
- [SSP Extensions Explorer](#)
- [IAMC 1.5°C Scenario Explorer](#)
- [AR6 Scenario Explorer](#)
- [ICONICS](#)
- [IAMC](#)
- [Scenarios Forum](#)

3. ENGAGE / JustMIP — Global Multi-Model Mitigation and Justice Consortia

The ENGAGE project (14-institution global consortium coordinated by IIASA) produced the first set of nationally consistent, regionally resolved mitigation pathways and examined the role of institutional capacity in determining feasibility of climate targets. IIASA is co-developing the JustMIP community model intercomparison project — the first multi-model effort to operationalise distributional, procedural, corrective, recognitional, and transitional justice in mitigation scenarios for IPCC AR7. JustMIP directly answers the equity gap UNFCCC RSO has consistently flagged and was presented at the RD during SBSTA 62. These scenarios will also inform the next generation of Earth Commission Transformation Pathways towards a safe and just future.

Publications & links:

- [Bertram et al. \(2024\) Nature Climate Change](#)
- [Brutschin et al. \(2025\) ERC](#)
- [JustMIP protocol](#)
- [JustMIP SBSTA 62 RD presentation](#)
- www.earthcomission.org

4. EDITS — Global Demand-Side Research Community

IIASA co-coordinates the Energy Demand changes Induced by Technological and Social innovations (EDITS) initiative together with [RITE](#), a Japanese research institute. EDITS is a global scientific community that aims to increase the evidence base, data, and scenarios, to deliver research, modeling, policies and implementation of demand-side solutions. EDITS frames the energy and material systems as an opportunity to provide high wellbeing for all with much less resources. EDITS directly addresses the demand-side gap flagged repeatedly by UNFCCC RSO and by IPCC AR6 WGIII. Flagship IIASA EDITS outputs include the High-with-Low framework for bottom-up and integrated assessment modelling (Wilson et al. 2023, Sugiyama et al. 2024). It deep-dives into modelling efforts of conventional demand sectors (i.e., building, industry, transport) (e.g., the Avoid-Shift-Improve buildings analysis (Mastrucci et al. 2025), filling the gap from the building model review (Mastrucci et al. 2023); , while understanding more novel demand-side components including the social and other drivers (Niamir et al. 2024). Other publications investigate the multiple benefits and requirements of low-demand solutions (e.g. for energy security by Bento et al. 2024, decent living standards for all by Chatterjee et al. 2024, decent mobility by Arnz et al. 2025, decent living materials by Streek et al. 2025).

Publications & links:

- [Wilson et al. \(2023\): High-with-Low narrative extending the Low Energy Demand \(LED\) scenario / EDITS scenario family](#)
- [Sugiyama et al. \(2024\): Commentary highlighting the importance of High-with-Low narrative](#)
- [Mastrucci et al. \(2025\) — Avoid-Shift-Improve buildings mitigation potential](#)
- [Mastrucci et al. \(2023\): Review and comparison of available models to assess demand-side solution in buildings](#)
- [Arnz et al. \(2025\): Quantifying Minimum Mobility and Transport Needs](#)
- [Streek et al. \(2025\): Material requirements for decent living standards](#)
- [Bento et al. \(2024\): Leverage demand-side policies for energy security](#)
- [Chatterjee et al. \(2024\): decent living standards in the Global South](#)
- [Niamir et al. \(2024\): Social Innovation Enablers of Low Energy Demand Future](#)

A. Understanding Climate Change, Related Climate Data, and Scenario Development and Use

IIASA has been a world-leading hub for integrated climate scenario development and scenario data stewardship. The core scenario infrastructure contributions — SSPs, SR15 scenarios, AR6 Scenario Database, Scenario Compass — are summarised in A.b below. The mitigation substance of those scenarios (overshoot, feasibility, CDR, demand, equity) is covered in Section D. Physical climate science contributions, including work on sea-level commitments, heatwave hotspots, tipping risks, and attribution, appear in A.f–A.g and B.

A.a Near-term climate change and its prediction

IIASA's contribution to near-term prediction focuses primarily on near-term emission trajectories and their policy implications. The GAINS model provides near-term GHG and air pollutant projections by country and sector. IIASA contributes as lead author institution to the annual UNEP Emissions Gap Reports. The Scenario Compass Initiative (SCI, described in the Flagship block above) is the community's primary new mechanism for annual near-term scenario benchmarks between IPCC cycles.

UNEP Emissions Gap Reports — Near-term emission trajectories and NDC gap assessment

IIASA researchers contribute as lead authors to the annual UNEP Emissions Gap Reports, which assess near-term emission trends against climate targets and are the primary reference for tracking progress under the Paris Agreement. The GAINS model underpins near-term GHG projections in these reports.

Publications & links:

- [UNEP Emissions Gap Reports \(IIASA contributions\)](#)
- [GAINS model](#)
- [Scenario Compass platform: scenariocompass.org](https://scenariocompass.org)

Evaluating the Near- and Long-Term Role of Carbon Dioxide Removal

Ganti, Gasser, Bui, Geden, Lamb, Minx, Schleussner, and Gidden (2024, Communications Earth & Environment) provided the first comprehensive evaluation of land-based CDR in IPCC AR6 scenarios, showing that afforestation and reforestation play a critical near-term role ($\approx 10\%$ of net GHG reductions to 2030), while novel CDR scales up after mid-century.

The study clarifies how CDR complements but cannot replace near-term emissions reductions in 1.5°C-consistent pathways. Gidden et al. (2025, Nature) for the first time maps safe areas that can practically be used for underground carbon storage and shows geological storage is a scarce, finite resource that must be used in a highly targeted way.

Publications & links:

- [Ganti et al. \(2024\) Communications Earth & Environment — Near- and long-term CDR role](#)
- [Gidden et al. \(2025\) A prudent planetary limit for geologic carbon storage.](#)

A.b Overall advances in scenario development and use, including scenarios that limit warming in 2100 to below 1.5 °C

IIASA led the quantification of the SSPs and the first comprehensive ensemble of 1.5°C-consistent mitigation scenarios, providing the scenario backbone for IPCC AR5, SR15, and AR6. The Scenario Compass (scenariocompass.org) and SCI now provide a continuously updated open infrastructure for these scenarios. For the mitigation substance of 1.5°C pathways — overshoot, demand, CDR, feasibility, equity — see Section D.

The Shared Socioeconomic Pathways (SSPs): Foundation Scenario Framework for Climate Research

IIASA led the quantification of the SSP2 ('Middle of the Road') pathway and coordinated the broader multi-model SSP process. The SSP–RCP framework is now the universal basis for IPCC AR5, AR6, and all associated impact and mitigation research. A 2020 Nature Climate Change assessment (O'Neill, van Ruijven, Riahi et al.) evaluated the framework and set directions for future development.

Publications & links:

- [Riahi et al. \(2017\) Global Environmental Change — SSP overview](#)
- [O'Neill et al. \(2020\) Nature Climate Change — Framework assessment](#)
- [IIASA SSP Scenario Explorer](#)
- [Scenario Compass](#)

Scenarios Towards Limiting Global Mean Temperature Below 1.5°C

Rogelj, Krey, Riahi, Fricko et al. (2018, Nature Climate Change) produced the first comprehensive multi-model ensemble of 1.5°C-consistent scenarios. This was the direct scientific backbone of the IPCC SR15. IIASA hosts the open SR15 Scenario Explorer (414 scenarios from 14+ modelling teams).

Publications & links:

- [Rogelj et al. \(2018\) Nature Climate Change — 1.5°C scenarios](#)
- [Huppmann et al. \(2018\) Nature Climate Change — SR15 scenario resource](#)
- [IAMC 1.5°C Scenario Explorer](#)

Feasibility of Peak Temperature Targets Under Institutional Constraints

Bertram, Brutschin, van Ruijven, Fricko, Fujimori, Krey et al. (2024, Nature Climate Change) showed that real-world institutional and political constraints are as binding as technological availability in determining whether 1.5°C and 2°C targets can be achieved, providing critical scientific grounding for the Global Stocktake.

Publications & links:

- [Bertram et al. \(2024\) Nature Climate Change](#)
- [Brutschin et al. \(2025\) ERC](#)

A.c Advances in climate model simulations, particularly by combining multiple lines of evidence and on a wider range of climate variables to improve parameterization of the physical climate system and understanding of scenarios

IIASA contributes to advances in climate model simulations by providing integrated scenario inputs and supporting coordinated multi-model analysis. Its MESSAGEix-GLOBIOM framework generates greenhouse gas emission trajectories, land-use change, and energy system data that are used as forcing inputs in CMIP6 climate simulations, contributing to improved representation of the physical climate system.

IIASA also supports scenario coordination through its role in the International Committee on New Integrated Climate Change Assessment Scenarios and related activities under the Integrated Assessment Modeling Consortium. Through this, IIASA contributes to ScenarioMIP and broader scenario intercomparison efforts, enabling the integration of multiple lines of evidence across models and domains.

In addition, IIASA convenes the global scenario community through initiatives such as the Scenarios Forum (e.g. hosted at IIASA in 2022), fostering exchange, methodological advances, and alignment across research communities.

Publications & links:

- [MESSAGEix model documentation](#)
- [SSP Scenario Explorer](#)

A.d Addressing sensitivities of climate simulations to varying scenarios and parameterizations

IIASA has contributed to understanding how climate outcomes depend on socioeconomic scenario assumptions through large-scale ensemble analyses. Schleussner, Ganti et al. (2024, Nature) showed that climate outcomes after temperature overshoot differ fundamentally from scenarios that avoid it — with Earth system feedbacks potentially undercutting temperature reversal — directly addressing an IPCC AR6 gap.

Overconfidence in Climate Overshoot

Schleussner, Ganti, Lejeune, Zhu, Gassen, Gidden, Rogelj et al. (2024, Nature) showed that climate outcomes after temperature overshoot differ fundamentally from scenarios that avoid it, with Earth system feedbacks potentially undercutting temperature reversal — making near-term emissions reductions the priority. This work directly speaks to an IPCC AR6 gap on scenario sensitivities to parameterization and physical system feedbacks.

Publications & links:

- [Schleussner, Ganti et al. \(2024\) Nature — Overconfidence in climate overshoot](#)

A.e Addressing uncertainties identified in the Intergovernmental Panel on Climate Change (IPCC) Reports (from the Fourth Assessment Report to date)

IIASA researchers have been central to addressing key IPCC uncertainties around carbon budgets, short-lived climate forcers, non-CO₂ GHGs, and land-use interactions. The GAINS model systematically quantifies non-CO₂ forcing uncertainties. The overshoot and CDR uncertainty work is consolidated in Section D.

Remaining Carbon Budgets — Quantifying a Central IPCC Uncertainty

Lamboll, Nicholls, Smith, Rogelj et al. (2023, Nature Climate Change; IIASA/Grantham Institute joint contribution) updated estimates of remaining carbon budgets consistent with

1.5°C and 2°C, addressing a persistent uncertainty flagged since AR5. The study resolved key discrepancies between observational and model-based budget estimates and provided revised numbers adopted in the AR6 WG I report.

Publications & links:

- [Lamboll et al. \(2023\) Nature Climate Change — Remaining carbon budgets](#)

A.f High resolution local and regional climate information, as well as improving the development and application of downscaled regional and sub regional climate models, for understanding risks and implementing climate actions

IIASA contributes to regional climate information through scenario-based impact assessment and national IAM downscaling. The ENGAGE project produced nationally resolved mitigation pathways. IIASA has produced landmark physical-climate results on regional sea-level commitments and regional attribution of wealthy-group emissions.

Global Warming Level Indicators of Climate Change and Hotspots of Exposure

Werning, Hooke, Krey, Riahi, van Ruijven and Byers (2024, Environmental Research: Climate) mapped hotspots of climate exposure across warming levels from 1.5°C to 4°C, quantifying regional exposure to compound risks including heat stress, water scarcity, and flood risk under each scenario.

Publications & links:

- [Werning, Krey, van Ruijven, Byers et al. \(2024\) Environmental Research: Climate](#)

National and Sub-national Scenario Downscaling through ENGAGE

IIASA advances national and sub-national scenario analysis through the development of **DSCALE (Downscaling Scenarios to the Country Level for Assessment of Low-Carbon Emissions)**.

Since Integrated Assessment Models (IAMs) typically operate at regional or global scales, their direct applicability for national policy design is limited. DSCALE addresses this gap by providing a **novel algorithm to systematically downscale IAM outputs to the country level**, generating nationally resolved energy and emissions pathways that remain consistent with global climate scenarios (including 1.5°C pathways).

Publications & links:

- [DSCALE](#)

A.g Advances and gaps in attribution science, including at regional and national scale, as well as attribution of monsoon pattern changes

Attribution science is an area to which IIASA contributes through scenario-based and emulator-based frameworks. Notably, the sea-level rise commitments work directly links near-term national emission choices to long-term physical climate risks, and the high-income groups study operationalises emulator-based attribution at population-group resolution.

Multi-Century Sea-Level Rise Commitments from Near-Term Emissions

Nauels, Nicholls, Möller, Hermans, Mengel, Klönne, Smith, Slangen, and Palmer (2025, Nature Climate Change) quantified how near-term mitigation decisions lock in multi-century sea-level rise. Under current policies, emissions from 2020–2050 commit ≈0.3 m additional sea-level rise by 2300; very stringent mitigation could spare ≈0.6 m. This paper directly links near-term national emission choices to long-term physical climate risks.

Publications & links:

- [Nauels, Nicholls, Möller et al. \(2025\) Nature Climate Change — Sea-level rise commitments](#)

High-Income Groups Disproportionately Drive Regional Climate Extremes [see also D.d]

Schöngart, Nicholls, Hoffmann et al. (2025, Nature Climate Change) linked GHG emissions attributable to the wealthiest population groups (1990–2020) to regional climate extremes using an emulator-based attribution framework. This work quantifies how inequality in emissions translates into inequality in regional climate impacts.

Publications & links:

- [Schöngart, Nicholls, Hoffmann et al. \(2025\) Nature Climate Change — High-income groups and climate extremes](#)

B. Adaptation, Loss and Damage and Extreme Events

IIASA has been a foundational contributor to the scientific and policy basis for Loss and Damage, adaptation assessment, and climate risk. Mechler and Schinko's 2016 Science paper defined the policy space for L&D action; the Springer book (2019, >1 million accesses) became the field's primary reference and informed IPCC AR6 WG2. IIASA researchers introduced adaptive capacity into the SSP framework and produced the first global multi-sector climate hotspot mapping and contributed heatwave hotspot detection (Kornhuber et al. 2024) and the RIME emulator linking IAM scenarios to physical climate impacts. IIASA contributes to SPARCCLE (integrated European climate risk) and to IPCC WG2 as lead authors.

B.a The evolution and dynamics of extreme events, and early warning systems and climate services

IIASA has contributed to understanding how extreme events will evolve under different warming scenarios. The Kornhuber et al. 2024 result — that heatwave hotspots are accelerating faster than models predict — has direct implications for early warning system design.

Global Emergence of Regional Heatwave Hotspots Outpaces Climate Model Simulations

Kornhuber, Bartusek, Seager, Schellnhuber, and Ting (2024, PNAS) showed that extreme heat in several regions is accelerating significantly faster than state-of-the-art climate models predict — models underestimate positive trends in the upper tail of extreme temperature distributions by a factor of two or more. This has direct implications for early warning systems and climate services that must account for model underestimation of extreme heat.

Publications & links:

- [Kornhuber, Bartusek, Seager, Schellnhuber, Ting \(2024\) PNAS — Heatwave hotspots outpace models](#)

Global Exposure and Vulnerability to Multi-Sector Climate Change Hotspots

Byers, Gidden, Leclère, Havlik, Burek, Obersteiner, Rogelj, Riahi et al. (2018, Environmental Research Letters) provided the first integrated global mapping of compound

exposure to water, energy, food, and health stress under different warming scenarios — identifying hotspots where multiple extreme-event-driven stressors converge simultaneously. Widely cited across IPCC AR6 WG2 and WG3.

Publications & links:

- [Byers et al. \(2018\) Environmental Research Letters — Multi-sector hotspots](#)

B.b Assessing adaptation progress, and the impact of adaptation actions on reducing risks, to inform adaptation planning and action

Identifying the Policy Space for Climate Loss and Damage

Mechler and Schinko (2016, Science) used a risk-based framework to delineate the space of L&D policy action — distinguishing what can be avoided (mitigation), managed (adaptation), and compensated (residual L&D). Mechler subsequently co-led the first comprehensive scholarly volume on L&D (Springer, 2019, >1 million accesses), which served as the primary scientific basis for IPCC AR6 WG2 Chapter 16.

Publications & links:

- [Mechler & Schinko \(2016\) Science — Policy space for Loss and Damage](#)
- [Mechler et al. \(2019\) Springer book — Loss and Damage from Climate Change](#)

Governance in Socioeconomic Pathways and Future Adaptive Capacity

Andrijevic, Cuaresma, Muttarak and Schleussner (2020, Nature Sustainability) extended the SSP framework with quantitative projections of governance quality and adaptive capacity. A follow-up study (Andrijevic, Schleussner, Byers et al., 2023, Nature Climate Change) operationalised adaptive capacity in global risk assessments, showing that ignoring it systematically underestimates climate risks in vulnerable regions.

Publications & links:

- [Andrijevic et al. \(2020\) Nature Sustainability — Governance in SSPs](#)
- [Andrijevic, Schleussner, Byers et al. \(2023\) Nature Climate Change — Adaptive capacity scenarios](#)

B.c Climate impacts across 1.5 °C warming scenarios at local and regional levels

IIASA's integrated assessment framework links warming scenarios to regional and sectoral climate impacts. The RIME emulator (Regional Impact Model Emulator) provides a fast, flexible tool linking IAM scenario outputs to physical climate impact estimates at regional resolution — enabling rapid scenario-impact integration within the SPARCCLE European climate risk framework and for global analyses.

RIME Emulator — Linking IAM Scenarios to Regional Physical Climate Impacts

The RIME (Regional Impact Model Emulator) provides a computationally efficient framework for connecting integrated assessment model scenario outputs to regional physical climate impact estimates — enabling analysis of how different warming levels, emission trajectories, and mitigation strategies translate into local and regional risk. RIME underpins IIASA's contribution to the SPARCCLE integrated European climate risk project.

Publications & links:

- [SPARCCLE project](#) (IIASA contribution to integrated European climate risk)

Global Warming Level Indicators of Climate Change and Hotspots of Exposure [see also A.f]

Werning, Hooke, Krey, Riahi, van Ruijven and Byers (2024, Environmental Research: Climate) mapped hotspots of climate exposure across warming levels from 1.5°C to 4°C, quantifying regional exposure to compound risks including heat stress, water scarcity, and flood risk under each scenario.

Publications & links:

- [Werning, Krey, van Ruijven, Byers et al. \(2024\) Environmental Research: Climate](#)

Sea-Level Rise Commitments from Near-Term Emissions [see also A.g]

Nauels, Nicholls, Möller et al. (2025, Nature Climate Change) quantified how near-term emission decisions lock in multi-century sea-level rise, providing regionally resolved impact estimates directly relevant to adaptation planning under different warming levels. Also listed under A.g.

Publications & links:

- [Nauels et al. \(2025\) Nature Climate Change](#)

MESSAGEix-GLOBIOM Nexus Module: Integrating Water Sector and Climate Impacts

Awais, Vinca, Byers, Frank, Fricko, Burek, Riahi, Krey et al. (2024, Geoscientific Model Development) extended IIASA's integrated assessment framework to explicitly represent water sector dynamics and climate impacts at regional resolution.

Publications & links:

- [Awais, Byers, Riahi, Krey et al. \(2024\) GMD — MESSAGEix nexus](#)

B.d Understanding of complex, cascading and transboundary risks

Global Multi-Sector Compound and Cascading Risk — and SPARCCLE

Byers et al. (2018, Environmental Research Letters) mapped where water, energy, food, and health climate risks simultaneously converge — the first systematic global analysis of compound, cascading climate risks across sectors. Schinko, Drouet, Mechler et al. (2020) further quantified economy-wide effects of coastal flooding from sea-level rise under simultaneous mitigation and adaptation, demonstrating how coastal cascades propagate through national economies. IIASA contributes to SPARCCLE — the pan-European integrated climate risk project — which explicitly addresses cascading and transboundary risk across the European continent.

Publications & links:

- [Byers et al. \(2018\) Environmental Research Letters](#)
- [Schinko, Drouet, Mechler et al. \(2020\)](#)

B.e Climate risks for vulnerable groups such as Indigenous Peoples, local communities, children and youth, people with disabilities and women

IIASA has contributed to understanding differentiated climate vulnerability and health co-benefits of mitigation through integrated scenario work, wellbeing cost of carbon research, and the Lancet Countdown.

Lancet Countdown on Health and Climate Change — IIASA Contributions

IIASA researchers contribute to the annual Lancet Countdown on Health and Climate Change, quantifying health co-benefits of mitigation including avoided premature mortality from air pollution reductions, heat exposure indicators, and energy poverty metrics. This work directly addresses the health dimension of climate risk for vulnerable populations.

Publications & links:

- [Lancet Countdown Rao et al. \(2021\)](#) — India inequality and climate risk

Subnational Living Standard Gaps in 75 Low- and Middle-Income Countries

Hoffmann, Zimm, Pachauri, Brutschin, Kikstra, Riahi, Schinko et al. (2025, Nature Communications) used subnational survey data from 75 low- and middle-income countries to reveal persistent and geographically concentrated gaps in living standards, mapping who bears the greatest climate vulnerability.

Publications & links:

- [Hoffmann, Zimm, Pachauri et al. \(2025\) Nature Communications — Living standard gaps](#)

Wellbeing Cost of Carbon — Linking Climate Action to Human Development

Eker, Reiter, Liu, Kuhn and Lutz (2026, Global Sustainability) introduced a framework quantifying the wellbeing cost of carbon integrating mortality, morbidity, and quality-of-life dimensions beyond GDP.

Publications & links:

- [Eker, Lutz et al. \(2026\) Global Sustainability — Wellbeing cost of carbon](#)

Representing Gender Inequality in Scenarios — Implications for Climate Adaptation and Mitigation

Andrijevic, Zimm, Moyer, Muttarak, and Pachauri (2025, Nature Climate Change) proposed a structured inclusion of gender inequality pathways in the SSP framework, demonstrating that the scale of climate adaptation and mitigation challenges changes substantially depending on the rate of progress towards gender equality across societies.

Publications & links:

- Andrijevic, Zimm, Muttarak, Pachauri et al. (2025) Nature Climate Change — Representing gender inequality in scenarios: <https://doi.org/10.1038/s41558-024-02242-5>

C. Ecosystems and Nature-Based Solutions

IIASA has produced landmark research on terrestrial ecosystem trajectories, nature-based solutions, and the conditions for bending the curve of biodiversity loss. The 2020 Nature paper by Leclère, Obersteiner, Havlik and 40+ (2020) co-authors was the first quantitative demonstration that halting biodiversity loss requires integrating food system transformation with conservation simultaneously. IIASA's GLOBIOM model underpins EU bioenergy policy, IPCC SRCCL, and IPBES scenario assessments.

C.a Opportunities and challenges of implementing nature-based solutions in land and ocean systems in support of climate adaptation and mitigation

Bending the Curve of Terrestrial Biodiversity Needs an Integrated Strategy

[Leclère, Obersteiner, Barrett, Butchart, Havlik, Valin et al. \(2020, Nature\)](#) led 60+ researchers in the first multi-model analysis of pathways to halt terrestrial biodiversity loss. Conservation and restoration alone are insufficient without simultaneous food system transformation. This informed the Kunming-Montreal Global Biodiversity Framework.

Publications & links:

- [Leclère, Obersteiner, Havlik et al. \(2020\) Nature — Bending the curve](#)

African Food System and Biodiversity — the Role of Urbanization

De Vos, Janssens, Kozicka, Leclère, Havlik et al. (2024, Nature Sustainability) showed that urbanisation-driven dietary shifts are the dominant pathway affecting food security and biodiversity in Africa, identifying a critical window for urban food demand transitions.

Publications & links:

- [De Vos, Kozicka, Leclère, Havlik et al. \(2024\) Nature Sustainability](#)

C.b Climate change impacts and risks for the ocean and cryosphere and related ecosystems

Global Warming Level Indicators and Cryosphere-Linked Exposure

Werning, Krey, van Ruijven, Byers et al. (2024, Environmental Research: Climate) quantified hotspots of climate exposure across warming levels, including cryosphere-dependent water systems and sea-level-linked coastal risk. IIASA's scenario infrastructure provides warming level trajectories used by IPCC SROCC and global ocean/cryosphere modelling communities.

Publications & links:

- [Werning et al. \(2024\) Environmental Research: Climate](#)

C.c Emissions and removals from terrestrial ecosystems, and information on ecosystems with high-carbon reservoirs

Climate Change Mitigation Through Livestock System Transitions

Havlik, Valin, Herrero, Obersteiner, Rufino et al. (2014, PNAS) established the quantitative basis for livestock mitigation in integrated assessment. A series of Nature Food papers (Frank, Havlík, Kozicka et al., 2021–2023) extended this to plant-based alternatives, nitrogen boundaries, and food system trajectories.

Publications & links:

- [Havlik et al. \(2014\) PNAS — Livestock mitigation transitions](#)
- [Kozicka, Havlik, Valin et al. \(2023\) Nature Communications — Plant-based alternatives](#)

Decline in Carbon Emission Intensity of Global Agriculture

Bai, Zhang, Winiwarter, Luo, Chang et al. (2024, PNAS) found that the rate of improvement in agricultural carbon emission intensity has stagnated — implying that meeting Paris targets requires systemic agricultural transformation.

Publications & links:

- [Bai, Winiwarter, Chang et al. \(2024\) PNAS — Agricultural emission intensity](#)

C.d The vulnerability of natural and human ecosystems (including their interactions and associated tipping points), and strengthening their resilience, particularly for the most vulnerable systems

Achieving Net Zero GHG Emissions Is Critical to Limit Climate Tipping Risks [see also D.b]

Möller, Högner, Schleussner, Bien, Kitzmann, Lamboll, Rogelj, Donges, Rockström, and Wunderling (2024, Nature Communications) showed that following current policies commits to a 45% tipping risk by 2300, even if temperatures are later returned below 1.5°C. Every

0.1°C of overshoot above 1.5°C increases tipping risk, with strong acceleration above 2°C. This is the physical-science counterpart to the overshoot scenario literature.

Publications & links:

- [Möller, Högner, Schleussner et al. \(2024\) Nature Communications — Net zero and tipping risks](#)

Reconciling Nitrogen Boundaries with Global Food Security

Chang, Havlik, Leclère, Winiwarter, Obersteiner et al. (2021, Nature Food) showed that regional nitrogen pollution boundaries are already transgressed in many areas; ambitious integrated strategies — fertiliser management combined with dietary shifts — are the only pathway to both goals simultaneously.

Publications & links:

- [Chang, Havlik, Leclère, Winiwarter et al. \(2021\) Nature Food — Nitrogen boundaries](#)
- [Guo, Winiwarter, Chang, Havlik et al. \(2024\) Science Advances — Nitrogen and ecosystem protection](#)

Quantifying Safe and Just Earth System Boundaries

Zimm, Nakicenovic and co-authors contributed to the Earth Commission’s landmark 2023 Nature and Lancet Planetary Health studies quantifying safe and just Earth system boundaries. Most boundaries have already been breached; stabilising them requires both physical transformation and global justice considerations.

Publications & links:

- [Rockström, \[...\] Zimm, Nakicenovic et al. \(2023\) Nature — Safe and just Earth system boundaries](#)
- [Gupta, J., \[...\] Nakicenovic, Zimm et al. \(2024\). The Lancet Planetary Health - A just world on a safe planet: a Lancet Planetary Health–Earth Commission report on Earth-system boundaries, translations, and transformations.](#)

D. Mitigation and Related Technologies, and Greenhouse Gas (GHG) Emissions and Reporting

IIASA’s contributions to Section D are organised around the five sub-categories of the UNFCCC RSO framework (D.a through D.f). GHG reporting infrastructure (GAINS, GLOBIOM) appears under D.a and D.f. CDR science appears under D.b–D.c. Demand-side mitigation and equity/justice work appear under D.c–D.d. Emission metrics are covered under D.e.

D.a GHG emissions by sources, removals by source and all reservoirs

IIASA’s GAINS model is the world’s leading tool for integrated multi-pollutant, multi-sector emission analysis, used by UNEP, the European Commission, and national governments. GLOBIOM-G4M provides land-use change and forestry emission estimates.

GAINS: Greenhouse Gas and Air Pollution Interactions and Synergies Model

IIASA’s GAINS model provides consistent, science-based GHG and air pollutant emission inventories and projections by source, sector, and country. It underpins UNEP assessment processes, EU air quality and climate policy, IPCC WG3 emission databases, and the EMEP/CIAM programme supporting the Gothenburg Protocol under the UNECE CLRTAP.

Recent flagship work includes global anthropogenic mercury scenarios (Broczka, Rafaj, Klimont et al., 2024, ACP), N₂O bacterial denitrification mitigation (Hiis et al. 2024), Kigali Amendment / F-gas phase-down analysis (Purohit et al. 2022), and ambitious nitrogen abatement for WHO PM_{2.5} targets (Guo, Winiwarter et al., 2024, One Earth). GAINS also underpins IIASA contributions to the CCAC Clean Air in ASEAN programme and the World Bank PMEH Indo-Gangetic Plain air quality initiative.

Publications & links:

- [Guo, Winiwarter et al. \(2024\) One Earth — Nitrogen abatement and PM_{2.5} targets](#)
- [Broczka, Rafaj, Klimont et al. \(2024\) ACP — Mercury emission scenarios](#)
- [GAINS model](#)

Decline in Carbon Emission Intensity of Global Agriculture

Bai, Zhang, Winiwarter, Luo, Chang et al. (2024, PNAS) found that the rate of improvement in agricultural carbon emission intensity has stagnated, implying that meeting Paris targets requires systemic transformation of the food system.

Publications & links:

- [Bai, Winiwarter, Chang et al. \(2024\) PNAS](#)

D.b Opportunities, risks and costs associated with the deployment and upscaling of carbon dioxide removal (CDR) technologies and options

IIASA has made foundational contributions to understanding the role, physical limits, and governance requirements of CDR, including the landmark 2025 Nature paper establishing a prudent planetary limit for geologic carbon storage. Overshoot scenarios are covered here alongside CDR, as they are intrinsically linked.

A Prudent Planetary Limit for Geologic Carbon Storage

Gidden, Joshi, Brutschin, Riahi, Schellnhuber, Schleussner, Rogelj et al. (2025, Nature) established that safe and practical geological carbon storage is limited to ≈1,460 Gt CO₂ — almost ten times smaller than industry estimates — and that using all of it for CDR would reduce warming by only 0.7°C. This reframes geologic storage as a finite, intergenerational resource requiring explicit policy prioritisation.

Publications & links:

- [Gidden, Joshi, Brutschin, Riahi, Rogelj et al. \(2025\) Nature — Prudent planetary limit for carbon storage](#)
- [Interactive carbon storage explorer](#)

Evaluating the Near- and Long-Term Role of CDR [see also A.a]

Ganti, Gasser, Bui, Geden, Lamb, Minx, Schleussner, and Gidden (2024, Communications Earth & Environment) showed that land-based CDR plays a critical near-term role (≈10% of net GHG reductions to 2030), while novel CDR scales up after mid-century. CDR complements but cannot replace near-term emissions reductions.

Publications & links:

- [Ganti et al. \(2024\) Communications Earth & Environment — CDR role](#)

CDR Certification and Governance Frameworks

Schenuit et al. (with IIASA contribution) assessed certification and governance frameworks for CDR — examining how different regulatory approaches affect the credibility, permanence, and equity of CDR deployment at scale, and what institutional conditions are needed for robust CDR governance under the Paris Agreement.

Publications & links:

- [Schenuit et al. — CDR certification and governance](#)

Beyond Emissions Trading to a Negative Carbon Economy

Bednar, Baklanov, Wagner, Obersteiner et al. (2024, Climate Policy) proposed a carbon removal obligation framework complementing emissions trading — establishing the institutional and regulatory conditions under which CDR can be deployed at scale without displacing near-term emission reductions.

Publications & links:

- [Bednar, Baklanov, Obersteiner et al. \(2024\) Climate Policy — Carbon removal obligation](#)

Fairness and Feasibility in Deep Mitigation Pathways with Novel CDR

Gidden, Brutschin, Ganti, Unlu, Zakeri, Fricko, Mitterrutzner, Lovat, and Riahi (2023, Environmental Research Letters) assessed the role of novel CDR in deep mitigation pathways under institutional capacity constraints. New CDR technologies can play a role, but cannot substitute for near-term emissions cuts.

Publications & links:

- [Gidden, Brutschin, Ganti, Riahi et al. \(2023\) ERL — Fairness and feasibility with novel CDR](#)

Negative Emissions to Mitigate Earth System Risks

Gasser, Rezai, Baklanov and Obersteiner (2026, Nature Communications) show that the need for CDR under overshoot depends strongly on the pace of mitigation and the tolerance for triggering tipping elements.

Publications & links:

- [Gasser, Rezai, Baklanov, Obersteiner \(2026\) Nature Communications — Negative emissions and Earth system risks](#)

D.c Role of CDR in meeting Paris Agreement goals and linkage with attaining sustainable development

IIASA has produced multi-model analysis of overshoot scenarios and their consequences, as well as foundational work on the feasibility of climate targets under real-world institutional constraints. These works directly address the role of CDR within Paris-consistent pathways and the linkage to sustainable development.

Cost and Attainability of Meeting Stringent Climate Targets Without Overshoot — Lead Reference

Riahi, Kriegler, Johnson, Bertram, den Elzen, Eom, Schaeffer, Edmonds, Clarke, Krey, Luderer, Tavoni, van Vuuren et al. (2021, Nature Climate Change) produced the first comprehensive multi-model overshoot comparison, showing the costs and attainability of stringent climate targets with and without temperature overshoot, and defining the scenario design used across the entire IAM community. This is the foundational paper that IPCC AR6 WGIII (Skea et al.) built on.

Publications & links:

- [Riahi et al. \(2021\) Nature Climate Change — Cost and attainability without overshoot](#)

A New Scenario Logic for the Paris Agreement Temperature Goal

Rogelj et al. (2019, Nature) demonstrated that the choice of temperature goal operationalisation (peak vs. end-of-century) fundamentally alters scenario parameterizations, carbon budget estimates, and CDR requirements — resolving a critical ambiguity in the climate policy-research interface that shaped IPCC AR6 WGIII.

Publications & links:

- [Rogelj et al. \(2019\) Nature — Paris Agreement temperature goal](#)

Feasibility of Climate Targets and the Role of Institutional Capacity

Brutschin, van Ruijven, Fricko et al. (2021) and Gidden, Brutschin, Ganti et al. (2023, Environmental Research Letters) together provide the IIASA framework for assessing feasibility of mitigation pathways under institutional constraints. Bertram, Brutschin, van Ruijven et al. (2024, Nature Climate Change) showed that institutional and political constraints are as binding as technological availability. These underpin the AR6 feasibility assessment.

Publications & links:

- [Brutschin et al. \(2021\) — Feasibility framework](#)
- [Gidden, Brutschin, Ganti, Riahi et al. \(2023\) ERL — Fairness and feasibility with novel CDR](#)
- [Bertram et al. \(2024\) Nature Climate Change — Feasibility under institutional constraints](#)

Achieving Net Zero GHG Emissions Is Critical to Limit Climate Tipping Risks [see also C.d]

Möller, Högner, Schleussner, Bien, Kitzmann, Lamboll, Rogelj, Donges, Rockström, and Wunderling (2024, Nature Communications) showed that following current policies commits to a 45% tipping risk by 2300, even if temperatures are later returned below 1.5°C. Every 0.1°C of overshoot above 1.5°C increases tipping risk, with strong acceleration above 2°C.

Publications & links:

- [Möller, Högner, Schleussner et al. \(2024\) Nature Communications — Net zero and tipping risks](#)

Implications of Overshoot for Climate Mitigation Strategies

Tavoni, Bauer, Fujimori, Riahi, Rogelj, van Vuuren et al. (2026, Nature Climate Change) build on Riahi et al. 2021, examining how overshoot raises stranded asset risks, requires substantially more CDR, and worsens equity outcomes — with deep implications for near-term policy.

Publications & links:

- [Tavoni, Fujimori, Riahi, Rogelj et al. \(2026\) Nature Climate Change — Implications of overshoot](#)

Net-Zero Emissions While Advancing SDGs: Evidence from China

Zhang, Chen, Krey, Byers, Rafaj, Riahi et al. (2024, Nature Sustainability) showed that China's net-zero target can be achieved while advancing multiple SDGs — including air quality, energy access, and health — but this requires co-benefit-designed pathways, not just emission minimisation.

Publications & links:

- [Zhang, Krey, Byers, Riahi et al. \(2024\) Nature Sustainability](#)

D.d Modelling of sustainable development in mitigation pathways and consideration of equity and justice in these

IIASA has led a sustained effort to bring equity, justice, and decent living standards into the core of integrated assessment modelling. This includes near-term mitigation benchmarks (UNEP Emissions Gap Reports, SCI) as well as the Pelz carbon debt framework, JustMIP, and the Grubler et al. demand scenarios.

A Low Energy Demand Scenario for 1.5°C Without Large-Scale BECCS

Grubler, Wilson, Boza-Kiss, Krey, Riahi et al. (2018, Nature Energy) showed that transformative demand-side changes in mobility, buildings, food, and industry could enable 1.5°C without large-scale BECCS — challenging dominant assumptions about CDR dependence and widening the mitigation solution space. Prominently assessed in IPCC SR15 and AR6 WGIII.

Publications & links:

- [Grubler et al. \(2018\) Nature Energy — LED scenario](#)

High-with-Low Scenario Family and EDITS Demand-Side Research

Wilson et al. (2023) developed the High-with-Low scenario family showing that high human development can be achieved at low energy and material throughput through systemic demand-side transformations. Mastrucci et al. (Avoid-Shift-Improve framework for buildings) quantified the ≈60% buildings mitigation potential through demand-side measures, addressing a gap flagged in IPCC AR6. Kikstra et al. (2021, COVID-recovery demand scenarios) provide the pandemic recovery demand context.

Publications & links:

- [Wilson et al. \(2023\): High-with-Low narrative extending the Low Energy Demand \(LED\) scenario / EDITS scenario family](#)
- [Sugiyama et al. \(2024\): Commentary highlighting the importance of High-with-Low narrative](#)
- [Mastrucci et al. \(2025\) — Avoid-Shift-Improve buildings mitigation potential](#)
- [Kikstra et al. \(2021\) — COVID-recovery demand scenarios](#)

Digitalisation and AI Impacts on Energy Transitions and Climate Targets (DIGSY)

Wilson et al. (2026) produced the first global IAM quantification of digitalisation and AI impacts on energy transitions and climate targets — directly addressing a gap explicitly flagged by the IPCC. The DIGSY paper shows how digitalisation and AI reshape energy demand, efficiency, and sectoral emission trajectories, with material implications for 1.5°C pathways.

Publications & links:

- [Wilson, Krey, Maczek et al. \(2026\) — Digitalisation and AI impacts on energy transitions. Research Square preprint DOI 10.21203/rs.3.rs-8941019/v1](#)

Material Transitions, Circular Economy, and Industry Decarbonisation

Materials account for approximately 25% of global GHG emissions and represent a core IIASA frontier. MESSAGEix-Materials (Unlu et al. 2024) integrates steel, cement, and aluminium production into the global IAM framework. Pedneault et al. (2021) addressed heavy industry decarbonisation. Zhang et al. (2022) quantified buildings material demand in China. The IIASA-led CircEUlar project (Horizon Europe) links end-use services to material flows and circular economy strategies across the EU.

Publications & links:

- [Unlu et al. \(2024\) — MESSAGEix-Materials: steel, cement, aluminium integration](#)
- [Pedneault et al. \(2021\) — Heavy industry decarbonisation](#)

- [Zhang et al. \(2022\) — China buildings material demand](#)
- [CircEUlar \(IIASA-led Horizon Europe\) — circular economy and end-use material flows](#)

Carbon Debt and Credit Framework — Tracking Fair Shares and Overshoot Responsibilities

Pelz et al. (2025, PNAS) introduced net-zero carbon debt, a forward-looking measure of how far a region will breach its fair share of the 1.5°C carbon budget by the time it reaches net-zero CO₂. Unlike traditional fair-share approaches, the framework remains operative after the global budget is exhausted. Applied to the IPCC AR6 ensemble under equal cumulative per capita allocation, persistent regional groupings emerge: always-debtor, later-debtor and never-debtors. Paired with lifetime heatwave exposure by birth cohort, the analysis exposes a compounding intergenerational inequity in early-debtor regions. Together with the JustMIP intercomparison (co-developed at IIASA) and the accompanying Carbon Debt Tool, this provides a quantitative foundation informing overshoot responsibility management and guiding equitable cooperation towards meeting ambitious climate goals.

Publications & links:

- [Pelz et al. \(2025\)](#), Using net-zero carbon debt to track climate overshoot responsibility. PNAS. <https://doi.org/10.1073/pnas.2409316122>
- Carbon Debt Tool: <https://data.ece.iiasa.ac.at/carbondebt/>
- [Companion fair-share tool: https://github.com/setupelz/fair-shares](#)
-

High-Income Groups Drive Regional Climate Extremes — Empirical Complement to Carbon Debt [see also A.g]

Schöngart, Nicholls, Hoffmann et al. (2025, Nature Climate Change) quantified how GHG emissions attributable to the wealthiest population groups (1990–2020) translate into regional climate extremes using an emulator-based attribution framework. This provides the empirical, physical-science complement to the Pelz carbon debt framework.

Publications & links:

- [Schöngart, Nicholls, Hoffmann et al. \(2025\) Nature Climate Change — High-income groups and climate extremes](#)

Justice Considerations in Climate Research and JustMIP

Zimm, Mintz-Woo, Brutschin, Kikstra, Pachauri, Riahi, Schinko et al. (2024, Nature Climate Change) proposed a comprehensive philosophical framework for incorporating distributional, procedural, corrective, recognitional, and transitional justice into climate mitigation scenarios — and called for a Justice Model Intercomparison Project (JustMIP) to operationalise this for IPCC AR7. Mintz-Woo, Zimm et al (2024) highlighted the need for broader communities for justice discussions. Scheifinger et al (2026) provided an assessment of distributional patterns in global climate change mitigation scenarios.

Publications & links:

- [Zimm, Mintz-Woo, Kikstra, Riahi et al. \(2024\) Nature Climate Change — Justice considerations](#)
- [Mintz-Woo, K. , Zimm, C. , Brutschin, E. , \(2024\). Nature Climate Change - \[Climate justice discussions need new participants and new audiences.\]\(#\)](#)
- [Scheifinger, K. , Brutschin, E. , et al, \(2026\). npj Climate Action - \[Exploring patterns of distributional justice in global climate change mitigation scenarios.\]\(#\)](#)

Decent Living Standards and Their Integration into Climate Scenarios

The Decent Living Standards (DLS) framework (Rao & Min, 2017) defined a measurable set of material prerequisites for human wellbeing, providing a quantitative basis for linking multi-dimensional poverty and justice concerns to IAM scenarios. A series of empirical assessments followed — on reducing inequality and climate outcomes (Rao & Min, 2018), climate-compatible diets in India (Rao, Min et al., 2018), decent mobility (Arnz. et al. 2025), energy floors for decent living in India, Brazil and South Africa (Rao, Min & Mastrucci, 2019), assessing Global South decent living futures with low environmental impact (Chatterjee et al. 2024 and Mastrucci et al. 2026), and a global scaling of decent living gaps and energy needs (Kikstra, Mastrucci, Min et al., 2021). This led to the development of normative income and inequality pathways for poverty eradication, enabling the latest contribution: the DESIRE framework (Kikstra, Daioglou, Min et al., 2025), which integrates DLS into global low-carbon scenarios.

Publications & links:

- [Rao & Min \(2017\)](#) — Decent Living Standards concept
- [Rao & Min \(2018\)](#) — Inequality and climate outcomes
- [Rao, Min et al. \(2018\)](#) — Healthy, affordable and climate-friendly diets in India
- [Rao, Min & Mastrucci \(2019\)](#) — Energy requirements for decent living
- [Kikstra, Mastrucci, Min et al. \(2021\)](#) — Global decent living gaps and energy requirements
- [Min et al. \(2024\)](#) — Normative income and inequality pathways
- [Arnz et al. \(2025\)](#) — Quantifying Minimum Mobility and Transport Needs
- Chatterjee, Mastrucci et al. (2024) — Balancing the energy transition in the Global South
- [Mastrucci et al. \(2026\)](#) — High wellbeing in India with low energy consumption
- [Kikstra, Daioglou, Min et al. \(2025\) — DESIRE framework](#)

Advancing Representations of Equity and Justice in Climate Mitigation Futures

Pachauri, Brutschin, Gidden, Kikstra, Rao, Rogelj, Riahi et al. (2026, PLOS Climate) synthesise how equity and justice can be embedded in integrated assessment modelling, including poverty alleviation, distributional outcomes within countries, and the political credibility of mitigation pathways.

Publications & links:

- [Pachauri, Brutschin, Rogelj, Riahi et al. \(2026\) PLOS Climate — Equity in mitigation futures](#)

UNEP Emissions Gap Reports — NDC Gap Assessment [see also A.a]

IIASA researchers contribute as lead authors to the annual UNEP Emissions Gap Reports, providing near-term GHG projections (GAINS model) and scenario-based assessment of the gap between current NDCs and Paris-consistent trajectories.

Publications & links:

- [UNEP Emissions Gap Reports \(IIASA contributions\)](#)

European Advisory Board on Climate Change (EUABCC) — EU 2040 Target Advice

IIASA researchers provided substantial input to the EUABCC's scientific advice on the EU 2040 climate target, recommending a 90–95% net GHG reduction.

Publications & links:

- [Pelz, S., Rogelj, J., Riahi, K., 2023. Evaluating equity in European climate change mitigation pathways for the European Scientific Advisory Board on Climate Change. International Institute for Applied Systems Analysis, Laxenburg. <https://pure.iiasa.ac.at/18830>](#)

- [Byers, E., Brutschin, E., Sferra, F., Luderer, G., Huppmann, D., Kikstra, J., Pietzcker, R., Rodrigues, R., & Riahi, K., 2023. Scenarios processing, vetting and feasibility assessment for the European Scientific Advisory Board on Climate Change. International Institute for Applied Systems Analysis, Laxenburg](#)

Entry Points Framework and fair-shares - Operationalising Equity in National Mitigation Contributions

Pelz et al. (2025, ERL) introduce a practical framework of 'entry points' structuring quantitative 'fair share' assertions in nationally determined contributions under the Paris Agreement - five sequential decisions (foundational principles, allocation quantity, allocation approach, indicators, implications for others) that make value judgements transparent and replicable. Applied to the EU27, both equal cumulative per capita and capability-adjusted allocations of a 1.5°C carbon budget yield negative remaining allocations as of 2023 (–35.7 and –86.1 GtCO₂-FFI), underscoring that many developed regions have already exceeded plausible fair shares. To make the framework directly usable, Pelz et al. developed fair-shares - an open-source Python package (BSD-3-Clause) implementing allocation approaches available in the literature across egalitarian, capability-based, and responsibility-based traditions, for both country-level and IAMC regional workflows. **Publications & links:**

- Pelz et al. (2025), Entry points for assessing 'fair shares' in national mitigation contributions. Environmental Research Letters 20, 024012. <https://doi.org/10.1088/1748-9326/ada45f>
- fair-shares codebase/tool - <https://github.com/setupelz/fair-shares>

D.e Implications of different emission metric choices towards climate change policies

Present-Day Methane Shortwave Absorption and Its Policy Implications

Allen, Smith (IIASA) et al. (2024, Atmospheric Chemistry and Physics) demonstrated that methane's shortwave absorption mutes surface warming — a finding with direct implications for how methane is treated in emission metric frameworks and how GWP-based accounting may under- or over-estimate methane's near-term climate forcing.

Publications & links:

- [Allen, Smith et al. \(2024\) ACP — Methane shortwave absorption](#)

D.f Science-based GHG reporting methodologies used, inter alia, for carbon accounting frameworks

GAINS and GLOBIOM: Science-Based GHG Reporting Infrastructure

IIASA's GAINS model provides science-based, bottom-up emission factors and projections adopted in IPCC AR5 and AR6 emission databases and by national inventory teams. GLOBIOM-G4M provides AFOLU emission estimates used in IPCC SRCCL and EU bioenergy policy assessments. Open-source MESSAGEix (Fricko et al. 2023, Kishimoto et al. 2024) and pyam (tens of thousands of installations) support transparent, reproducible GHG reporting and scenario analysis — directly addressing the Convention's open-science and transparency requirements.

Publications & links:

- [GAINS model](#)
- [GLOBIOM model](#)
- [MESSAGEix \(open source\)](#) — [Fricko et al. 2023](#), [Kishimoto et al. 2024](#)

E. Cross Cutting

IIASA's cross-cutting research integrates insights from across its research portfolio to illuminate synergies and trade-offs across the climate, nature, and sustainable development agenda. Section E.c below carries the full capacity-building and Convention-support story explicitly requested by the RSO, including national modelling partnerships named by institution, open-source tool deployment, and direct policy advisory work.

E.a Synergies and trade-offs between mitigation, adaptation and Sustainable Development Goals and the consideration of equity

Synergies and Trade-Offs Across Multiple SDG and Climate Pathways

Soergel, Rauner, Daioglou, Mastrucci, Kikstra, van Ruijven et al. (2024, Environmental Research Letters) conducted a systematic multi-model analysis identifying win-win opportunities (air quality, health, energy access) and genuine trade-offs (food security, land use) between climate targets and SDGs. IIASA's ENGAGE project quantifies these co-benefits and avoided damages by sector and region.

Publications & links:

- [Soergel, Mastrucci, van Ruijven et al. \(2024\) ERL](#)
- [ENGAGE project \(IIASA-coordinated\)](#)

Translating Earth System Boundaries for Cities and Businesses

Bai, Nakicenovic et al. (2024, Nature Sustainability) provided the first systematic translation of planetary boundaries into actionable frameworks for cities and businesses — bridging global biophysical science and sub-national implementation scales.

Publications & links:

- [Bai, Nakicenovic et al. \(2024\) Nature Sustainability](#)

Drivers and Attitudes of Public Support for Technological Climate Solutions

Brutschin, Baum, Riahi et al. (2024, Nature Communications) showed that across 30 countries, political ideology and trust in government are stronger predictors of support for CDR, geoengineering, and nuclear than risk perception.

Publications & links:

- [Brutschin, Baum, Riahi et al. \(2024\) Nature Communications](#)

Inequities in Contribution to and Health Impacts of Air Pollution and SLCF

Rao, Keiswetter, Min et al. (2021, Nature Sustainability) quantified consumption-based PM2.5 contributions from, as well as the mortality burden suffered by, urban and rural households India. They showed that impacts were distributed differently from contributions, with indirect mortality risks falling disproportionately on lower-income households, who also faced higher risks of premature deaths due to much higher indoor air pollution.

Publications & links:

- [Rao, Keiswetter, Min et al. \(2021\) Nature Sustainability](#)

E.b Contribution of Indigenous and traditional knowledge towards understanding climate change and its consequences

IIASA's research on adaptive capacity, governance, and subnational vulnerability (Andrijevic et al. 2020, 2023; Hoffmann et al. 2025) provides methodological frameworks that can incorporate traditional and local knowledge in climate vulnerability assessments. IIASA engages with the UNFCCC Nairobi Work Programme, which addresses this topic.

E.c Other research activities relevant for and aimed at supporting work under the Convention and Paris Agreement such as the Nairobi Work Programme

IIASA's engagement with the Convention and Paris Agreement extends across scenario infrastructure, capacity building, direct policy advisory work, and participation in UNFCCC processes. Key activities are listed below.

National Modelling Partnerships — Embedded Capacity Building

IIASA maintains direct technical partnerships for national IAM development, enabling countries to produce their own scenario-based tools for NDC implementation, adaptation planning, and UNFCCC reporting. Documented partnerships and collaborations include: India (NITI Aayog, with CEEW as a co-convenor of the India Energy Modelling Forum), Brazil (COPPE/UFRJ), China (Chinese Academy of Environmental Planning under MEE, developer of the MESSAGEix-CAEP model), Pakistan (GCISC, through GAINS applications, LUMS for MESSAGEix), Israel (Tel Aviv University and the IIASA-affiliated Archimedes Center, in cooperation with the Ministry of Energy), Egypt (ASRT and the Institute of National Planning, through the North Africa Applied Systems Analysis Centre), Lebanon and Uzbekistan (under IIASA's Green Climate Fund Country Programme support for vulnerability assessment and GHG analysis), Canada (University of Victoria's SESIT Group, co-developer of MESSAGEix-Canada), Australia (CSIRO, Australia's National Member Organization), Indonesia (ASEAN Centre for energy), and Sub-Saharan Africa including Zambia (engaged through SSARMO, IIASA's Sub-Saharan Africa Regional Member Organization). This direct, embedded approach — explicitly requested by RSO — distinguishes IIASA's engagement. The YSSP (Young Scientists Summer Program, running annually since 1977 with over 2,600 fellows from more than 90 countries to date) provides the pipeline of early-career researchers who lead these national efforts. In October 2023, IIASA co-organized a week-long water-energy-land nexus workshop with the World Resources Institute in Addis Ababa, bringing together 30 researchers and practitioners from 14 African countries for training that included the MESSAGEix-Nexus framework.

Publications & links:

- [IIASA Young Scientists Summer Program](#)
- [MESSAGEix model \(open source, Fricko et al. 2023, Kishimoto et al. 2024\)](#)

Scenario Compass Initiative — Open Scenario Infrastructure for Convention and Research Communities

IIASA, the IAMC, and the Bezos Earth Fund launched the Scenario Compass — an open, continuously updated platform for browsing, comparing, and analysing climate mitigation scenarios. The Scenario Compass Initiative (SCI) co-led by IIASA provides the annual near-term benchmark between IPCC cycles. Both directly support UNFCCC processes, including the Global Stocktake, NDC development, and RSO.

Publications & links:

- [Scenario Compass](#)

- [IIASA SSP Scenario Explorer](#)

NGFS Climate Scenarios — Supporting Central Banks and Financial Regulators

IIASA provides the climate scenarios underpinning the Network for Greening the Financial System (NGFS) scenario framework — used by 138 central banks and supervisors worldwide for transition risk assessment, stress testing, and climate-related financial disclosure. This is a direct, large-scale UNFCCC-relevant impact of IIASA scenario work on financial system resilience.

Publications & links:

- [NGFS Climate Scenarios](#)

National and Local-level Scientific and Policy Advice

IIASA regularly provides input and advice to national and local assessments of climate and energy systems, as well as policy development and implementation assistance.

IIASA evaluated Austria's National Energy and Climate Plan ([NECP](#)) for the period 2021-2030 and proposed measures to address current plan deficiencies and help Austria reach its climate goals. Two out of four co-chairs of the Second Austrian Assessment Report (AAR2) came from IIASA, as well as large share of the authors. The AAR2 is scientific analysis of climate change impacts, risks, and mitigation pathways in Austria, designed to support evidence-based policy for climate neutrality. Furthermore, scientific advice is given at different levels, e.g. to the Vienna Climate Law, as well as to the European Climate Law via the European Scientific Advisory Board on Climate Change (Edenhofer et al. 2025). The NetZero2040 scenarios were developed to evidence the pathways to reach climate neutrality by 2040 in Austria.

Publications & links:

- [Second Austrian Assessment Report on Climate Change | AAR2](#)
- [Edenhofer, O. et al. \(2025\)](#) – Scientific advice for amending the European Climate Law
- [Schmidt et al. \(2025\)](#) - Co-created Austrian net-zero scenarios

Open-Source Science Infrastructure — MESSAGEix and pyam

IIASA's commitment to open science is embodied in MESSAGEix (Fricko et al. 2023, Kishimoto et al. 2024 — fully open-source integrated assessment modelling platform) and pyam (open-source scenario data analysis tool with tens of thousands of installations). Both tools support reproducible, transparent GHG reporting and scenario analysis — directly addressing the Convention's open-science and transparency requirements. pyam has become the de facto standard for IPCC scenario data processing.

Publications & links:

- [MESSAGEix \(open source\)](#)
- [pyam \(open source\)](#)

International Livestock Research Institute (ILRI), Alliance of Bioversity and CIAT -CGIAR centers- submission to the request for input and mapping of responses to research needs (SBSTA/RSO)

1) Index-Based Livestock Insurance (IBLI)

Timeline: 2010–present
Geographic scope: Kenya and Ethiopia

The Index-Based Livestock Insurance (IBLI) research programme led by ILRI has developed and tested an insurance approach to help pastoral and agro-pastoral households manage drought-related livestock losses in arid and semi-arid lands. The research agenda combined fieldwork, stakeholder consultation, product design, testing and learning on the effectiveness of index-based livestock insurance as a tool for managing climate-related risks. Insurance payouts are linked to remotely sensed vegetation conditions, allowing support to be triggered when forage scarcity indicates drought-related stress. The programme has informed the design and scaling of insurance products and contributed to broader public and private investment in drought risk management in the drylands of the Horn of Africa. This work responds particularly to research needs related to extreme events, early warning and climate services, adaptation effectiveness, and reducing climate-related losses and damages in vulnerable systems.

Cooperative efforts and capacity strengthening:
IBLI has been implemented through long-term collaboration with government partners, insurers, universities and development institutions, including partners in Kenya and Ethiopia, helping strengthen national and regional capacity to use climate-risk information and risk-financing tools for pastoral systems.

<https://ibli.ilri.org/>

2) KAZNET: crowd-sourced information for drylands decision-making

Timeline: 2017–present
Geographic scope: Northern Kenya, with broader relevance for drylands in the Horn of Africa

KAZNET is an ILRI-linked crowdsourcing and decision-support research effort designed to improve monitoring of climate and non-climate shocks in remote dryland areas. It uses near-real-time, community-linked data collection to monitor multidimensional indicators of shocks and resilience, including livestock markets, forage conditions, and household food and nutrition security. The platform supports resilience programming, targeted intervention, early warning and early action, while also improving the timeliness and flexibility of data collection in hard-to-reach settings. This work is especially relevant to research needs on the evolution

and dynamics of extreme events, early warning systems and climate services, and on understanding complex and cascading risks in vulnerable dryland systems.

Cooperative efforts and capacity strengthening:

KAZNET has been developed with academic, technical and development partners and is designed to support communities and national stakeholders with real-time information for decision-making and resilience programming. Its model also contributes to institutional learning on how local monitoring systems can strengthen early warning and response in developing-country contexts.

<https://www.ilri.org/knowledge/publications/kaznet-open-source-micro-tasking-platform-remote-locations>

3) Assessing Agroecological Practices as Non-Market Approaches for Climate Action: A Synthesis of Evidence from the Andes

Description: This project evaluates how agroecological practices can serve as non-market approaches (NMAs) under Article 6.8 of the Paris Agreement. It tests the assumption — drawn from a UNFCCC report — that agroecology facilitates NMAs, by examining agroecological projects in the Andes. The research assesses projects against the UNFCCC checklist for NMA Platform registration, covering mitigation and adaptation co-benefits, sustainable development contributions, technology transfer, gender and human rights, and NDC alignment. The primary output is a peer-reviewed manuscript synthesizing evidence from Andean agroecological projects. Findings will feed into UNFCCC submissions and policy briefs for national focal points.

Timeline: 2024–2027

Geographic scope: Regional — the Andes (Bolivia, Ecuador, Peru)

Relevant links: <https://alliancebioiversityciat.org/projects/agroecological-practices-non-market-approaches-climate-action-andes>

Cooperative efforts and capacity strengthening: Partnership with the International Potato Center (CIP) and Universidad Mayor de San Andrés (UMSA), Bolivia; capacity-building support for developing country NMA proponents; project document reviewed by the UNFCCC Secretariat, whose feedback directly informed the research design, specifically the addition of a guiding question on how agroecological projects contribute to implementing host Parties' NDCs, in line with decision 4/CMA.3; co-organization of official UNFCCC side events with observer organizations to raise awareness on agroecology as a viable NMA pathway and communicate project progress to a policy audience. Needs addressed are: synergies and trade-offs between mitigation, adaptation and the SDGs (2023).

4) Adaptation Insights Project

Timeline: 3 April 2024–31 December 2026
Geographic scope: Africa, with broader global relevance

Adaptation Insights is a CGIAR science group project led by the Alliance of Bioversity International and CIAT, with ILRI and IWMI as implementation partners, designed to advance access to and use of data and methods for adaptation measurement. The project responds directly to a major research gap: the lack of robust, usable metrics, methods and data for tracking adaptation progress and effectiveness. It develops adaptation tracking frameworks, datasets and analytical tools, while engaging stakeholders to ensure that products respond to policy and investment needs. The project has been framed around improving the production, accessibility and application of adaptation-related data, with particular emphasis on Africa. This is a very strong fit with RSO needs related to assessing adaptation progress, understanding the effects of adaptation actions on reducing risks, and strengthening the evidence base for climate resilience planning and implementation.

Cooperative efforts and capacity strengthening: Adaptation Insights is funded by the Gates Foundation and implemented in close collaboration among the Alliance, ILRI and IWMI. Its design explicitly relies on stakeholder engagement and partnerships to improve uptake, and it has built linkages with initiatives and actors working on adaptation tracking, investment planning and climate resilience in Africa.

<https://alliancebioversityciat.org/projects/adaptation-insights>

5) The Livestock and Climate Solutions Hub

Timeline: January 2025 – December 2027
Geographic scope: Low- and middle-income countries (LMICs), with a particular focus on supporting country transitions in livestock systems through collaboration with local and regional actors.

The Livestock and Climate Solutions Hub is an ILRI-led platform designed to support countries in transitioning toward more sustainable, low-emission and climate-resilient livestock systems. It brings together research, innovation and partnerships to accelerate practical solutions to the linked challenges of climate change and livestock production. Its focus includes scaling climate-smart livestock innovations, enhancing resilience and productivity across livestock systems, reducing greenhouse gas emissions while supporting smallholder and pastoralist livelihoods, and helping countries integrate livestock into climate action under the Paris Agreement.

Cooperative efforts and capacity strengthening: The Hub operates through collaboration with CGIAR centers, universities, innovation actors, private sector partners and local and regional institutions in LMICs. It emphasizes co-development and scaling of solutions, policy

support for integrating livestock into climate action plans, and capacity building to strengthen institutions and enable transformative change.

<https://www.ilri.org/research/projects/livestock-and-climate-solutions-hub>

6) Science-based GHG reporting methodologies for livestock systems

Timeline: 2022–present

Geographic scope: Sub-Saharan Africa, with specific empirical work highlighted in Ethiopia and Kenya

This research stream, led through ILRI’s Mazingira Centre and partners, contributes to the development of more robust and context-specific greenhouse gas reporting methodologies for livestock systems. The 2022 review found that research progress in sub-Saharan Africa still falls short of national inventory ambitions and highlighted the need for country-specific Tier 2 emission factors, activity data and soil carbon information to improve inventories. Subsequent work has generated more locally grounded evidence. In Ethiopia, Mazingira-supported research compared IPCC and CSIRO Tier 2 methodologies to establish a baseline for GHG emissions in smallholder systems and showed the importance of validating emission estimates with local data. In Kenya, Mazingira research showed that default Tier 1 values can over- or under-estimate methane emissions depending on production system, and that breed, body weight, feed quality and animal mobility materially affect emissions. Together, this work responds directly to the RSO category on science-based GHG reporting methodologies used, inter alia, for carbon accounting frameworks, while also contributing to improved estimates of emissions by source.

Cooperative efforts and capacity strengthening: The broader research ecosystem around this work is collaborative and explicitly capacity-oriented. The 2022 review identifies Mazingira Centre as a hub for scientific research, capacity building and research infrastructure on livestock-environment interactions in sub-Saharan Africa, especially East Africa. The Ethiopia work was supported through the GIZ/BMZ-funded Programme for Climate-smart Livestock Systems (PCSL), with the intention that findings from representative Ethiopian systems could inform work across East Africa. More broadly, the research supports countries’ efforts to improve national inventories by generating locally relevant evidence and methodologies that can strengthen technical capacity for GHG estimation and climate planning.

<https://www.ilri.org/news/why-livestock-emission-estimates-might-vary-tier-2-model-effect>;
<https://www.frontiersin.org/journals/soil-science/articles/10.3389/fsoil.2022.927452/full>;
<https://www.ilri.org/news/why-kenyan-rangeland-cattle-need-new-methane-emission-factors>

7) Transboundary and cascading climate risks in Africa

Timeline: 2021–2025

Geographic scope: Regional / multi-country (Africa), with particular relevance for African Least Developed Countries (LDCs) and regional cooperation mechanisms.

This collaborative research stream examines how climate impacts, and responses to them, can generate risks that cascade across borders, sectors and systems. The 2021 report documents how African policymakers and experts perceive transboundary climate and adaptation risks (TCARs), including their pathways through biophysical systems, finance, trade, people-centred mobility and geopolitics. The 2023 roadmap then translates this evidence into proposed actions for enhancing African coordination on transboundary and cascading climate risks under the African Union Climate Change and Resilient Development Strategy and Action Plan (2022–2032). The 2025 brief further connects this agenda to the UNFCCC context, synthesising opportunities for the LDC Group to strengthen awareness, assessment and management of cross-border and cascading climate risks within adaptation planning and related negotiation processes. This work aligns strongly with RSO needs on complex, cascading and transboundary risks, as well as cross-cutting research supporting implementation under the Convention and the Paris Agreement.

Cooperative efforts and capacity strengthening: This work has been undertaken through extensive partnership and dialogue. The 2023 roadmap was developed through a multi-stakeholder policy dialogue in Nairobi involving 30 representatives from organizations working on transboundary climate risks in Africa, including Regional Economic Communities. The 2025 brief explicitly describes ongoing dialogue between Adaptation Without Borders (AWB) and the LDC Group, and notes engagement by AWB partners including ODI Global, Stockholm Environment Institute (SEI), Enda Energie, ILRI and AGNES, with negotiators and policymakers, including workshops and discussions aimed at strengthening awareness, networks and capacity to assess and manage TCARs within national adaptation planning and regional cooperation.

<https://www.preventionweb.net/media/89756/download>;

<https://cgspace.cgiar.org/bitstreams/ad5295b8-39be-4c1b-a19d-2d5bb7d8193f/download>;

<https://www.sparc-knowledge.org/publications-resources/transboundary-climate-and-adaptation-risks-africa-perceptions-2021>

8) High resolution downscaled climate data portal

Timeline: 2009–present

Geographic scope: Global

The CCAFS-Climate data portal provides users with robust, high-resolution climate data that can help assess the impacts of climate change on agriculture. The portal offers researchers worldwide easy access to climate information formatted for use in agro-climatology, crop and

livestock modeling, and ecology, aiming to increase understanding of climate change effects on the environment. These data are also useful for policymakers, NGOs and investors, as they can help them understand local climate change impacts and therefore make better decisions regarding adaptation measures at watershed, region, municipality and country levels.

Since its creation, the portal has been visited more than 230,000 times and more than 1.4 million file downloads have been made. Some 4745 institutions from 180 countries have used the portal for a range of purposes. The number of refereed publications using CCAFS-Climate data currently stands at over 700, including 40 book chapters, 100 reports and about 570 peer-reviewed articles. In a previous single year, 203,802 files were downloaded from CCAFS-Climate, containing downscaled Global Circulation Model data. The 17,252 total visits led to 59.72 TB of data downloads.

Cooperative efforts and capacity strengthening:

The portal and the datasets hosted on the platform are provided by the International Center for Tropical Agriculture (CIAT), with support from a range of partners including international research institutes such as the International Livestock Research Institute (ILRI) and the International Food Policy Research Institute (IFPRI); academic institutions such as the University of Washington, the University of Southern Mississippi, and Santa Clara University; research organizations such as the Potsdam Institute for Climate Impact Research and Climate Central; as well as development and conservation organizations including HarvestChoice, The Nature Conservancy (TNC), and the World Bank.

<https://ccafs-climate.org/>

<https://doi.org/10.1038/s41597-019-0343-8>

<https://cgspace.cgiar.org/bitstream/handle/10568/35692/Climate%20Portal.pdf>

9) Future scenarios

Timeline: 2010–present

Geographic scope: Global (with strong regional applications in Africa, Latin America and Asia)

The Future Scenarios methodology, developed by the University of Oxford and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), supports decision-making under uncertainty by integrating climate change with broader socio-economic and political drivers. By combining multiple dimensions of change—such as population growth, governance systems, and economic development—the methodology enables policymakers, researchers, and stakeholders to explore diverse and plausible future pathways for agriculture and food systems.

Through a participatory and interdisciplinary approach, the methodology brings together policymakers, private sector actors, researchers, and civil society to co-create narratives of possible futures that are grounded in local and regional contexts. These qualitative storylines are then complemented with quantitative modeling using global and regional agricultural models, allowing users to assess potential impacts on food security, water resources, livelihoods, and resilience.

The scenarios process is iterative and action-oriented. Using techniques such as backcasting, participants work from desirable future outcomes to identify present-day actions and “no-regrets” options that remain robust across a wide range of uncertainties. This approach has been widely applied to support national climate strategies, including Nationally Determined Contributions (NDCs), and long-term planning processes.

Since its development, the methodology has been implemented in multiple regions, supporting governments and institutions in strengthening their capacity to anticipate and plan for future challenges. It has contributed to scenario-building exercises, policy dialogues, and capacity development processes, helping stakeholders better understand trade-offs and synergies across climate, development, and food system goals.

Cooperative efforts and capacity strengthening:

The Future Scenarios methodology has been implemented through collaborations between CCAFS, the University of Oxford, and a wide network of partners including national governments, academic institutions, and international organizations. In countries such as Costa Rica, local experts and government representatives have been trained to facilitate participatory scenario-building processes, strengthening institutional capacities to conduct forward-looking analyses and support iterative policy design.

Partnerships with organizations such as the University of Costa Rica (UCR), RAND Corporation, and the Inter-American Development Bank (IDB) have further strengthened the approach by integrating open-access models capable of running thousands of scenarios across climate, energy, land, and water systems. These tools allow stakeholders to complement qualitative narratives with robust quantitative evidence, improving understanding of the potential benefits and trade-offs of different policy choices in terms of public health, economic development, climate resilience, and mitigation.

<https://ccafs.cgiar.org/news/costa-rica-increases-climate-ambition-collectively-imagining-futures>

<https://hdl.handle.net/10568/121244>

<https://hdl.handle.net/10568/69238>

CSA Prioritization Framework

Timeline: 2014–present

Geographic scope: Global (with strong applications in Latin America, Africa, and Asia)

The CCAFS–CIAT Climate-Smart Agriculture Prioritization Framework (CSA-PF) is a participatory, multi-criteria decision-making methodology designed to support evidence-based investments in climate-smart agriculture (CSA). The framework helps decision-makers identify context-specific portfolios of CSA practices and technologies that enhance food and nutrition security, strengthen farmers' resilience and adaptive capacity, and, where possible, reduce greenhouse gas (GHG) emissions.

Through a structured and iterative process, the framework evaluates existing and promising CSA options by analyzing trade-offs and synergies across the three CSA pillars—productivity, adaptation, and mitigation. It integrates technical, economic, environmental, and socio-institutional dimensions to support balanced and informed decision-making.

The methodology is implemented in four main phases: (1) an initial assessment to identify and evaluate a broad range of CSA practices; (2) the prioritization of the most promising options through stakeholder engagement and indicator-based analysis; (3) the calculation of costs and benefits, including cost-effectiveness and synergies among practices; and (4) the identification of adoption barriers and enabling conditions to co-develop investment portfolios.

The resulting CSA investment portfolios are tailored to specific national or subnational contexts and aim to maximize returns on investment, minimize risks, and align with stakeholder priorities. These portfolios support strategic planning by helping decision-makers explore synergies, avoid trade-offs, and design integrated interventions across agricultural systems.

Since its development, the CSA-PF has been applied in multiple countries to inform national and subnational planning processes, including climate strategies and investment plans. It has supported stakeholders in identifying high-impact interventions and improving the allocation of resources toward resilient and sustainable agricultural systems.

Cooperative efforts and capacity strengthening:

The CSA Prioritization Framework has been co-developed and implemented by CIAT and CCAFS in collaboration with a wide range of partners, including national governments, research institutions, universities, and development organizations. Its participatory nature ensures strong stakeholder engagement, bringing together policymakers, technical experts, farmers' organizations, and the private sector to co-create locally relevant solutions.

Capacity strengthening is a central component of the framework. Through workshops, training sessions, and collaborative processes, stakeholders build skills in multi-criteria analysis, economic evaluation, and scenario-based planning. This enables institutions to independently apply and adapt the methodology in future planning cycles.

<https://hdl.handle.net/10568/68397>

<https://hdl.handle.net/10568/113943>

Agricultural Knowledge and Innovation Systems (AKIS)

Timeline: 2024–present

Geographic scope: National-level implementation in Panamá, Perú, Dominican Republic, Guatemala, and Colombia

The Agricultural Knowledge and Innovation Systems (AKIS) project focuses on strengthening national systems that enable the scaling of agricultural innovations in the context of challenges associated with climate change, including the need to improve resilience, adaptation, and sustainability of agricultural systems. AKIS are understood as networks of actors, organizations, and institutions whose interactions shape knowledge flows and innovation processes in the agricultural sector.

The project is based on a shift from linear models of technology transfer toward a systemic, interactive, and demand-oriented approach. Innovation is understood as a non-linear process that results from interactions among multiple actors, including producers, research institutions, extension services, the private sector, and public entities.

Methodologically, the project analyzes AKIS through four dimensions: (1) the structural dimension, which examines actors, networks, and coordination mechanisms; (2) the functional dimension, which assesses the performance of key innovation functions; (3) the capacity dimension, which analyzes the abilities of actors to collaborate, innovate, and adapt; and (4) the enabling environment, which includes institutional, regulatory, and policy conditions.

The analysis focuses on identifying systemic gaps that affect the performance of AKIS in each country. These gaps are examined across dimensions to identify misalignments between actors, functions, capacities, and the enabling environment.

Based on this analysis, the project defines lines of action that can be operationalized through country-level roadmaps. These lines of action address coordination, knowledge flows, capacities, and institutional conditions associated with innovation processes and their scaling.

The project links AKIS analysis with scaling by focusing on system conditions and the enabling environment that influence the adoption, adaptation, and expansion of innovations, supporting the functioning of AKIS and shaping scaling outcomes at the national level

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International Science Council

Dear Colleagues,

This is a list of climate change research from our members from the year 2025 which we had gathered before COP30, in case useful:

<https://airtable.com/appUOzqT2A8ytLLQX/shrb8vUwGP0aVPbJ4/tb1RGiZWBSYNM3Xcp>

Please let us know if sharing in an excel would be helpful for your purposes.

Climate Attribution and Complex/Cascading Risks

1. Title and Short Summary

A critical synthesis of remote sensing and machine learning approaches for climate hazard impact on crop yield

This study provides a systematic review of remote sensing (RS) and machine learning (ML) approaches used to detect climate hazards and assess their impacts on crop yields across spatial and temporal scales. Using a PRISMA-based methodology, the review analyzes over 350 studies (177 on climate hazards and 197 on RS–ML applications) to identify dominant methods, datasets, and research gaps.

The analysis shows that drought is the most frequently studied climate hazard, followed by broader climate variability and extreme events such as flooding, heat stress, and rainfall extremes. These hazards are examined both individually and as compound events (e.g., drought–heat or drought–flood interactions), which are increasingly recognized as critical drivers of agricultural risk.

In terms of methodology, traditional statistical approaches remain widely used, but ML techniques are increasingly applied. Among these, Random Forest (RF) emerges as the most used algorithm across hazard detection and yield modeling, followed by Support Vector Machines (SVM), Artificial Neural Networks (ANN), and other advanced models such as LSTM and XGBoost.

Remote sensing datasets, including MODIS, CHIRPS, TRMM, and ERA5, play a central role in climate hazard monitoring due to their wide spatial coverage and accessibility, especially in data-scarce regions such as sub-Saharan Africa. However, limitations related to spatial resolution and ground validation affect their ability to capture fine-scale variability.

The study highlights strong regional disparities. Asia leads in the use of advanced ML and deep learning methods, while Africa relies more on simpler, interpretable models due to data and infrastructure constraints. Research is also biased toward major crops such as maize and wheat, with limited attention to underrepresented crops (e.g., cocoa, cassava, and cashew) that are critical for food security in vulnerable regions.

Overall, the review identifies key gaps, including limited sub-national analyses, insufficient validation, and weak integration of compound hazards. It recommends the development of hybrid modeling frameworks, improved data integration, and enhanced monitoring systems to support climate-resilient agriculture and food security.

2. Timeline: 2015–2023, Literature review period (peer-reviewed studies and reports)

3. Geographic Scope

Scale: Global

Coverage: Multi-scale analysis, including Global, Continental, Regional, National, Sub-national, and Agro-ecological levels.

4. Relevant Links: <https://hdl.handle.net/10568/177349>

Title: Projecting Climate Change Impacts through High Resolution Dynamically Downscaled Climate Scenarios for Sri Lanka

Short summary:

Sri Lanka is widely recognized as one of the most climate-vulnerable countries in Asia due to its sensitivity to monsoon variability, extreme rainfall events, and large-scale climate oscillations such as ENSO and the Indian Ocean Dipole (IOD). The island's steep elevation gradients and coastal setting intensify localized climate impacts, contributing to recurring floods, landslides, and seasonal droughts. Sri Lanka's economy depends heavily on climate-sensitive sectors including agriculture, irrigation, hydropower generation, and coastal livelihoods, making it highly vulnerable to projected changes in climate.

Although Global Climate Models (GCMs) serve as the backbone of global climate assessments, their coarse spatial resolution (typically 100–250 km) prevents them from adequately simulating mesoscale climatic features over Sri Lanka, especially when considering that the maximum length and width of the country is approximately 432 Km and 224 km respectively. These include orographic rainfall, land–sea interactions, localized convection, and rapid spatial transitions in wet and dry zones. Such limitations introduce substantial uncertainties when raw GCM outputs are used directly for national planning.

Downscaling of GCM outputs is therefore essential to bridge this knowledge gap. In general, three types of downscaling are currently in use: Statistical downscaling (using mathematical relationships to convert large-scale climate patterns to local-scale variables) and Dynamical downscaling (running high-resolution Regional Climate Models (RCMs) nested within GCMs with GCM outputs supplying boundary conditions). Hybrid downscaling combines elements of both statistical and dynamical downscaling.

Dynamical downscaling refines coarse GCM information into higher-resolution climate fields using physically based models capable of resolving fine-scale atmospheric processes, which is vital generally considered more reliable for small islands with complex terrain. However, a combined statistical-dynamical approach is often recommended to address data limitations and model biases and to integrate the strengths of both methods to achieve better outcomes

This work represents the first long-term, island-wide, dynamically downscaled climate projection dataset developed for Sri Lanka. In this exercise the Weather Research and Forecasting (WRF-ARW) model was forced using outputs from a single CMIP6 GCM, MPI-ESM-HR-2 as boundary conditions. Although using a multi-model ensemble would have been ideal (providing a more complete assessment of uncertainty) outputs from a single GCM was used due to computational and resource constraints. However, using one well-performing GCM provides a scientifically robust starting point for generating credible regional climate information in resource-limited contexts. It is expected that the finer-scale outputs produced by the study will provide a useful data set for applications such as water-resource planning, agriculture, hydropower development, climate-risk mapping, and disaster management in Sri Lanka.

Timeline: May 2022 to May 2025

Geographic Scope: Sri Lanka

Relevant Links: <https://www.iwmi.org/blogs/detailed-climate-projections-bolster-sri-lankas-adaptation-planning/>

Title- Drought Risk and Resilience Assessment (DRRA) in Central Asia: From Climate Risk Evidence to Adaptation Prioritization and Investment Planning

Short summary

IWMI Central Asia, within the scope of the World Bank DRRA project and with support from national/regional partners, is preparing a set of national and regional Drought Risk and Resilience Assessment profiles for Central Asia. The work covers Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and the regional/transboundary drought risk dimensions.

The assessment applies the World Bank DRRA methodology to examine drought risk, institutional readiness, early warning capacities, water and land management vulnerabilities, and priority adaptation measures. The work is structured around four analytical blocks:

1. coordination, institutional readiness, policy and data systems;
2. drought risk and vulnerability assessment;
3. resilience and preparedness assessment; and
4. Prioritization of practical measures for drought resilience.

The research directly addresses several gaps identified by Parties, especially:

- **Adaptation progress and risk reduction**, by assessing how countries are moving from reactive drought response toward proactive preparedness, early warning, and investment-oriented resilience planning;
- **Complex and cascading risks**, by analyzing drought impacts across water, agriculture, livestock, energy, ecosystems, rural livelihoods, food security, and transboundary water allocation;
- **High-resolution regional and national information**, by combining country-level drought profiles with regional/transboundary analysis, including vulnerable basins, drought-prone regions, institutional gaps, and priority measures.

The work is particularly relevant to the Global South and dryland regions because it links climate-risk evidence with policy processes, national drought dialogues, stakeholder validation, and practical adaptation planning. It also highlights the specific vulnerabilities of irrigation-dependent economies, pastoral systems, mountain-fed river basins, downstream water users, and communities exposed to water scarcity, heatwaves, land degradation, and dust-related risks.

Timeline

2025–2026. Country drought profiles and the regional drought profile are under preparation and validation during 2025–2026. National Drought Dialogues are being organized to discuss findings with government institutions, research organizations, development partners, and practitioners. A regional synthesis and final reporting are expected in 2026.

Geographic scope

Regional: Central Asia. National coverage: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan.

Transboundary dimension: Aral Sea Basin and selected shared river-basin contexts, including the Chu–Talas basin and Amu Darya/Syr Darya-related drought and water-scarcity risks.

Relevant links/outputs

- Draft outputs: Country Drought Profiles for Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan; Central Asian Regional Drought Profile. These are currently draft/internal technical products and can be shared subject to clearance.
- Related outputs: National Drought Dialogue materials and country-level prioritization matrices for drought resilience measures.
- Link: <https://www.iwmi.org/blogs/iwmi-introduces-regional-drought-risk-assessment-to-central-asia/>

Evaluating Adaptation Effectiveness in Climate-Vulnerable Contexts: A Multi-Country Analysis of Risk Reduction and Resilience

Al Murunah (2022–2027) and Al Murunah+ (2024–2026) are multi-country research-for-development initiatives implemented in Egypt, Lebanon, Palestine, and Jordan. Together, they address a central adaptation challenge: how to rigorously assess whether adaptation interventions lead to measurable reductions in climate risk and strengthened resilience in water-stressed and conflict-affected contexts. The projects generate empirical evidence on adaptation effectiveness by integrating three core components: (i) high-resolution, locally tailored climate risk information, (ii) a theory-driven monitoring, evaluation, learning, and impact assessment (MELIA) framework, and (iii) analysis of scaling processes and enabling conditions. This integrated approach allows for the systematic examination of adaptation outcomes across household, community, and system levels. A key innovation lies in the development and operational use of downscaled climate projections and spatially explicit hazard–exposure analyses. By embedding these data within planning and assessment processes, the projects examine how improved climate information influences adaptation decision-making and outcomes, addressing persistent gaps in the accessibility and usability of climate data in developing contexts. To assess adaptation effectiveness, the projects apply a theory-based MELIA framework to examine how adaptation interventions influence selected dimensions of climate risk and resilience, adaptive capacity, and livelihood outcomes. MELIA provides a structured approach to tracking and analyzing adaptation processes and results over time, combining quantitative indicators with qualitative insights to understand how and why changes occur, while supporting iterative learning and adaptive project management. Using mixed methods, the approach moves beyond output tracking to evaluate whether interventions alter underlying risk pathways and contribute to sustained resilience. The projects further strengthen the evidence base by incorporating return on investment and value-for-money analysis into adaptation assessment. This enables joint evaluation of effectiveness, efficiency, and equity, including the distributional and gender-transformational impacts of adaptation actions. In parallel, the projects analyze the conditions required for sustained uptake and scaling. This includes examining behavioural drivers, institutional capacity, and market dynamics influencing long-term adoption, drawing on evidence from community-level learning interventions, institutional capability frameworks, and market assessments. Finally, the implementation findings are translated into policy-relevant outputs through structured engagement processes, supporting the integration of robust, locally grounded evidence into national adaptation planning and decision-making. Collectively, these initiatives contribute methodological advances and empirical insights to the global evidence base on adaptation progress and climate risk reduction, directly responding to many of the priority research for development gaps.

- Al Murunah project page: [Al Murunah](#) (All project publications are listed on the outputs page)
- Al Murunah Project Brief (technical overview of RNBWS innovations): <https://almurunah.iwmi.org/wp-content/uploads/sites/52/2025/06/Al-Murunah-Project-Brief-Eng-250602.pdf>
- Al Murunah+ project page (IWMI): <https://almurunah.iwmi.org/al-murunah-plus/>
- Al Murunah+ Fact Sheet (overview of gender-transformative and household-resilience components): [Fact Sheet - AL-MURUNAH+](#)

Assessing Greenhouse Gas Emissions from a Tropical Hydropower Reservoir Using Earth Observation and Cloud-Based Modelling: Insights from Maithon, India

Summary

This study evaluates greenhouse gas (GHG) emissions from a tropical large hydropower reservoir (LHR) using an integrated framework combining Earth Observation (EO) data, cloud computing platforms, and process-based modelling tools. It directly addresses key gaps in GHG accounting, science-based reporting methodologies and mitigation pathways, particularly in the context of rapidly expanding hydropower infrastructure in developing countries. Hydropower is widely considered a clean energy source; however, tropical reservoirs can act as significant GHG sources due to the decomposition of inundated organic matter under warm climatic conditions. The research focuses on the Maithon reservoir in India and applies the G-res tool with Google Earth Engine (GEE) to estimate emissions using biophysical, climatic and hydrological parameters derived from EO datasets.

The study integrates long-term datasets such as CHIRPS precipitation (1990–2023), Sentinel-1 SAR imagery (2017–2023), ESA WorldCover land use, and in-situ reservoir water levels to quantify spatial and temporal variation in water extent and reservoir dynamics. A key methodological advancement is the incorporation of site-specific water-level–water-extent relationships derived from Sentinel-1 using Otsu thresholding, with accuracy up to 0.98 in dry conditions, and a polynomial fit with $R^2 = 0.97$ enabling improved representation of reservoir dynamics in emission calculations.

Results reveal that the Maithon reservoir has transitioned from a pre-impoundment GHG sink ($-132 \text{ gCO}_2\text{e/m}^2\text{/yr}$) to a significant post-impoundment source ($1,871 \text{ gCO}_2\text{e/m}^2\text{/yr}$). Methane (CH_4) emissions dominate the footprint ($\approx 1,373 \text{ gCO}_2\text{e/m}^2\text{/yr}$), primarily via degassing ($970 \text{ gCO}_2\text{e/m}^2\text{/yr}$), while CO_2 contributes $498 \text{ gCO}_2\text{e/m}^2\text{/yr}$. Reservoir operational dynamics strongly influence emissions: near dead-storage levels emissions reach $3,855 \text{ gCO}_2\text{e/m}^2\text{/yr}$ compared to $786 \text{ gCO}_2\text{e/m}^2\text{/yr}$ near full-reservoir levels, indicating that reservoir management is a material lever for mitigation.

From a climate-mitigation perspective, the findings emphasise that optimising operating levels, managing sedimentation, improving turbine design and capturing methane for use as renewable energy can significantly reduce net emissions. Methodologically, combining EO data with cloud-based platforms provides a scalable, cost-effective alternative to resource-intensive field-based measurement. The work strengthens science-based GHG reporting and carbon accounting frameworks for reservoir emissions and supports evidence-based energy and climate policy in developing countries.

Timeline

Long-term datasets 1990–2023. Detailed emission modelling conducted for the 2022–2023 water year.

Geographic Scope

Maithon reservoir, eastern India (Jharkhand–West Bengal). Methodology transferable to other tropical hydropower reservoirs globally.

Relevant Links

- De Sarkar, K., Ghosh, S., Bhattacharyya, S., Chowdhury, A., Holmatov, B. (2025). *Assessing GHG emissions of a tropical large hydropower reservoir using G-res and GEE*. Journal of the Indian Society of Remote Sensing, 53(4), 1053–1064. DOI: <https://doi.org/10.1007/s12524-024-02045-3>.

Adaptation Progress and Risk Reduction

1. Title and Short Summary

Hydroclimatic extremes and food security hotspots in West Africa: evidence from rainfall–yield interactions

Short Summary

This study investigates the association between hydroclimatic extremes and crop yield variability across West Africa to identify food security hotspots under increasing climate variability. It focuses on how changes in rainfall patterns, particularly extreme events and wet–dry spell dynamics, relate to the productivity of major staple crops, including maize, rice, and soybean.

Using multi-decadal datasets (1981–2024) from CHIRPS (precipitation), CHIRTS (temperature), and GDHY (crop yields), the study evaluates a comprehensive set of rainfall extreme indices, including PRCPTOT, SDII, CDD, CWD, and heavy-rainfall thresholds. A combination of correlation and sensitivity analyses (based on Ordinary Least Squares regression) is used to quantify how crop yields respond to climatic variability across agroclimatic zones.

The results reveal strong north–south contrasts in hydroclimatic conditions. The Sahelian and Sudanian zones show increasing rainfall totals and intensified wet events (up to 80% increases locally), while parts of the Guinean zones exhibit stagnating or declining rainfall alongside significant increases in consecutive dry days, indicating rising drought stress.

Crop responses vary spatially and by crop type. Maize yields are generally associated with increases (up to 40–50%) in regions experiencing improved rainfall conditions, whereas rice yields show declines (20–50%) in areas affected by excessive rainfall or poor drainage. Soybeans exhibit localized gains but remain highly sensitive to rainfall deficits and temperature extremes.

Overall, the study identifies climate-sensitive food production hotspots, where both drought and flood-related risks influence agricultural outcomes. It highlights that rainfall variability has both beneficial and adverse associations with crop yields, depending on intensity, timing, and agroclimatic context. The findings emphasize the need for region-specific climate adaptation strategies, including improved water management, supplemental irrigation, flood control in northern zones, and drought resilience in southern regions, to enhance food security under changing climatic conditions.

2. Timeline: 1981–2024

3. Geographic Scope

Scale: Regional /West Africa

Coverage: Six agroclimatic zones:(Northern Sahel, Southern Sahel, Sudanian, Western Guinea, Central Guinea, and Eastern Guinea)

4. Relevant Links

DOI: <https://doi.org/10.3389/fclim.2025.1717323>

Information meets innovation: Climate data for resilient food value chains in CWANA

Short Summary

This work aims to strengthen the resilience of agrifood systems by improving how climate information is accessed and used in practice. In many parts of Central and West Asia and North Africa (CWANA), decision-making is often limited by gaps in reliable climate data, weak infrastructure, and limited technical capacity. At the same time, the region is increasingly exposed to droughts, heatwaves, and changing rainfall patterns, making it more difficult for farmers and institutions to respond effectively.

Under the CGIAR F2R-CWANA initiative, a Satellite-based Climate Data Extractor has been developed to make climate data more accessible and easier to use. The platform brings together satellite observations, climate reanalysis data such as ERA5-Land, and available ground data into a simple interface. It allows users to explore temperature, precipitation, and drought indicators over time and across locations.

The main value of this work lies in turning complex data into practical information. Farmers, researchers, and policymakers can use it to better understand climate trends, plan agricultural activities, and adjust irrigation and crop choices. By supporting more informed decisions, the approach helps reduce climate-related risks and improves the resilience of food value chains. It also offers a practical example of how data and digital tools can support climate adaptation in regions where information is often limited.

Geographic Scope:

Regional (Central and West Asia and North Africa), with applications in Egypt, Lebanon, Morocco, Sudan, and Uzbekistan

Relevant Link: <https://www.iwmi.org/blogs/information-meets-innovation-climate-data-for-resilient-food-value-chains-in-cwana/>

Monitoring Drought Dynamics Using Earth Observation and Digital Twin Technology: Insights from the Limpopo River Basin

Summary

This study presents an integrated Earth Observation (EO) and Digital Twin-based framework to monitor, analyse, and support decision-making for drought conditions in the Limpopo River Basin (LRB), a highly vulnerable transboundary basin in southern Africa. The research directly contributes to advancing drought risk assessment, early warning systems, and climate-resilient water resource management in data-scarce regions.

The Limpopo River Basin spans Botswana, Mozambique, South Africa, and Zimbabwe and is characterized by highly variable rainfall and recurrent drought conditions that significantly affect agriculture and livelihoods. Most areas receive less than 500 mm of rainfall annually, making the basin highly sensitive to climatic variability and extreme events. The study leverages multi-source EO datasets and cloud-based processing platforms such as Google Earth Engine to assess drought dynamics using key indicators including the Standardized Precipitation Index (SPI), Vegetation Condition Index (VCI), and dry-day frequency.

A central innovation of this work is the application of a Digital Twin platform for the Limpopo River Basin, which integrates near real-time datasets including rainfall (CHIRPS), satellite-derived vegetation indices (MODIS NDVI), hydrological simulations (SWAT), and land-use data to create a dynamic, interactive representation of basin conditions. The platform enables visualization of river flows, rainfall anomalies, and hydrological changes, supporting scenario analysis and improved resource planning. A comparative assessment of dry-day patterns across 2022 (La Niña), 2023 (transition), and 2024 (El Niño) reveals a clear intensification of dry conditions, with increased dry-day frequency observed particularly in Mozambique and Zimbabwe during the El Niño phase.

SPI-based analysis indicates prolonged precipitation deficits during 2024, corroborated by VCI analysis showing declining vegetation health across key agricultural regions. Approximately 37% of the basin experienced drought conditions during the 2023–2024 cropping season, with significant impacts on ecosystems, crop yields, and water availability. From a policy and operational perspective, the Digital Twin framework demonstrates strong potential as a decision-support system for climate risk management, enabling proactive planning for irrigation management, water allocation, and drought mitigation, and providing a scalable and transferable solution for other transboundary basins facing similar climate risks.

Timeline

The study focuses on the 2022–2024 period, capturing La Niña, transition, and El Niño phases, with real-time monitoring enabled through continuous EO data integration.

Geographic Scope

The study covers the Limpopo River Basin (Southern Africa), spanning Botswana, Mozambique, South Africa, and Zimbabwe, with applicability to other semi-arid transboundary basins globally.

Relevant Links

- Ghosh, S., Vigneswaran, K., Dickens, C., Retief, H., Garcia Andarcia, M. (2025). *Recent drought prevalence in the Limpopo River Basin: insights from the digital twin platform*. Journal of the Indian Society of Remote Sensing, 8p. (Online first). DOI: <https://doi.org/10.1007/s12524-025-02133-y>.
- <https://digitaltwins.iwmi.org/programmes/limpopo-river-basin/>

Complex/Cascading Risks and high-resolution regional information

1. Title and Short Summary

Implications of Changes in Water Stress and Precipitation Extremes for Cocoa Production in Côte d'Ivoire and Ghana

Short Summary

This study investigates the association between climate variability, particularly water stress and precipitation extremes, and cocoa production in Ghana and Côte d'Ivoire, which together account for over 60% of global cocoa output. Cocoa production in these countries is largely rainfed, making it highly vulnerable to climate variability and change.

Using long-term climate and agricultural data from 1981 to 2022, the study evaluates trends in drought conditions, soil moisture deficits, and key precipitation indices such as total rainfall (PRCPTOT), number of wet days (RR1), consecutive wet days (CWD), consecutive dry days (CDD), and rainfall intensity (SDII).

The results show a significant decline in annual precipitation, particularly in recent decades. Ghana experienced reductions of up to 15% (~200 mm/year), driven by fewer rainy days and longer dry spells. Concurrently, there has been an increase in the number of consecutive dry days and in prolonged drought periods, especially during the 2011–2022 decade.

These changes have led to increased agricultural drought and sustained water stress, with several cocoa-growing regions experiencing multiple consecutive months with insufficient rainfall (<100 mm/month). These changes were associated with a decline in cocoa productivity of approximately 5%.

The study highlights that climate change is intensifying both dry conditions and rainfall variability, making cocoa systems more vulnerable. It emphasizes the need for adaptation strategies, particularly the introduction of supplementary irrigation and improved water management, to sustain cocoa production under changing climate conditions.

2. Timeline: 1981–2022

Publication 2025 (International Journal of Climatology)

3. Geographic Scope

Scale: Regional

Countries covered: Ghana and Côte d'Ivoire in West Africa

4. Relevant Links

<https://hdl.handle.net/10568/174321>

Issue: Adaptation Progress and Risk Reduction

Title: Building bottom-up adaptive capacity through collaborative aquatic ecosystem management in the face of basin-level hydro-contestations and climate change

Sanjiv de Silva, Deepa Joshi, and Karthikeyan Matheswaran

Location: Tonle Sap Lake Floodplain (TSLF), Cambodia

Short Summary:

Cambodia is identified as a key climate hot spot in Southeast Asia's growing biodiversity crisis. There is strong official acknowledgement and commitment to reversing intensive agrifood practices and top-down interventions towards sustainable agriculture and decentralized stewardship that allows for decentralized, bottom-up practices, enabling reimagining agrifood economics that speak to biodiversity loss. Our work demonstrates how building collaboration matrices across decentralized vertical and horizontal governance structures can transform natural resource management from sectorally fragmented systems unsuited for addressing climatic and other risks, to collaborative, co-creative processes that generate locally adaptive and appropriate solutions to manage uncertainty and sustain multiple food production ecosystems in the TSLF. This decentralized governance model is scalable across the TSLF and the wider Mekong basin and contributes to the underlying aim of the Kunming-Montreal Global Biodiversity Framework's focus - that continued loss of biodiversity poses threats not only to local ecosystems, but also to food security and human well-being.

Interrelated adaptation challenges addressed by this Initiative:

1. **Seasonal water vulnerability** from upstream hydropower projects in the Mekong River Basin is further intensified by climate change. These changes drive an unpredictable flood pulse in the TSLF, causing water conflicts between rice, fish, livestock sectors and domestic and ecological, water needs.
2. **Decades of centralized, top-down interventions have impeded the evolution of adaptive, collaborative natural resource management structures locally in Cambodia.** The inability to address variable water availability undermines both food and aquatic ecosystems' sustainability and productivity, affecting biodiversity, food and income security, also driving social conflicts and contestations. Decentralization is a first, but not the only step to collaborative, transformative governance. Local stewardship to manage multi-functional resources such as aquatic ecosystems and water requires processes and capacities for cross-sectoral and vertical coordination, as well as the financing to support and sustain these practices.
3. **The costs of inaction undermine multiple development goals:** 1. Biodiversity; 2. food and nutritional security, especially for marginal households and women and children; 3. risks hard-won gains in rural poverty reduction; 4. social cohesion, and 5. revenue of rice and fish exports.

Adaptation actions implemented (2023 – present): Multi-actor 'Technical Working Groups' that replace siloed vertical and top-down governance structures with a coordinated matrix of vertical and horizontal collaborations for co-designed, efficient management of ecosystems and agrifood systems. These TWGs include local water users, Community-Based formal and informal Organizations (CBOs), line agencies, local government, and District Administration representation.

Implementers: International Water Management Institute; WorldFish with the Institute of Fisheries Research and Development (IFReDI); Council for Agriculture and Rural Development (CARD); the Center for Development Research and Innovation (CDRI) and relevant provincial and district administrations

Achievements: 1. A foundation established for integrated, decentralized, aquatic ecosystem management based on co-created management plans developed by the TWGs; 2. Local water rice-fish conflicts addressed through infrastructure renovation and agreements between water users, including irrigators for reduced dry season water abstraction; 3. Prevention of other drivers of ecosystem degradation (e.g. illegal flooded forest conversion); 4. Development of locally applicable methods for water availability assessments and allocation decision-making; 5. Reduced social conflict between water users; 6. A shift

in perspectives and behaviour from previously sectoral interests to a shared understanding of ecosystem management needs and willingness to compromise to balance diverse sectoral needs. **7.** New multi-actor governance spaces for district-to-community collaborative planning and collective action, including closer collaboration between community and government, and **8.** An emerging network of adaptively managed aquatic ecosystems, building resilience across the TSLF landscape.

Evidence: **1.** <https://www.cgiar.org/news-events/news/new-innovation-integrates-water-resources-management-in-cambodias-tonle-sap-floodplain-and-mekong-delta/>; **2.** <https://cgspace.cgiar.org/items/04a6201b-89f2-4ada-851f-d6d57ab4e90e>; **3.** <https://cgspace.cgiar.org/items/e7244046-bb0e-4f64-b159-0715081e3d42>; **4.** [Cambodia: Major Win for Boeng Sneh Water Gate Upgrade | CGIAR System](#); **5.** <https://www.cdri.org.kh/publication/decentralised-food-system-governance-at-the-district-level-in-cambodia>

Lessons for climate adaptation: **1.** Building local capacities is critical to generate locally driven adaptive solutions and resilience in the face of complex basin-level hydro-politics and uncertainty; **2.** Longer term stewardship through local initiatives requires nested institutional support through vertical-horizontal matrices for collaboration and coordination - as well as financial and governance autonomy; **3.** Agro-ecological knowledge for more context-appropriate and socially equitable solutions minimizes mal-adaptation and enables maintaining resilient biodiversity and food systems in developing countries, where nature-based production systems drive livelihoods and economies.

Funding: CGIAR Asian Mega Deltas (AMD) Initiative; CGIAR Resilient Aquatic Foods (RqFS) Initiatives; CGIAR Science Program on Scaling for Impact (S4I), and CGIAR Science Program on Sustainable Animal and Aquatic Foods (SAAF).

Climate Extremes Walking Together: Evidence from Cascading and Compound Hazards Triggered by Tropical Cyclone Remal (2024)

Summary

This study investigates the cascading and compound nature of climate hazards associated with Tropical Cyclone Remal (May 2024) across the lower Ganga–Brahmaputra–Meghna (GBM) basin, covering parts of India and Bangladesh. It directly addresses key gaps in complex/cascading risks, high-resolution regional analysis, and integration of climate risk assessment into disaster risk reduction frameworks. The research captures a sequence of interacting climate extremes, pre-existing heatwave conditions, cyclone landfall, intense rainfall, early monsoon onset, flooding, landslides, and subsequent resurgence of heat stress, demonstrating how multiple hazards can occur in rapid succession and amplify overall risk, highlighting the limitations of single-hazard approaches. Using multi-source EO datasets (IbTracks, INSAT-3D, GPM, Sentinel-1, PlanetScope) integrated within Google Earth Engine, the study tracks cyclone progression, rainfall dynamics, flood extent and landslide occurrence. Remal's slow movement, persisting for over 50 hours, intensified impacts, particularly on the right side of the cyclone track. Sentinel-1 flood mapping reveals extensive inundation in Jogipara and Silchar (Assam, India), and Jashore, Narail and Khulna (Bangladesh). In Silchar, the flooded area expanded from $\approx 8\%$ to 42% of the study region within days, indicating rapid-onset flood dynamics. Concurrently, rainfall anomalies and terrain conditions triggered landslides across hilly regions of Assam, Meghalaya, Nagaland, and Mizoram, demonstrating strong interactions between hydro-meteorological and geomorphological processes.

Multi-sectoral impacts include disruption to agriculture, infrastructure damage, urban flooding, road inaccessibility, and public health risks; flood impacts in Silchar alone affected over 21,000 people, while millions were affected across Bangladesh. From a risk and adaptation perspective, the research shows how EO-based near real-time monitoring, high-resolution flood mapping, and rainfall tracking can strengthen early warning systems, evacuation planning and emergency response, and identifies communication and interpretation gaps at the community level, indicating the need for simplified, actionable risk information.

Methodologically, the study advances cloud-based EO platforms for rapid, scalable, and data-driven assessment of compound hazards, providing a replicable framework for understanding hazard interactions under complex climate scenarios. It contributes to adaptation planning and risk reduction by improving understanding of cascading climate risks and offering actionable insights to enhance resilience in highly vulnerable deltaic and coastal regions of the Global South.

Timeline

Event period: 25–29 May 2024 (Tropical Cyclone Remal). Additional historical cyclone data spanning ~ 120 years (1904–2023) were used for contextual analysis.

Geographic Scope

Lower Ganga–Brahmaputra–Meghna (GBM) basin, including coastal and inland regions of India (West Bengal, Assam, Meghalaya) and Bangladesh. Findings are relevant to other deltaic and cyclone-prone regions globally.

Relevant Links

- Ghosh, S., Dawn, A., Kour, S., Mallick, A., Chowdhury, A., Kundu, K., ... & Shaw, R. (2025). *Climate extremes walking together: Evidence from recent compounding climate hazards after Remal*. International Journal of Disaster Risk Reduction, 118, 104974. DOI: <https://doi.org/10.1016/j.ijdr.2024.104974>.

INFORMATION NOTE FOR THE UNFCCC RESEARCH DIALOGUE

Bonn Climate Conference – June 2026

Advancing Water Reuse for Climate Adaptation in the Middle East and North Africa: The ReWaterMENA Programme

by Javier Mateo-Sagasta (senior researcher at IWMI)

Submitting Organisation	International Water Management Institute (IWMI)
Programme	ReWaterMENA – Water Reuse Research in MENA
Timeline	2018 – 2025 (current/recent)
Geographic Scope	Regional – Middle East and North Africa (MENA)
Primary Thematic Area	Adaptation Progress and Risk Reduction
Project Website	https://rewater-mena.iwmi.org/

Summary

The ReWaterMENA programme, led by the International Water Management Institute (IWMI), addresses one of the most pressing climate adaptation challenges facing the Global South: ensuring safe and productive water reuse in one of the world's most water-scarce and climate-vulnerable regions. The Middle East and North Africa (MENA) region is already experiencing severe freshwater stress—a condition that climate change is projected to intensify dramatically through rising temperatures, shifting precipitation patterns, and increased drought frequency.

ReWaterMENA generates evidence, tools, and policy guidance to enable the safe, efficient, and equitable use of treated wastewater across the MENA region. By doing so, the programme directly contributes to building the adaptive capacity of agricultural systems, rural communities, and national water sectors in climate-vulnerable countries.

The programme addresses three interlinked dimensions of climate adaptation:

- **Risk characterisation and reduction:** Assessing human health and environmental risks associated with water reuse under current and projected climate conditions, and developing science-based standards and monitoring frameworks adapted to MENA contexts.
- **Governance and institutional capacity:** Supporting governments and water utilities to develop regulatory frameworks, national water reuse strategies, and institutional capacities required to scale up safe reuse practices.
- **Equity and livelihood outcomes:** Ensuring that the benefits of water reuse are equitably distributed—particularly for smallholder farmers and rural communities who are disproportionately affected by water scarcity and have the least adaptive capacity.

The programme's work spans multiple countries including Jordan, Egypt, Morocco, Tunisia, and Lebanon, and is designed to generate findings with broader applicability across the MENA region and beyond. ReWaterMENA is distinguished by its strong engagement with national governments, local stakeholders, and international partners, embedding its research within real-world policy and investment processes.

Critically, ReWaterMENA addresses a well-documented adaptation finance and knowledge gap: while water security is consistently identified by MENA countries in their Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) as a top-priority climate risk, science-based guidance on how to operationalise water reuse as an adaptation strategy remains scarce—particularly evidence generated from and for the Global South.

Relevance to UNFCCC Research Gaps (2023 & 2025)

ReWaterMENA's research directly responds to several of the priority research gaps identified by Parties, most centrally under Adaptation Progress and Risk Reduction. It also contributes to cross-cutting themes of equity, justice, and sustainable development in the context of climate mitigation and adaptation co-benefits.

Adaptation progress and risk reduction

This is the programme's primary area of contribution. ReWaterMENA produces:

- Evidence on the effectiveness of water reuse as a concrete, scalable adaptation measure for agriculture and water security in arid and semi-arid climates.
- Quantitative assessments of risk reduction outcomes—documenting how improved water reuse governance reduces exposure to waterborne pathogens, groundwater depletion, and crop failure under climate stress.
- Country-level findings on adaptation progress, including assessments of policy implementation gaps and institutional barriers that slow adaptation in the water sector.
- High-resolution, sub-national data on water use, reuse potential, and adaptation needs—filling the gap in regional and national-level adaptation evidence that Parties have specifically identified.

Complex and cascading risks / high-resolution regional information

MENA is a region where climate risks interact and compound: drought drives groundwater depletion, which increases reliance on treated wastewater, which in turn raises health risks if governance is inadequate. ReWaterMENA maps and models these cascading risk pathways, providing granular, country-specific insights that are directly relevant to UNFCCC calls for improved regional information.

Equity, justice, and sustainable development

A central concern of ReWaterMENA is ensuring that climate adaptation through water reuse does not exacerbate existing inequalities. The programme examines access to safely treated water for marginalised farming communities, gender dimensions of water access and decision-making, and the socioeconomic co-benefits of reuse for livelihoods—directly responding to UNFCCC Party calls for adaptation research that centres equity and justice.

Key Outputs and Links

Research outputs, policy briefs, datasets, and tools generated by ReWaterMENA are available at:

Programme Website: <https://rewater-mena.iwmi.org/>

ReWaterMENA Publications Repository: <https://rewater-mena.iwmi.org/resources/>

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This information note has been prepared for submission to the UNFCCC Secretariat Research and Systematic Observation team for inclusion in the June 2026 Research Dialogue. IWMI is a CGIAR Research Centre.

Issue: GHG reporting and carbon accounting

Title: Study on Greenhouse Gas (GHG) emissions linked to wastewater-based aquaculture system

Surajit Ghosh, Avinandan Taron, and Marie-Charlotte Buisson

Location: East Kolkata Wetlands, India

Timeline: ongoing from 2025

Short Summary:

The East Kolkata Wetlands (EKW) is a globally recognized 12,500 hectare Ramsar site and a unique example of nature-based urban wastewater management, where untreated sewage from Kolkata is recycled through a network of ponds to support aquaculture and agriculture. This wastewater-fed aquaculture system provides low-cost fish production, and agriculture sustains 100,000-150,000 people and their livelihoods, delivering essential ecosystem services, including nutrient recovery, water purification, and reducing the pressure on freshwater resources. By harnessing ecological processes, the wetlands represent a highly efficient circular bioeconomy model with significant social and environmental co-benefits.

However, the high organic content and nutrient loads in wastewater can stimulate anaerobic conditions in pond sediments, leading to the generation of greenhouse gases such as methane (CH₄), carbon dioxide (CO₂) and nitrous oxide (N₂O). As aquaculture expands to meet growing food demand, these emissions may offset some of its environmental advantages if left unquantified. Monitoring GHG emissions from wastewater aquaculture is therefore imperative for accurately assessing its climate footprint, identifying mitigation opportunities, and informing sustainable management practices. This is particularly critical in the context of climate policy, carbon accounting, and scaling climate-smart aquaculture systems that balance productivity with environmental integrity. Understanding whether high productivity comes at the cost of increased emissions or whether management interventions can balance both goals is essential for developing sustainable aquaculture strategies aligned with climate commitments.

Methodology:

The main experimentation has been carried out in the northern part of the wetlands, while the southern part is presently being studied. The area of the studied *bheris* (ponds/waterbodies) ranged between 25.29 and 197.05 ha. For each of these sites, water and air temperatures were recorded, gas samples were collected to study the GHG emissions, sub-surface water samples were collected from the inlet area, midpoint and outlet area of the sewage-fed *bheri*, along with sewage water from the feeding channel, and sediment to analyse pH, organic carbon, total nitrogen and electrical conductivity.

Main findings:

The study generated site-specific estimates of methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O) fluxes, providing one of the first integrated GHG baselines for sewage-fed aquaculture systems in EKW. It identified clear spatial gradients in emissions driven by variations in sewage loading, hydrodynamics, and sediment–water interactions. Strong empirical relationships were established between GHG fluxes and key water quality parameters, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), pH, and nutrient concentrations, thereby improving the mechanistic understanding of emission drivers in wastewater-fed *bheris*. Organic carbon (%) varied from 2.13% to 6.12% at different sites in the sewage-fed ponds. The system was found to be persistently eutrophic to hypereutrophic, supporting high primary productivity essential for aquaculture, while also intensifying biogeochemical cycling linked to emissions. Sediment characteristics—including texture, organic carbon content, and nutrient accumulation—emerged as critical regulators of both productivity and GHG flux dynamics. Collectively, these findings provide a robust evidence base for designing management strategies that optimize wastewater treatment, sustain fish production, and mitigate climate impacts.

The forthcoming phase will extend spatial coverage across the entire East Kolkata Wetlands to capture system-wide heterogeneity, while significantly enhancing temporal resolution through repeated and seasonally stratified sampling. This approach is intended to better represent interannual variability and capture the influence of extreme events such as heatwaves, flooding, and fluctuations in sewage inflows. In addition, higher-frequency GHG measurements will be undertaken to account for diurnal variability and episodic emission pulses, thereby improving the accuracy of flux estimates. Collectively, these efforts aim to strengthen the robustness of emission inventories and enable more reliable upscaling from individual *bheris* to the wetland complex, supporting improved climate reporting and evidence-based mitigation strategies.

Funding: CGIAR Science Program on Sustainable Animal and Aquatic Foods (SAAF).

Geospatial Multi-Criteria Assessment of Small Hydropower Potential in Vietnam Using Earth Observation and Cloud-Based Analytics

Summary

This study evaluates the potential for small hydropower development in Vietnam using a geospatial multi-criteria decision-making framework that integrates Earth Observation (EO) data and cloud-based analytics. It directly contributes to key thematic gaps in mitigation pathways, sustainable development, and equitable energy transitions by identifying environmentally viable and low-impact renewable energy options. The research addresses the growing demand for sustainable energy in developing countries, where increasing electricity needs are often met through carbon-intensive sources or large hydropower projects with significant ecological disruption and GHG emissions. Small hydropower plants (SHPs), defined as installations below 30 MW, are explored as a more sustainable alternative that minimises environmental impacts while supporting decentralised energy production.

A GIS-based Analytical Hierarchy Process (AHP) is applied within Google Earth Engine to assess site suitability across Vietnam's diverse topography. Geophysical and hydrological criteria elevation, slope, rainfall, drainage density and flow accumulation are integrated into a composite suitability index. Pairwise comparison identifies flow accumulation (44.4%) as the most influential factor, followed by rainfall (25.7%), with elevation contributing least (7%). Acceptable consistency ratios confirm methodological robustness.

The resulting suitability map identifies spatial patterns of hydropower potential, with highly suitable areas primarily located in northern and upland regions characterised by favourable hydrological and topographic conditions. Classification indicates 24% highly suitable, 39% moderately suitable and 37% least suitable, with an AUC accuracy of 82.45%. Model validation, conducted by overlaying existing hydropower plant locations, confirms strong predictive reliability, with approximately 60% of operational plants falling within highly suitable zones.

From a mitigation and sustainability perspective, optimised siting of small hydropower can reduce GHG emissions and support Vietnam's transition toward net-zero targets while prioritising climate-resilient development and energy equity in rural and underserved regions. Methodologically, the integration of EO datasets (SRTM DEM, CHIRPS, Sentinel imagery, MERIT Hydro) within cloud platforms provides a scalable, data-driven alternative to costly field surveys. The framework is transferable to other developing regions pursuing low-impact renewable energy planning aligned with sustainable development goals and equity considerations.

Timeline

Analysis conducted during 2024–2025, using contemporary geospatial datasets reflecting current hydrological and environmental conditions in Vietnam.

Geographic Scope

Vietnam, covering diverse physiographic regions including mountainous terrains, river basins and deltaic systems. Methodology transferable to other regions with comparable data availability.

Relevant Links

- Ghosh, S., Kour, S., Rajakaruna, P., Holmatov, B., Banerjee, B., Chon, L.T. (2025). *Small Hydropower Suitability of Vietnam Using Multi-Criteria Decision Making Approach*. IGARSS 2025 IEEE International Geoscience and Remote Sensing Symposium, Brisbane, Australia, pp. 2696–2700. DOI: [10.1109/IGARSS55030.2025.11314015](https://doi.org/10.1109/IGARSS55030.2025.11314015).

Title: **Between interest and influence**

The WE-ACT project is fostering effective transboundary water collaboration and streamlined decision-making.

Short Summary

This work focuses on improving how water is managed in transboundary river basins under increasing climate pressure. In Central Asia, shared rivers such as the Syr Darya are influenced not only by climate change, but also by competing national priorities, including energy production upstream and irrigation demands downstream. These differences often make coordinated decision-making difficult and can increase vulnerability to water scarcity and climate risks.

Through the WE-ACT project, this research supports more coordinated and risk-informed water allocation by bringing together stakeholders from different sectors and countries. A key component of the work is the development of a climate-sensitive Decision Support System (DSS), designed to help evaluate different water allocation scenarios under changing climatic and socio-economic conditions.

The approach combines technical tools with structured stakeholder engagement to better understand the roles, interests, and influence of different actors involved in water management. By identifying common priorities and potential points of cooperation, the work helps move beyond fragmented decision-making toward more integrated and balanced solutions.

This contributes to reducing climate-related risks in shared river basins, improving transparency in decision-making, and strengthening cooperation between upstream and downstream users. It also offers practical insights into how governance and data-driven tools can be combined to support more resilient and equitable water management.

Geographic Scope:

Regional (Central Asia), with a focus on transboundary river basins, particularly the Syr Darya Basin (Kyrgyzstan and Uzbekistan)

relevant link: <https://www.iwmi.org/blogs/between-interest-and-influence/>

Assessing El Niño-Induced Drought Impacts Using Cloud-Based Earth Observation: A Multi-Sectoral Analysis in Zambia (2023–2024)

Summary

This study presents a comprehensive assessment of the 2023–2024 El Niño-induced drought in Zambia using multi-source Earth Observation (EO) data and cloud-based geospatial analytics. The research directly addresses critical gaps in climate attribution, complex and cascading risk interactions, and the need for high-resolution regional analysis, particularly in data-sparse regions of the Global South. The analysis integrates satellite-derived precipitation (CHIRPS), vegetation indices (MODIS-based VCI), and indicators such as the Standardized Precipitation Index (SPI) and rainfall anomalies, processed through Google Earth Engine and Digital Earth Africa.

Results establish a statistically significant linkage between El Niño conditions and drought severity, with a moderate negative correlation between the Oceanic Niño Index (ONI) and rainfall, demonstrating strong regional climate attribution. Approximately 40.46% of Zambia experienced drought conditions during 2023–2024, with the most severe impacts in agriculturally critical Southern, Central, Eastern, Lusaka, and Copperbelt provinces. VCI analysis reveals widespread vegetation stress during key cropping stages, while SPI and rainfall anomaly trends confirm prolonged meteorological drought.

The study highlights the cascading and compound nature of drought impacts across multiple sectors: agricultural systems experienced crop losses of up to 70% in key regions with significant food-security threats; reduced inflows into major hydropower reservoirs (Lake Kariba, Itezhi Tezhi Dam, Mita Hills Dam) resulted in decreased electricity generation and widespread power shortages; and declining water resource availability contributed to drinking-water scarcity and public-health challenges including cholera outbreaks. These interconnected impacts illustrate the food–water–energy–health nexus under climate extremes.

From an adaptation and risk-reduction perspective, the study evaluates Zambia's evolving disaster management and climate policy framework (Disaster Management Act 2010, National Drought Plan 2018, recent meteorological policies) and demonstrates how EO-based monitoring systems, including the Zambia Drought Management System, are enabling a shift from reactive to proactive disaster management through improved early warning, near real-time monitoring, and targeted response. The approach provides a scalable, cost-effective and transferable solution for climate attribution, cascading-risk assessment and adaptation planning in developing regions.

Timeline

Long-term climate baseline 1981–2024. Primary focus on the 2023–2024 El Niño event, during which the detailed drought assessment and multi-sectoral impact analysis were conducted.

Geographic Scope

Zambia, with a broader regional context through analysis of El Niño-driven climate variability across Southern Africa. Findings are relevant for other drought-prone regions influenced by large-scale climate teleconnections.

Relevant Links

- Ghosh, S., Kour, S., Taron, A., Kaywala, K., & Rajakaruna, P. (2025). *Assessing El Niño-induced drought in Zambia and its effects using earth observation data*. *Natural Hazards*, 121(4), 4505–4530. DOI: <https://doi.org/10.1007/s11069-024-06976-5>.
- <https://www.iwmi.org/news/climate-finance-for-resilience-is-a-necessity-to-counter-the-ongoing-drought-in-zambia/>



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UNFCCC - Scientific research information_SBSTA/RSO

Section X: Carbon Dioxide Removal (CDR)

In the last Research Dialogue SB63, the following research gap has been identified as key for further climate action: “Scientific findings, advances and gaps in relation to the deployment of carbon dioxide removal technologies and approaches, the importance of their role in meeting the long-term goals of the Paris Agreement and linkages with sustainable development”. In this section we present new insights and evidence since the dialogue as input for SB64.

1.1 Role of CDR in mitigation pathways

Summary: Net-zero commitments have become the focal point for countries to communicate long-term climate targets. However, to this point it is not clear to what extent emissions reductions and CDR will contribute to net-zero. An integrated market for emissions and removals with a uniform carbon price delivers the economically efficient contribution of CDR to net-zero. Yet it might not fully internalise sustainability risks of CDR and hence could lead to its overuse. In this study, we explore the implications of separating targets for emissions and for removals delivered by novel CDR in global net-zero emissions pathways with the Integrated Assessment Model REMIND. We find that overall efficiency losses induced by such separation are moderate. Furthermore, limiting the CDR target comes with increasing emission prices but also significant benefits: lower cumulative emissions, a lower financial burden for public finance of CDR and limited reliance on geologic CO₂ storage but fails to lower the biomass demand. Proposed targets should also ensure sufficient CDR deployment to achieve net-negative emissions in the second half of the 21st century.

In a second study, we explored the potential contribution of ocean liming to ambitious climate targets. Due to the expected time needed for scale-up, the deployment potential in the first half of the century is limited, such that ocean liming can hardly reduce peak temperature. However, in the second half of the century, substantial deployment may be economically competitive. In addition, the availability of ocean liming reduces the dependence on other carbon removal options, and specifically on bioenergy. This could reduce the pressure on land and improve the sustainability of ambitious climate mitigation scenarios. However, impacts on the ocean ecosystems are still poorly understood and need to be clarified before deployment.

Geographic scope: Global

References

- Merfort, A. *et al.* Separating CO₂ emission from removal targets comes with limited cost impacts. *Nat. Comm.* 16, 5298 (2025).
<https://doi.org/10.1038/s41467-025-60606-7>



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- Strefler, J. *et al.* Ocean liming can help achieve the Paris climate target. *Environ. Res. Lett.* **20** 094004. <https://doi.org/10.1088/1748-9326/adf12c>

1.2 CDR side effects/other SDGs

Summary: With overshoot imminent and an increased need for CDR, concerns about the sustainability of land-based CDR measures and the impact of their rollout on other SDGs have scaled as well. Building on the research gaps identified in an [earlier mapping of the state-of-the-art knowledge on CDR side effects](#) and the gaps identified therein, we analyse the tradeoffs between CDR deployment and impacts on biodiversity, for the first time in a risk-risk setting: Pathways consistent with global climate objectives typically deploy billions of tonnes of carbon dioxide removal (CDR) from land-intensive methods such as forestation and bioenergy with carbon capture and storage. Such large-scale deployment of land-intensive CDR may have negative consequences for biodiversity. [Here](#) we assess scenarios across five integrated assessment models and show that scenarios consistent with limiting warming to 1.5 °C allocate up to 13% of global areas of high biodiversity importance for land-intensive CDR. These overlaps are distributed unevenly, with higher shares in low- and middle-income countries. Understanding the potential conflicts between climate action and biodiversity conservation is crucial. An illustrative analysis shows that if current biodiversity hotspots were protected from land-use change, over half the land allocated for forestation and bioenergy with carbon capture and storage in the assessed scenarios would be unavailable unless synergies between climate and conservation goals are leveraged. Our analysis also indicates CDR-related biodiversity benefits due to avoided warming.

Geographic scope: Global

References:

- Prütz, R. *et al.* Biodiversity implications of land-intensive carbon dioxide removal. *Nat. Clim. Chang.* **16**, 155–163 (2026). <https://doi.org/10.1038/s41558-026-02557-5>
- Prütz, R. *et al.* A taxonomy to map evidence on the co-benefits, challenges, and limits of carbon dioxide removal. *Commun Earth Environ* **5**, 197 (2024). <https://doi.org/10.1038/s43247-024-01365-z>

1.3 CDR governance and policy

Summary: A major question in this area is how to incorporate CDR into the existing climate policy architecture given that financial incentives will be needed to achieve the necessary upscaling. We analyze [in a new study](#) how conventional emissions trading schemes (ETS) can be modified by introducing "clean-up certificates" to allow for a phase of net-negative emissions. Clean-up certificates bundle the permission to emit CO₂ with the obligation for its



removal. We show that demand for such certificates is determined by cost-saving technological progress, the discount rate and the length of the compliance period. Introducing extra clean-up certificates into an existing ETS reduces near-term carbon prices and mitigation efforts. In contrast, substituting ETS allowances with clean-up certificates reduces cumulative emissions without depressing carbon prices or mitigation in the near term. We calibrate our model to the EU ETS and identify reforms where simultaneously (i) ambition levels rise, (ii) climate damages fall, (iii) revenues from carbon prices rise and (iv) carbon prices and aggregate mitigation cost fall. For reducing climate damages, roughly half of the issued clean-up certificates should replace conventional ETS allowances. In the context of the EU ETS, a European Carbon Central Bank could manage the implementation of clean-up certificates and could serve as an enforcement mechanism.

In a second publication, we tackle the open question of how such an integration of CDR credits into emissions trading schemes can overcome issues related to heterogeneous durability of carbon storage when using different CDR methods. [The research](#) develops a welfare and public economics perspective on optimal policies for carbon removal and storage (CDR) in permanent and non-permanent sinks. Non-permanent CDR reduces mitigation costs, even though the stored carbon is released into the atmosphere eventually. It may serve as bridge technology until permanent CDR becomes available. In contrast to permanent removals, non-permanent CDR does not reduce the optimal long-run temperature level. Its valuation differs from the social cost of carbon since a social cost of carbon removal arises from marginal damages caused by emissions released from non-permanent storage. We discuss three policy regimes that ensure optimal deployment of non-permanent CDR in terms of their informational and institutional requirements for monitoring, liability, and financing.

In a [third study](#), Franks et al. (2023) examine the different implications of CDR versus mitigation regarding international emission leakage. They point out that CDR causes less supply-side carbon leakage compared to emission reductions. Because of this difference in inter-regional leakage, they find that the optimal subsidy for CDR should be greater than the optimal carbon tax on emissions.

Furthermore, a [comprehensive survey](#) on the "Economics of CDR" by Edenhofer et al. (2025) discusses CDR in the context of international cooperation. The survey highlights that CDR reduces the free-rider and leakage problems, thus enhancing the ambition for international cooperation. It also discusses the terms-of-trade effect, noting that net fossil-fuel exporters prefer deploying more CDR relative to abatement to preserve fossil fuel prices, whereas net importers prefer abatement.

Geographic scope: EU, possible applications to other ETS



References:

- Lessmann et al., Journal of Environmental Economics and Management, vol. 137, May 2026, 103307; <https://doi.org/10.1016/j.jeem.2026.103307>
- Franks, M., Gruner, F., Kalkuhl, M. *et al.* Pigou's Advice and Sisyphus' Warning: Carbon Pricing with Non-Permanent Carbon Dioxide Removal. *Environ Resource Econ* 89, 11 (2026). <https://doi.org/10.1007/s10640-025-01060-3>
- Franks, M., Kalkuhl, M., & Lessmann, K. (2023). Optimal pricing for carbon dioxide removal under inter-regional leakage. *Journal of Environmental Economics and Management*, 117, 102769. <https://doi.org/10.1016/j.jeem.2022.102769>
- Edenhofer, O., Franks, M., Gruner, F., Kalkuhl, M., & Lessmann, K. (2025). The Economics of Carbon Dioxide Removal. *Annual Review of Resource Economics*, 17(1), 301-321. <https://doi.org/10.1146/annurev-resource-010224-094505>

1.4 Accountability, justice & equity, uncertainty

Summary: [A new study](#) sheds more light on questions of needing to move ahead with CDR while many uncertainties are not resolved, looking into the robustness of different CDR strategies. In particular, the research explores future CDR uncertainty in three key dimensions: realisable mitigation potentials, cost dynamics, and resource constraints. Leveraging an optimization model identifying cost-optimal and time-dependent CDR portfolios that sustainably meet climate targets, the results demonstrate that uncertainty matters, as different assumptions about cost dynamics and resource constraints lead to very different CDR pathways. Specifically, afforestation and reforestation, and soil carbon sequestration appear as robust options, deployed regardless of removal requirements. DACCS emerges as the most deployed technology in 2100 at median value (6.7 GtCO₂ yr⁻¹), but with the widest range of possible outcomes (interquartile range from 4 to 8.7 GtCO₂ yr⁻¹), depending largely on future renewable energy capacity and annual geological storage injection rates. BECCS deployment remains severely constrained by available land, but gains portfolio share when future energy availability is bounded. Diversification is also shown to be salient not only across CDR technologies, but also across time, as simulations reveal that ocean alkalisation could become a dominant solution towards the end of the century in high removal scenarios. Evaluating the performance of portfolios beyond economic costs, the research also provides a framework to explore trade-offs across different aspects relevant to planetary boundaries.

A follow-on [commentary](#) disentangles questions around accountability and justice in the context using CDR to steer back from an overshoot. In particular, it argues strongly against a shifting of goalposts, as ambitious climate targets become more difficult or costly to reach, as it would absolve nations from the responsibility for past inaction and suggests a new framework of accountability using CDR as an entry point to make up for past failures to stabilize climate.



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Geographic scope: Global

References:

- Ganti et al. *Nature* 649, 1107-1109 (2026).
<https://doi.org/10.1038/d41586-026-00247-y>
- Rodriguez Mendez et al. *Environ. Res. Lett.* 20 054013 (2025)
<https://doi.org/10.1088/1748-9326/adc613>

1.4 Permanence and uncertainty

Climate mitigation pathways critically depend on the permanence of forest carbon storage, yet increasing vulnerability of forests to disturbances from climate change and human activities is often neglected in current mitigation scenarios. In this study, the coupled Integrated Assessment Model REMIND-MAGPIE is used to explore how neglecting major forest disturbances affects mitigation pathways and what the consequences of delayed policy responses are. Stylized disturbance rates within observed ranges are introduced to both natural and planted forests. The results show that accelerated decarbonization can still achieve climate targets despite substantial forest carbon losses, requiring deeper emission cuts across all sectors and expanded CDR deployment. However, delaying action on forest carbon loss by just five years consistently doubles the additional mitigation costs and efforts across key sectors, regardless of the disturbance rate. Moreover, these myopic responses to forest carbon loss are as stringent, or even more demanding, than immediate responses to twice the forest disturbance rate. The findings underline the urgent need to monitor and safeguard forests and to incorporate realistic forest disturbance regimes into global mitigation models for the economic feasibility of the Paris Agreement's climate goals.

Geographic scope: Global

References:

Windisch, M. G. et al. Hedging our bet on forest permanence for the economic viability of climate targets. *Nat. Commun.* 16, 2460 (2025). <https://doi.org/10.1038/s41467-025-57607-x>

Section Y: Synergies and trade-offs

2.1 Distributional impacts of carbon pricing

Summary: Carbon pricing is widely recognised as a key mitigation instrument, but its alignment with equity objectives and the SDGs depends on understanding who bears its costs. This study addresses a persistent research gap: the *within-income-group* (horizontal)



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heterogeneity of carbon pricing burdens, which has historically received less attention than distributional effects across income groups.

The authors construct a novel dataset capturing the carbon intensity of consumption for 1.5 million individual households across 88 countries, and show that horizontal differences in carbon pricing costs are generally larger than vertical differences. A reform that appears progressive in aggregate may therefore still impose disproportionate hardship on specific subgroups. Using supervised machine learning, the study shows that features such as vehicle ownership, geographic location, and energy use patterns improve predictions of households' carbon intensity beyond income alone, with country-specific variation. Six clusters of countries are identified that differ systematically in the distribution of climate policy costs, and the effectiveness of compensation policies in reducing horizontal heterogeneity is shown to vary by context.

The findings imply that income-based transfers alone are frequently insufficient to protect households carrying high carbon burdens for structural reasons — such as rural location or dependence on carbon-intensive cooking fuels — and that compensation schemes must be calibrated to country-specific cost distributions to reconcile mitigation ambition with equity under the Paris Agreement and the 2030 Agenda.

Geographic scope: Global — 88 countries across all income levels and regions, including a substantial share of low- and middle-income countries

Reference: Missbach, L., & Steckel, J. C. (2025). Compensation design for carbon pricing with horizontal heterogeneity: Evidence from 88 countries. CESifo Working Paper No. 12258

2.2 Trade offs between mitigation, household welfare and gender equality

Summary: Evidence from Uganda and Malawi highlights the trade-offs that mitigation-related energy price increases can create for sustainable development in low-income countries. These trade-offs affect equity, food security, health, and gender equality. In Uganda, a consumer demand analysis shows that a carbon price of USD40/tCO₂ would reduce demand for electricity by 11% and kerosene by 20%. At the same time, it would raise firewood demand by 10%. The analysis also finds welfare losses of 0.2–12% of household expenditure on food and fuel, together with adverse effects on protein and micronutrient intake. In Malawi, a collective household model combined with panel evidence shows that higher electricity prices increase firewood consumption by 2.6–3.8% and shift time away from paid work towards fuel collection. These effects fall disproportionately on women and girls, whose collection time rises most strongly. The findings further show that greater women's decision-making power reduces the likelihood of firewood use when energy prices increase. Taken together, the results show that mitigation policies and energy price reforms can interact strongly with poverty, food security, clean cooking, and gender equality



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goals. They also underline the importance of complementary measures, including cash transfers and women's empowerment, to support equitable low-carbon development.

Geographic scope: National (Uganda and Malawi)

Reference:

- Aggarwal, R., Ayhan, S. H., Jakob, M. and Steckel, J. C. *Carbon pricing and household welfare: evidence from Uganda. Environment and Development Economics* (2024). [doi:10.1017/S1355770X24000214](https://doi.org/10.1017/S1355770X24000214).
- Aggarwal, R. and Steckel, J. C. *Electricity price hikes raise firewood consumption and women's collection time in Malawi. Environmental Research: Energy 2*, 025014 (2025). [doi:10.1088/2753-3751/ade1dd](https://doi.org/10.1088/2753-3751/ade1dd)

Section Z: Science Panel for the Global Energy Transition

In response to the Brazilian COP30 initiative to develop a roadmap for accelerating the transition away from fossil fuels, a **Science Panel for the Global Energy Transition (SPGET)** is being established. The mission of the panel is to provide rapid, authoritative and policy-relevant scientific input to the development of a global roadmap for the phase-out of fossil fuels, identifying implementable pathways at country, regional and sectoral levels consistent with keeping 1.5°C within reach. The panel will be co-chaired by Professor Ottmar Edenhofer (Germany), Dr Vera Songwe (Cameroon) and Professor Gilberto M. Jannuzzi (Brazil). An advisory group, comprising industry experts, stakeholders and experienced practitioners, will be embedded in the knowledge-production structures of the panel, to help bridge the gap between scientific outputs and assessment and real-world application.

Two interconnected objectives will be addressed:

1. Collect existing knowledge and generate new insights on annual benchmarks for high ambition energy transition pathways (globally and at country scale) to minimise overshoot and return to 1.5°C within this century.
2. Map and develop the most promising policy mixes, financial arrangements, sustainable technology solutions and governance dimensions that can support an accelerated transition to a decarbonised energy system.

The scientific work of the panel will be organised into four working groups covering the following topics: (1) transition pathways, (2) technology solutions, (3) policy evaluation and design, and (4) finance markets and governance.

The science panel will be an independent, global science support function for the global energy transition away from fossil-fuels. The initiative has received support from the Brazilian COP30 Presidency together with the Colombia/Netherlands Santa Marta



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conference organisers. While not being a formal part of the COP process or UNFCCC framework, the science panel will serve the COP, providing long-term scientific support to countries committed to phasing out fossil fuels. The work of the science panel will nonetheless contribute to strengthening the evidence base for the IPCC.



- A. Understanding climate change, related climate data, and scenarios development and use:
b. Overall advances in scenario development and use, including scenarios that limit warming in 2100 to below 1.5 °C, relative to pre-industrial times.

1.1 Scenario development and use

Since 2011, we are coordinating and leading the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) that provides a framework for the collation of a consistent set of climate impact data across sectors and scales. It also provides a unique opportunity for considering interactions between climate change impacts across sectors through consistent scenarios.

The upcoming ISIMIP4 simulation round will use CMIP7 outputs to drive climate impact models with consistent climate forcing data. The workflows within the different scientific communities involved in the scenario development and use (Integrated Assessment Modeling - IAM, Earth System Modeling - ESM, Impact Modeling - ISIMIP, Regional climate modeling/dynamical downscaling - CORDEX) are critically interconnected and need to be highly integrated to generate robust modeling output in a timely manner. To facilitate such an efficient process, we coordinated a workflow to contribute the perspective of the climate impact modelling community to the ScenarioMIP process for CMIP7 (Van Vuuren et al. 2026), especially concerning priority scenarios for the first set of simulations (CMIP7 Assessment Fast Track, ISIMIP4 Fast Track). Furthermore, we convened a [session on scenarios and timelines](#) for CMIP7-based contributions to the 7th Assessment Report of the IPCC (AR7) during the [OptimESM and ISIMIP workshop](#) 2025, bringing together key representatives from the IPCC Working Group II, the IAM, ESM and ISIMIP communities. This has laid the ground for a process including immediate provision of forcing data along the modeling chain (IAMs - ESMs - Impact models), to start the ISIMIP4 Fast Track as early as possible, optimizing the chance for developing CMIP7-based climate impact studies in time for the Working Group II contribution to the AR7.

1.2 Development of ScenarioMIP-/CMIP-based forcing data required by the impact modeling community

Summary: The ISIMIP3b, group III simulations account not only for the impacts of climate change but also for future socio-economic development and mitigation measures along the SSPs. In close cooperation with the IMAGE and MAgPIE land use modelling teams and the Marine Ecosystems and Fisheries sector within ISIMIP, the ISIMIP coordination group was able to provide the necessary land use and irrigation patterns (Molina Bacca et al. 2025) and develop an approach to represent changes in fishing efforts (Maury et al. 2025) for this new set of simulations. In addition, Perrette & Mengel (2025) developed a Bayesian spatial model constrained by historical tide gauge records, Global Positioning System (GPS) measurements, and satellite altimetry, to provide future estimates of relative sea level rise and vertical land motion. The model allows for projections of local relative sea level rise smoothly extending the observational records for any given global mean temperature pathway (see also section B.c). It represents the basis for future sea level projections within



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ISIMIP3/4b and for the attribution of historical impacts of total sea level rise to its individual contributions within ISIMIP3/4a.

Geographic scope: global

g. Advances and gaps in attribution science, including at regional and national scale, as well as attribution of monsoon pattern changes.

2. Impact attribution

In the first Global Stocktake, the ‘Conference of the Parties [...] 183. Encourages the scientific community to continue enhancing knowledge on and addressing knowledge gaps in adaptation and availability of information on climate change impacts, including for monitoring and progress, and to provide relevant and timely inputs to the second and subsequent global stocktakes [...]’(UNFCCC 2024). Such a monitoring of observed impacts of climate change first of all needs the attribution of observed changes in natural, human and managed systems to climate change (‘impact attribution’) to quantify what really is the impact of climate change.

To address this gap we have performed the following research activities:

2.1 Development of the ISIMIP3a impact attribution framework to enable a multi-impact model based quantification of observed impacts of climate change as defined the the WGII contribution to the IPCC AR6 (O’Neill et al. 2022):

Summary: Within the ISIMIP3a simulation round we have developed an impact attribution framework (Frieler et al. 2024) that is in line with the IPCC AR6 where an observed impact of climate change is defined as ‘the difference between the observed state of a natural, human or managed system and a counterfactual baseline that characterises the system’s state in the absence of changes in the climate-related systems, defined here as climate system including the ocean and the cryosphere as physical or chemical systems’. To enable the associated impact model simulations in addition to the observational (‘factual’) climate and sea level data, counterfactual sets of atmospheric forcings (Mengel et al. (2021), code at <https://github.com/ISI-MIP/attrici/releases/tag/v1.0.0>) and coastal water levels (Treu et al. 2025) where observed trends have been removed are provided as input data for the historical impact model simulations within ISIMIP3a. In addition we provide factual (accounting for observed sea level rise) and counterfactual (assuming no historical sea level rise) simulations of surge induced coastal flooding induced by observed tropical cyclones (Mengel 2025). The modelling chain has been developed by Vogt et al. (2024).

Geographic scope: global



2.2 Impact attribution studies

Meanwhile impact modelling teams from different disciplines have already uploaded 61 contributions to ISIMIP3a, the associated global impact model simulations have been made publicly available via the [ISIMIP repository](#) and a range of different impact attribution studies have already been published based on the new framework:

Observed impacts of climate change in areas affected by wild fire:

Summary: In this study, Burton et al. (2024) demonstrate that climate change increasingly explains regional burned area patterns, using an ensemble of global fire models. The simulations show that climate change increased global burned area by 15.8% (95% confidence interval (CI) [13.1–18.7]) for 2003–2019 and increased the probability of experiencing months with above-average global burned area by 22% (95% CI [18–26]). In contrast, other human forcings contributed to lowering burned area by 19.1% (95% CI [21.9–15.8]) over the same period. Moreover, the contribution of climate change to burned area increased by 0.22% (95% CI [0.22–0.24]) per year globally, with the largest increase in central Australia. Our results highlight the importance of immediate, drastic and sustained GHG emission reductions along with landscape and fire management strategies to stabilize fire impacts on lives, livelihoods and ecosystems.

Geographic scope: global

Fire-induced health impacts:

Summary: In another study, Park et al. (2024) study the influence of climate change on fire-induced health impact by using three well-tested fire–vegetation models in combination with a chemical transport model and health risk assessment framework to attribute global human mortality from fire fine particulate matter (PM_{2.5}) emissions to climate change. Of the 46,401 (1960s) to 98,748 (2010s) annual fire PM_{2.5} mortalities, 669 (1.2%, 1960s) to 12,566 (12.8%, 2010s) were attributed to climate change. The most substantial influence of climate change on fire mortality occurred in South America, Australia and Europe, coinciding with decreased relative humidity and in boreal forests with increased air temperature. The study highlights the role of climate change in fire mortality, aiding public health authorities in spatial targeting adaptation measures for sensitive fire-prone areas.

Geographic scope: global

West Nile virus:

Summary: Erazo et al. (2024) investigated the extent to which the West Nile virus (WNV) spatial expansion in Europe can be attributed to climate change while accounting for other direct human influences such as land-use and human population changes. Our findings demonstrate a notable increase in the area ecologically suitable for WNV circulation during the period 1901–2019, whereas this area remains largely unchanged in a no-climate-change counterfactual. We show that the drastic increase in the human population at risk of exposure is partly due to historical changes in population density, but that climate change has also been a critical driver behind the heightened risk of WNV circulation in Europe.

Geographic scope: Europe



Malaria:

Summary: During the last decade, the Horn of Africa has experienced an unexpected surge in urban malaria cases, with annual outbreaks intensifying each year in some countries. Training ecological niche models on geo-referenced records of *An. stephensi* collected across its native range and comparing factual to counterfactual model simulations, Erazo et al. (2026) could show that the recent range expansion of this vector in the Horn of Africa is likely driven by other factors (potentially expanding urban environments) other than climate change. These findings highlight the need for further investigation into the ecological and anthropogenic drivers shaping the spread of *An. stephensi* to inform targeted and effective malaria control strategies.

Geographic scope: Horn of Africa

Disaster-induced displacement:

Summary: Extreme weather events, especially floods and tropical cyclones, often trigger population displacement. The frequency and intensity of tropical cyclones are affected by anthropogenic climate change. Mester et al. (2023) for the first time quantified the effect of historical climate change on displacement risk, and showed how displacement can be partially attributed to climate change; using the example of the 2019 Tropical Cyclone Idai in Mozambique. Using a combination of storm surge and flood depth modeling and counterfactual analysis, their main estimates indicate that climate change has increased displacement risk from this event by approximately 12 600–14 900 additional displaced persons, corresponding to about 2.7 % to 3.2 % of the observed displacements. Besides highlighting the significant effects on humanitarian conditions already imparted by climate change, the study provides a blueprint for event-based displacement attribution.

Geographic scope: Mozambique

West African Monsoon:

Summary: Africa's central Sahel region has experienced prolonged drought conditions in the past, while rainfall has recovered more recently. Global climate models project anything from no change to a strong wetting trend under unabated climate change; and they have difficulty reproducing the complex historical record. Schewe & Levermann (2022) showed that when a period of dominant aerosol forcing is excluded, a consistent wetting response to greenhouse-gas induced warming emerges in observed rainfall. This corroborates the contribution of anthropogenic climate change to historical rainfall trends in the region dominated by the West African monsoon. Coupled Model Intercomparison Project Phase 6 climate models with a realistic past rainfall response show a smaller spread, and higher median, of projected future rainfall change, compared to the full ensemble.

Geographic scope: Central Sahel



B. Adaptation, loss and damage and extreme events:

a. The evolution and dynamics of extreme events, and early warning systems and climate services

3.1 Dynamics of extreme events

Summary: Lange et al. (2020) assessed future exposure to six different types of extreme events (floods, tropical cyclones, droughts, heatwaves, wildfires, and crop failures) at different levels of global warming, finding substantial and widespread increases for all event types (see also below under B.c). Zantout et al. (2025) investigate whether extreme climate events occur regularly, and how regularity patterns change under global warming. They calculate dominant periods in crop failure, heatwave, and wildfire data; where a dominant period is found, this indicates some regularity in the occurrence of an extreme event. Under pre-industrial conditions dominant periods emerge in 28% of cropland exposed to crop failure and 10% of wildfire-affected areas, likely related to climatic oscillations such as the El Niño-Southern Oscillation, while heatwaves occur irregularly. The number of dominant periods increases by 2–13% during the transition from the pre-industrial era to the anthropocene. In the anthropocene, the occurrence of extreme events shifts towards monotonic growth, replacing previous natural regularity patterns. Linearly de-trended projections reveal an additional shift towards smaller dominant periods due to climate change, meaning extremes become more frequent.

Geographic scope: global

3.2 Monsoon dynamics

Summary: Katzenberger et al. (2022) showed that the frequency of extreme monsoon seasons in India strongly increases under global warming. Using CMIP6 climate models, they find up to eight times as many such very wet monsoon years under strong warming compared to historical conditions.

Geographic scope: India

b. Assessing adaptation progress, and the impact of adaptation actions on reducing risks, to inform adaptation planning and action

4.1 Tracking historical adaptation progress

The combination of process-based or empirical climate impact model simulations with observed changes in natural and human systems used within the impact attribution framework has developed into a highly valuable approach to also indirectly ‘measure’ historical adaptation progress in terms of vulnerability reductions. We have contributed a series of papers with a focus on tracking historical changes the vulnerability to weather extremes:



Flood induced damages and fatalities in Europe, historical adaptation progress:

Summary: The magnitude of flood impacts is regulated not only by hydrometeorological hazard and exposure, but also flood protection levels (e.g. structural flood defenses reducing flood extent) and vulnerability (reported losses such as damages or fatalities in relation to potential losses described by exposed assets or exposed people). Paprotny et al. (2025), demonstrate how potential losses estimated by process-based model simulations of flood extent driven by observed weather and assuming no flood protections can be combined to information about actual flood occurrence and reported damages to infer the variation of protection levels and vulnerability. The study uses data on historical riverine, coastal, and compound floods and associated impacts obtained from the HANZE database (Paprotny et al. 2018, 2024), in 42 European countries over the period 1950–2020. The study shows that riverine flood protection levels are much lower than assumed in previous pan-European studies. Many parts of western Europe have relatively high vulnerability, with lowest value observed in central and northern Europe. Still, a strong decline in flood vulnerability over time is also observed for all three indicators of relative losses, suggesting improved flood adaptation. Flood protection levels have also improved since 1950, particularly for coastal floods.

Geographic scope: Europe

Flood induced damages and fatalities in Europe, impacts of climate change compared to exposure and vulnerability changes:

Summary: In a follow-up impact attribution study covering 1729 riverine, flash, coastal, and compound events that were responsible for an estimated 83 to 96% of flood-related impacts in Europe between 1950 and 2020, Paprotny et al. (2025) show that, in most regions, the magnitude of flood impacts relative to the 1950 baseline has been regulated primarily by direct human actions. The population and economic value at risk have increased, but the effect of exposure growth has been largely compensated by reductions in vulnerability due to improved risk management. Observed long-term changes in climate and human alterations of river catchments were also important drivers of flood hazard in many regions, but ultimately less relevant for trends in total, continental-wide impacts.

Geographic scope: Europe

Flood-induced damages, impacts of climate change in comparison to the effects of exposure and vulnerability changes:

Summary: In another study, Sauer et al. (2021) develop an empirical model to reconstruct observed damages and quantify the contributions of climate and socio-economic drivers to observed trends. We show that, on the level of nine world regions, trends in damages are dominated by increasing exposure and modulated by changes in vulnerability, while climate-induced trends are comparably small and mostly statistically insignificant, with the exception of South & Sub-Saharan Africa and Eastern Asia. However, when disaggregating the world regions into subregions based on river-basins with homogenous historical discharge trends, climate contributions to damages become statistically significant globally, in Asia and Latin America. In most regions, we find monotonous climate-induced damage



trends but more years of observations would be needed to distinguish between the impacts of anthropogenic climate forcing and multidecadal oscillations.

Geographic scope: global

Flood-induced damages, fatalities, displacement; historical adaptation progress:

Summary: Global flood impacts have risen in recent decades. While increasing exposure was the dominant driver of surging impacts, counteracting vulnerability reductions have been detected by comparing the reported impacts to estimated exposure (=potential maximal impact) accounting for changes in hazards and exposure (top-down approach) (Formetta and Feyen 2019; Jongman et al. 2015; Tanoue et al. 2016). To assess the ongoing progress on vulnerability reduction, we have combined a newly available dataset of flooded areas derived from satellite imagery for 913 events with four global disaster databases and socio-economic data (Sauer et al. 2024). Event-specific flood vulnerabilities for assets, fatalities and displacements reveal a lack of progress in reducing global flood vulnerability from 2000—2018. We examine the relationship between vulnerabilities and human development, inequality, flood exposure and local structural characteristics and find that vulnerability levels are significantly lower in areas with good structural characteristics and significantly higher in low developed areas. However, socio-economic development was insufficient to reduce vulnerabilities over the study period. Nevertheless, the strong correlation between vulnerability and structural characteristics suggests further potential for adaptation through vulnerability reduction.

Geographic scope: global

Heat-related mortality, comparison of impacts of climate change in comparison to the effects of improving health status:

Summary: Huber et al. (2025) find that declining vulnerability, associated with improvements in life expectancy, has led to decreasing trends in heat-related excess mortality in most cities despite summer warming. In contrast, if life expectancies had not improved, climate change would have induced increasing trends in the heat-related death burden. The growing anthropogenic fingerprint also emerges in the relative proportion of heat-related excess mortality attributable to climate change, which increased by 5.6% per decade (95% confidence interval: 2.6%, 8.6%), averaging 53.6 % (49.8%, 58.9%) across the study period. Our results underline the importance of accounting for evolving vulnerability when attributing human health outcomes to climate change.

Geographic scope: national (largest cities in Germany)

4.2 Effectiveness and limits of future adaptation efforts

Summary: Within the ISIMIP3 simulation round a dedicated set of experiments targets the question to what extent adaptation measures alter climate change impacts. To enable such studies we have developed the ISIMIP3b adaptation framework including a set of direct human forcing data that are changing over time and represent various adaptation measures, such as land use changes, irrigation measures, water management (dams), etc.



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Geographic scope: global

c. Climate impacts across 1.5 °C warming scenarios at local and regional levels

5.1 Use of climate and socioeconomic scenarios

ISIMIP has been explicitly designed to facilitate the assessment of climate impacts across different levels of warming, globally in a spatially explicit manner. E.g., scenarios have been selected with this application in mind; for instance, ISIMIP3 included SSP1-2.6 in order to closely study warming near 1.5°C, as well as high-end scenarios to cover a large range of warming levels. The design of ISIMIP4 follows a similar rationale.

5.2 Climate impacts at different warming levels

Summary: Many papers have used the ISIMIP framework to study climate impacts at different global warming levels, including 1.5°C and 2°C. For example, Schleussner et al. (2016) studied impacts on water availability and crop yields (using ISIMIP simulation ensembles) as well as a number of meteorological indices, finding substantial differences between 1.5°C and 2°C. More recently, Lange et al. (2020) assessed future exposure to six different types of extreme events (floods, tropical cyclones, droughts, heatwaves, wildfires, and crop failures) at different levels of global warming, based on ISIMIP data such that results are comparable across different event types. Results indicate that annual population exposure to any type of extreme event has already more than doubled, and will have increased by a factor of more than 5 at 2°C of global warming, compared to pre-industrial conditions. These results will be updated with ISIMIP3 data and further with the availability of ISIMIP4.

Many further examples of impact studies for different global warming levels, including for crop yields (Ostberg et al., 2018) or groundwater recharge (Reinecke et al., 2021) are available in the [ISIMIP publication database](#). Also in the context of ISIMIP, a methodology was recently developed to project coastal relative sea level rise for any future global warming trajectory (Perrette & Mengel, 2025), which will facilitate studies of coastal water levels and related impacts and risks at different levels of global warming.

Geographic scope: global

d. Understanding of complex, cascading and transboundary risks

6.1 Risks to supply and consumption security from cascading climate impacts

The global economy is a strongly interlinked network of firms and consumers. In consequence, local disaster-induced supply failures can cascade along global supply chains, causing supply security risks for producers and consumers. The increase in the frequency and intensity of weather extremes under global warming requires a sound understanding of these risks to develop targeted and effective adaptation strategies that reduce supply insecurities.



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Summary: In response, we have developed the global agent-based supply network model *Acclimate* (Otto et al. 2017). Explicitly accounting for the main short-term flexibilities of supply networks such as storages, production extension and demand shifts to unaffected suppliers, it allows assessing the spreading of disaster-induced losses in the global supply network, accounting for price increases and distributional effects for consumers. Assessing the global economic response to river floods, we could show the importance of strong-equilibrated trade relations to mitigate supply chain losses (Willner et al. 2018). Further, we showed that the indirect losses of recurrent extreme weather events can resonate and disproportionately amplify consumption losses (Kuhla et al. 2021). In addition, we assessed the impact of tropical cyclones on trade (Middelanis et al. 2022), including impacts on the maritime transport network (Kuhla et al. 2023). In times of crises, in particular during the Covid-19 crisis, the global economy is more susceptible to extreme weather-induced shocks (Middelanis et al. 2023). Studying the distributional effects of temperature and rainfall variability and extremes on consumption, we found that overall low-income consumers face the highest consumption risks in high- and low-income countries alike. But risk increases with ongoing global warming are greatest for high-income consumers. Across countries, risks are highest for middle-income countries due to unfavorable trade dependence and seasonal climate exposure. In most countries, consumption risks increase under global warming (Quante et al. 2024).

In a complementary approach, Auer et al. (2025) integrated stakeholder-co-produced impact chains with quantitative data for 102 countries across foreign policy, human security, trade and finance to reveal critical intervention points related to water, livelihoods, agriculture, infrastructure and economy, and violent conflict. Livelihood instability, with violence exacerbating conditions in conflict-prone regions, tends to amplify risks of cascading impacts emerging from low-income countries. Their findings highlight the importance of policy coherence in addressing interconnected vulnerabilities rather than isolated risks.

Geographic scope: global, Europe (Auer et al. 2025)

6.2 Compounding climate and geopolitical risks to food security

Global markets for main food staples are volatile and subject to frequent crises with pronounced price spikes. These are often triggered by a combination of global production failures and uncoordinated unilateral policy responses such as escalating export restrictions or hoarding. The resulting short-term food price volatility can cause severe food insecurities, in particular in import-dependent low- and middle-income countries with large vulnerable populations (Headey and Ruel 2023). In an increasingly fragmented geopolitical landscape and under global warming, which may increase production volatility, it is important to understand these short-term risks in order to find effective adaptation and coping strategies tailored to the different risk profiles of countries. Unfortunately, agricultural integrated assessment models, which are designed to assess the long-term sustainability of the food system under climate and socioeconomic change, are not well suited to capturing these short-term risks.



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Summary: To this end, we have developed complementary modelling approaches, TWIST and Agrimate, which allow for assessing short-term risks to food security resulting from compounding climate and geopolitical stressors. In hindcasting exercises, we have shown that these models can quantitatively reproduce the world market price spikes of the main food staples (wheat, rice, maize, and soy) and associated (regional) storage movements and consumption changes during the 2008/9 and 2010/11 World Food Price Crises (Schewe et al. 2017; Kuhla et al. 2025). We have then applied these models to estimate potential food-security risks resulting from the Covid-19 pandemic (Falkendal et al. 2021) and the full-scale Russian invasion of Ukraine in February 2022 (Kuhla et al. 2024). In both cases, we found international collaboration to be key to reducing food security risks. In particular, in the first months following the invasion, the Black Sea Grain Initiative and the EU's Solidarity Lane Initiative may have substantially mitigated food security risks. Further, a combination of moderate short-term demand- and supply-side coping measures of affluent large wheat-producing countries could have reduced the crises to a still tense but manageable situation (Kuhla et al. 2024).

In an additional study Auer et al. showed that the full-scale Russian invasion of Ukraine led to sharp energy price increases in Europe, strong reactions in European commodity futures markets with gains for fossil fuel companies and losses for firms most exposed to the belligerents, and a marked deterioration in food affordability, placing an additional 10 million people at risk of hunger (Auer, Bosello, et al. 2025).

These cross-sectional studies were enabled through the intersectoral harmonization of impact model simulation within ISIMIP, the PIK-lead EU Horizon project CASCADES "Making Europe adaptive and resilient by cascading climate risks" (2019-2023). These efforts are currently supported by the EU Cooperation in Science and Technology Action [CROSS-CASCADE](#) "Modeling Cross-Sectoral Climate Impacts".

Geographic scope: global, Europe (Auer et al. 2025)

E. Cross cutting

c. Other research activities relevant for and aimed at supporting work under the Convention and Paris Agreement such as the Nairobi Work Programme.

7. Data management, provision, and archiving

As part of the ISIMIP framework, we curate the [ISIMIP data repository](#), providing both input data to force cross-sectorally consistent climate impact model simulations (climate data and direct human forcings (population and landuse patterns, GDP, etc.)), as well as the simulation data that is submitted to us by the participating modeling teams. The repository is hosted at PIK and adheres to persistent, FAIR-compliant data publication, and since 2020, ISIMIP datasets have been published with DOIs assigned by the ISIMIP data team, in accordance with the [DataCite Consortium Agreement](#) which PIK has joined. All data provided through the ISIMIP repository is openly available, preferably under CC0-license. For a consistent and reproducible publication work flow, we developed the curation code [ISIMIP Publisher](#), and to ensure the provision of high-quality, consistent data, we developed



the [ISIMIP quality control tool](#) which is continuously updated and extended to match evolving needs according to specifications of submitted data sets.

Currently, there are c. 800k files of approximately 200 TB online, and about 90 DOIs can be used to cite the data. On average, c. 30 users download around 2TB of data each day. Numerous actors in climate finance (e.g. NGFS; European companies under the Corporate Sustainability Reporting Directive; consultancies such as Deloitte, S&P Global, MSCI), humanitarian (FAO; IOM; World Bank; German Development Bank KfW), or conservation (e.g. WWF) areas are relying on ISIMIP data for climate-related risk assessments and stresstesting.

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April 24, 2026

Subsidiary Body for Scientific and Technological Advice (SBSTA)
Submission in Response to SBSTA Call for Information
Submitted via email to rso@unfccc.int

Dear Chair of the Subsidiary Body for Scientific and Technological Advice,

On behalf of the Princeton University Water Energy Technologies (WET) Lab, we are pleased to submit this response to the call for information under the Research and Systematic Observation (RSO) agenda item, in preparation for the eighteenth meeting of the research dialogue at the June Subsidiary Bodies session. This submission focuses on GHG emissions from municipal wastewater systems. Many of the findings were jointly obtained through collaborations with the U.S. Water Research Foundation, U.S. Water Alliance, Brown & Caldwell, Jacobs, Lawrence Berkeley National Lab, University of Queensland in Australia, Delft University in the Netherlands, and more than 70 wastewater utilities around the globe.

The WET Lab at Princeton conducts research at the intersection of water systems, energy, and climate, with a focus on GHG emissions, resource recovery, and carbon management. The research summarized here addresses gaps identified by **Parties under Category D, with particular relevance to (a) GHG emissions by sources and (f) science-based GHG reporting methodologies**. Since the 2019 Refinement to the IPCC National GHG Inventory Guidelines, progress has improved understanding and quantification of wastewater process emissions. However, significant challenges remain, including incomplete emissions coverage, high variability across processes, and limitations in existing inventory methods. Advances in process-level characterization and expanded use of direct monitoring and measurement are helping to address these gaps and improve the accuracy and transparency of emissions estimates. Improving the quantification and reporting of methane and nitrous oxide emissions remains critical to ensuring that inventories are accurate and policy-relevant.

This submission contains four one-page summaries related to the following topics:

- Oversimplification and misestimation of emissions from wastewater treatment plants
- Gaps in application of science-based methodologies in national inventory reports
- Monitoring and direct measurement of wastewater process emissions
- Sewer methane emissions and characterization
- Development of standardized methodologies for facility-level GHG accounting

We appreciate the opportunity to contribute to the SBSTA research dialogue and would be pleased to provide additional information as needed.

Sincerely,

A handwritten signature in black ink, appearing to read "Z. Jason Ren".

Z. Jason Ren

[Professor of Civil and Environmental Engineering](#)

Associate Director, Andlinger Center for Energy and the Environment

Princeton University

Email: zjren@princeton.edu; LinkedIn: <https://www.linkedin.com/in/zjasonren>

Systematic underestimation of wastewater GHG emissions in national inventory reporting

Description of the research

National inventory reports (NIRs) are the primary mechanism for reporting methane (CH₄) and nitrous oxide (N₂O) emissions from wastewater systems under the UNFCCC. However, the extent to which these inventories capture sector-wide emissions remains uncertain due to inconsistent accounting methodologies, incomplete system boundaries, and variability in how emission pathways are represented.

This research, led by Princeton University and collaborators, conducts a detailed assessment of wastewater GHG accounting approaches across 38 national inventory reports. The analysis identifies systematic gaps in pathway coverage, method selection, and alignment between reported methodologies and underlying wastewater infrastructure. Key emission sources, including decentralized sanitation, effluent discharge, and certain treatment pathways, are frequently omitted or only partially represented. In addition, many inventories rely on simplified or outdated emission factors that do not reflect current methodological guidance or observed variability.

These limitations result in consistent underestimation of wastewater emissions and reduce comparability across countries. Across the inventories analyzed, total CH₄ and N₂O emissions are estimated to be 19 to 27 percent higher than reported values, corresponding to an emissions gap of 52 to 73 million metric tons CO₂-equivalent per year. When extrapolated globally, this gap increases to approximately 94 to 150 million metric tons CO₂-equivalent per year.

The findings highlight the need for more complete and harmonized inventory approaches, including clearer guidance on system boundaries, pathway inclusion, and method selection. Strengthening these elements is critical to improving the accuracy, consistency, and comparability of wastewater GHG reporting in national inventories.

Timeline

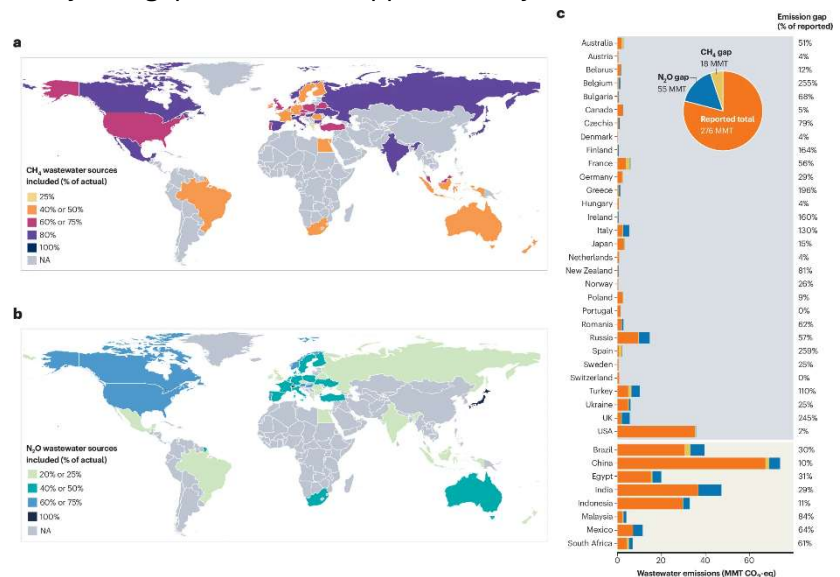
2023–2026

Geographic scope

Multi-country analysis (38 national inventory reports), with global extrapolation

Relevant links

- Song, C.H., Ponder, D., Peng, W., Ren, Z. J. (2026). Discrepancy of National Inventories Reveals Significant Emission Gap in the Wastewater Sector. *Nature Climate Change*. <https://doi.org/10.1038/s41558-025-02540-6>
- Song, C.H., Ponder, D., Peng, W., Ren, Z. J. (2026). Inconsistent national reports undercount wastewater emissions. *Nature Climate Change*. <https://doi.org/10.1038/s41558-026-02555-7>
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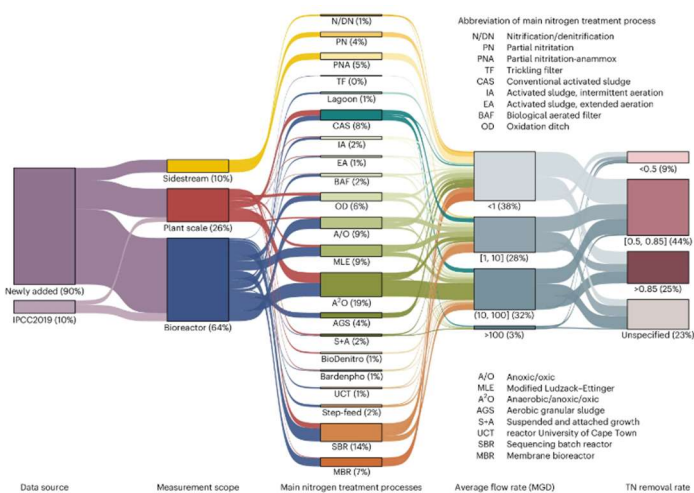
Oversimplification and misestimation of GHG emissions from wastewater treatment plants

Description of the research

Centralized wastewater treatment is a major source of anthropogenic methane (CH₄) and nitrous oxide (N₂O) emissions, which vary widely across sites, processes, and time. Current estimates rely on uniform emission factors (EFs) recommended by the IPCC, derived from a limited evidence base. For centralized treatment, the 2019 IPCC guidelines draw on seven studies covering 14 facilities for CH₄ and fourteen studies covering 30 plants for N₂O.

This research, led by Princeton University and collaborators, conducted both more than 100 field measurements and developed a literature mining model, and the findings demonstrates that these simplified approaches lead to systematic misestimation by expanding both the scale and resolution of available data. For N₂O, the study compiles 376 emission factor observations from 119 publications, representing approximately 200 full-scale facilities worldwide, increasing the dataset more than 12-fold and differentiating emissions across bioreactor, plant-wide, and side-stream scales. For CH₄, complementary synthesis and field studies extend analysis across sewer networks and treatment plants, including plant-integrated measurements at 63 full-scale facilities.

Together, these results show that emissions span orders of magnitude depending on process configuration, operating conditions, and measurement scale, and that applying a single EF obscures this variability. Applying these datasets to U.S. systems yields mean emissions of 10.9 million metric tons CO₂-equivalent per year for CH₄ and 11.6 million metric tons CO₂-equivalent per year for N₂O, highlighting substantial differences from estimates based on uniform EFs. These findings underscore the need for process-informed approaches that better reflect treatment configuration and measurement scale, improving facility-level estimates and their integration into national GHG inventories.



Geographic scope: Global

The database of CH₄ and N₂O emission factors for wastewater treatment plants compiled in this research are applicable at the global scale.

Relative links

- Song, C.H., Zhu, J. J., Willis, J. L., Moore, D. P., Zondlo, M. A., & Ren, Z. J. (2024). Oversimplification and misestimation of nitrous oxide emissions from wastewater treatment plants. *Nature Sustainability*, 1-11. <https://doi.org/10.1038/s41893-024-01420-9>
- Moore, D.P., Li, N.P., Song, C., Zhu, J.J., Yi, H., Tao, L., McSpirtt, J., Sevostianov, V.I., Wendt, L.P., Rojas-Robles, N.E. and Hopkins, F.M., 2025. Comprehensive assessment of the contribution of wastewater treatment to urban greenhouse gas and ammonia emissions. *Nature Water*, pp.1-11. <https://doi.org/10.1038/s44221-025-00490-z>
- Song, C.H., Zhu, J. J., Willis, J. L., Moore, D. P., Zondlo, M. A., & Ren, Z. J. (2023). Methane emissions from municipal wastewater collection and treatment systems. *Environmental Science & Technology*, 57(6), 2248-2261. <https://doi.org/10.1021/acs.est.2c04388>
- Moore, D.P., Li, N., Wendt, L., Castañeda, S., Falinski, M., Zhu, J.J., Song, C., Ren, Z. J., Zondlo, M. A. 2023. Underestimation of wastewater treatment methane emissions in the United States. *Environmental Science & Technology*, 57, 10, 4082–4090. <https://doi.org/10.1021/acs.est.2c05373>

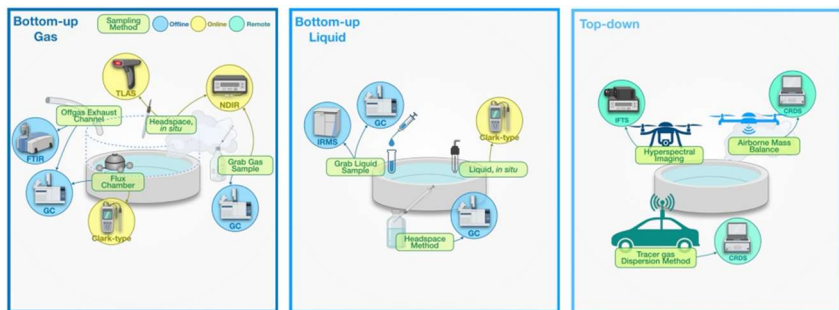
Gaps and inconsistencies in monitoring methodologies for wastewater GHG emissions

Description of the research

Accurate GHG quantification from wastewater systems remains a major gap in national climate inventories, particularly for methane (CH₄) and nitrous oxide (N₂O), whose emissions vary widely across technologies, operating conditions, and regional contexts. Research led by Princeton University and collaborators addresses a key barrier to robust accounting: inconsistencies in emission measurement methodologies.

Through a systematic evaluation of current monitoring approaches, the study finds that bottom-up methods, such as flux chambers and in situ liquid sensors, remain the primary tools for unit-level measurements, while emerging top-down approaches provide integrated, facility-scale estimates. Although no consistent methodological bias is identified, reported emissions vary substantially due to differences in sampling design, treatment configuration, operating conditions, and calibration between dissolved- and gaseous-phase measurements.

The study proposes a harmonized monitoring framework that combines plant-wide hotspot screening, targeted long-term unit process monitoring, and more transparent, standardized reporting. This approach is intended to improve comparability across studies and better reconcile differences between measurement methods and scales.



The findings also identify a structural limitation in the current evidence base. Most available datasets and commonly used methods are derived from large, centralized wastewater systems, while non-sewered and resource-constrained contexts remain underrepresented. This limits the applicability of existing inventories and methodologies in regions where wastewater infrastructure differs substantially. Expanding measurement and methodological development in these contexts is critical to improving representation of undercounted sanitation pathways and strengthening the technical basis for national reporting and mitigation planning.

Timeline

2023–2025

Geographic scope

Global methods synthesis, with implications for diverse system types including underrepresented decentralized and non-sewered systems

Relevant links

- Yan, Y. et al. (2025). Methodology Discrepancy and Data Comparability of GHG Monitoring from Water Resource Recovery Facilities. *Environmental Science & Technology*. <https://doi.org/10.1021/acs.est.5c00345>

Emerging methods for quantifying methane emissions from sewer networks

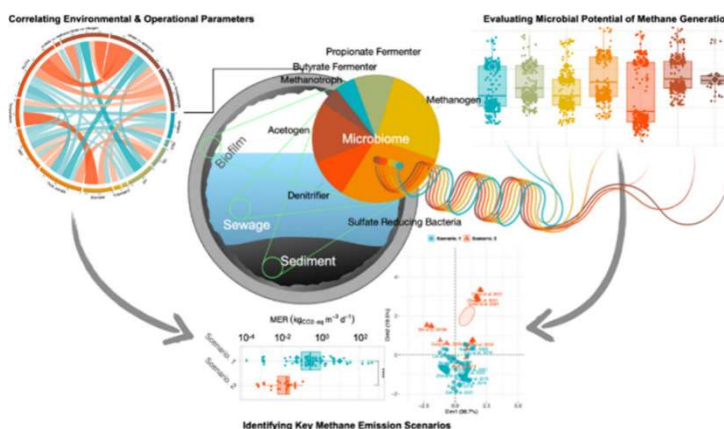
Description of the research

Methane emissions from sewer networks remain substantially underrepresented in GHG inventories because direct monitoring is costly, logistically difficult, and challenged by the internal heterogeneity of buried conveyance systems. Research led by Princeton University and collaborators develops a data-driven alternative that estimates sewer methane potential using microbiome-informed analysis, complementing conventional measurement approaches.

Using a literature-mined dataset comprising 633 observations and 53 variables, the study finds that sewer sediments have the highest methanogenic potential, approximately 250 to 870 percent greater than wetted pipe biofilms or sewage water. Higher emission conditions are associated with smaller pipe diameters, elevated water levels, and stronger organic loading, while microbial interactions such as sulfate reduction indicate links with other co-emitted gases. These results identify sediments as a critical and often overlooked emission source and show that methane generation varies systematically with both infrastructure and biochemical conditions.

The findings demonstrate that integrating microbiome data with hydraulic and infrastructure information can improve understanding of methane generation in complex sewer systems and provide a scalable framework for identifying emission hotspots where direct monitoring data are limited.

Current inventory methods do not adequately capture sewer emissions, and approaches for quantifying these sources remain underdeveloped at the global scale. Microbiome-informed screening can complement measurement programs by prioritizing high-risk locations, improving representation of sewer emissions in national inventories, and reducing uncertainty in wastewater-sector methane estimates. Expanding these approaches is particularly important in rapidly urbanizing regions, where sewer systems are growing but monitoring capacity remains limited.



Timeline

2022–2024

Geographic scope

Global dataset derived from literature-mined observations, with broad applicability to sewer systems across regions

Relevant links

- Yan, Y. et al. (2024). Methanogenic Potential of Sewer Microbiomes and Its Implications for Methane Emission. *Environmental Science & Technology*. <https://doi.org/10.1021/acs.est.4c04005>

Standardizing water sector inventory guidelines and methodologies

GHG accounting for water and wastewater systems has been constrained by inconsistent boundary definitions, incomplete source coverage, and fragmented methodological guidance. Key pathways, including sewer networks, biosolids management, effluent discharge, and certain drinking water processes, are often omitted or inconsistently represented, limiting inventory completeness and comparability.

This research, developed under Water Research Foundation Project 5188, establishes a standardized, sector-specific framework and updates methodologies to support GHG inventories at national, subnational, and facility levels. The guidance strengthens boundary definition to ensure more complete source inclusion, refines default methods from the 2019 IPCC National GHG Inventory Guidelines, and introduces previously unaddressed source categories.

The work extends methodologies across water systems, including improved representation of nitrous oxide emissions from sidestream treatment, expanded coverage of effluent-related emissions, and new methods for drinking water treatment, including dissolved methane release and carbonate chemistry effects.

A central focus is biosolids management and fugitive methane emissions from anaerobic digestion (AD) and biogas systems. Current IPCC guidance does not treat biosolids comprehensively within the wastewater sector, instead relying on methods from other sectors that are not fully aligned with wastewater processes. This work refines methane estimation by differentiating emissions across digestion, gas handling, storage, and combustion, and by incorporating recent measurement-based evidence on fugitive emissions and methane slip.

These advances support more complete and comparable GHG inventories and are directly relevant to improving the treatment of biosolids, drinking water emissions, and methane estimation in future IPCC guidance, while also identifying key gaps where further methodological refinement and improved default factors are needed.

Timeline

2022–2025

Geographic scope

North America–based development with applicability to wastewater systems globally

Relevant links

- Water Research Foundation Project 5188: Water Sector Climate Emissions Reporting (WSCER) Guidelines and Tool
- Supporting materials and tool: www.waterghgs.com

Please see below some brief text addressing the ask on “Advances, research needs and gaps in knowledge and methodologies related to assessing the impact of adaptation action on reducing risk, to inform adaptation planning and action, particularly in developing countries.”

Advances:

One [recent scientific paper](#) shows that the nature-based solutions strategies that have the most potential to provide ecosystem service benefits to population, including to adaptation, are not necessarily those sites that deliver the most climate change mitigation benefits. For instance, per area of conservation action, agroforestry provides substantial human well-being benefits to three times more people on average than reforestation while providing less than one tenth the carbon sequestration per unit area. Focusing on nations with high climate mitigation potential as well as high local ecosystem service potential, such as Nigeria in the case of reforestation, India for agroforestry, and the Republic of Congo for avoided forest conversion, can help identify win-win sites for implementation. The study concludes that targeting these critical places for protection, restoration, and agroforestry interventions will be key to achieving adaptation and human wellbeing goals while also increasing nature-based carbon mitigation and provide a useful set of maps that can be used for international priority setting.

Research needs and gaps:

One report, the [European Roadmap for Nature-based Solutions Research and Innovation](#), reviewed gaps in knowledge around NBS, and listed specific research needs. Identified gaps in knowledge that related to adaptation planning and action, particularly in developing countries, would include:

- There is a gap of long-term monitoring data “on the effectiveness and multiple impacts of NBS, especially in the context of climate change adaptation and disaster risk reduction”*

- *“The sustainability of NBS and their performance over time and in the face of global change is also an area of significant unknowns, both in terms of the long-term delivery of benefits by NBS as well as the costs of NBS over time”*

With respect to your inquiry we'd like to make you aware of the following research at UNU-EHS that may contribute to your requests:

- SBSTA 52–55, 2021: Understanding the opportunities for and challenges of implementing nature- based solutions in land and ocean ecosystems for supporting adaptation and mitigation action
- SBSTA 48–1, 2018: The vulnerabilities of terrestrial, marine, coastal and urban ecosystems to climate change and the value of ecosystem-based approaches, particularly synergies of mitigation and adaptation action and related co-benefits:
 - o Publication on *Nature-based solutions for climate change adaptation and resilience in urban informal settlements: Insights from kibera, kenya and Villa 20, Argentina*, showcasing the need for integrated approaches including local communities in planning of NbS to address climate change and social vulnerability
<https://doi.org/10.1016/j.nbsj.2025.100216>
- SBSTA 56, 2022: Climate change impacts on and risks for vulnerable groups, such as indigenous peoples and local communities, children and youth, people with disabilities and women
 - o Study on *Loss and Damage in Informal Urban Settlements*, identifying particular risks and related needs for L&D policies and financial mechanisms <https://collections.unu.edu/view/UNU:9869#viewMetadata> (with summary report <https://collections.unu.edu/view/UNU:9868> and summary for civil society organizations <https://collections.unu.edu/view/UNU:9867>) and G20 policy paper on *Operationalizing Loss & Damage Financing for Marginalised Urban Communities* <https://collections.unu.edu/view/UNU:9776>

Let me know if you would like to have further details.

Kind regards

Research Need: Advances, research needs and gaps in knowledge and methodologies related to assessing the impact of adaptation action on reducing risk, to inform adaptation planning and action, particularly in developing countries;

Project name: Climate Smart Farming in Africa: A History of Regenerative Agricultural Practices

TEAM: University of Pennsylvania: Carl H. Goldsmith Sustainable Agriculture Fund, Kleinman Center for Energy Policy (lead), Udugu Institute (Zimbabwe), Great Lakes University Kisumu / GLUK (Kenya), USDA

Description. The project identifies and validates indigenous and traditional regenerative agriculture practices in Sub-Saharan Africa, then turns them into a continent-wide policy framework. It distinguishes regenerative agriculture from climate-smart agriculture by emphasizing a reduced reliance on imported external inputs such as synthetic fertilizers, pesticides, and fuel. That distinction matters because, in low-income, import-dependent settings, dependence on those inputs is itself a major source of carbon emissions and climate vulnerability.

- **High-resolution regional information.** Sub-national, agroecologically disaggregated evidence across highland, mid-altitude, and semi-arid zones. A regional digital dashboard (*ongoing*) will visualize yields, soil health, and climate metrics at sub-national resolution.
- **Enabling environments, technologies, and support.** The Harare workshop (June 2025) convened 20+ regional experts and applied a 10-step Evidence-Based Policy Model addressing the "implementation gap." Outputs include a forthcoming policy digest, a peer-reviewed case-study template, and a continental Community of Practice.
- **Synergies and trade-offs across mitigation, adaptation, and SDGs.** Input-reducing practices deliver adaptation, mitigation, and multiple SDGs simultaneously. The project calls for holistic metrics beyond yield to surface trade-offs that single-variable metrics obscure.
- **Equity.** Treated structurally: The project reframes low-input traditional systems as a knowledge contribution, with country reports authored by in-country researchers, the regional convening hosted in Zimbabwe, and a regionally based Community of Practice.

Timeline. Phase 1: foundational research and scoping (Jan–June 2024). Phase 2: country fieldwork and validation, including the Harare regional workshop, 3–5 June 2025 (June 2024–July 2025). Project synthesis report completed August 2025. Phase 3: flagship case studies, policy digest, digital dashboard, and Community of Practice formalization (Sept 2025 through 2026).

Geographic scope. Regional (Sub-Saharan Africa): Ethiopia, Kenya, and Zimbabwe

Links and outputs. Synthesized Project Report: <https://upenn.box.com/v/africanregenag>

PI Contact. Thabo Lenneiye: lenneiye@upenn.edu

Research Need: Needs and gaps in the modelling of sustainable development in mitigation pathways, including the consideration of equity and justice, while recognizing ongoing and encouraging further efforts to address

Although these papers are less about integrated mitigation-pathway modeling itself, they analyze how equity and justice should be incorporated into transition analysis, evaluation, and policy design. Links to the papers are provided in the titles.

1/ [Carley, S. et al. \(2023/2024\), "Metrics for Decision-Making in Energy Justice," Annual Review of Environment and Resources.](#)

Energy equity and justice have become priority considerations for policymakers, practitioners, and scholars alike. To ensure that energy equity is incorporated into actual decisions and analysis, it is necessary to design, use, and continually improve energy equity metrics. In this article, the authors review the literature and practices surrounding such metrics. They present a working definition for energy justice and equity, and connect them to both criteria for and frameworks of metrics. They then present a large sampling of energy equity metrics, including those focused on vulnerability, wealth creation, energy poverty, life cycle, and comparative country-level dynamics. They conclude with a discussion of the limitations, gaps, and trade-offs associated with these various metrics and their interactions thereof.

2/ [Carley, S. & Konisky, D.M. \(2020\), "The justice and equity implications of the clean energy transition," Nature Energy.](#)

The transition to lower-carbon sources of energy will inevitably produce and, in many cases, perpetuate pre-existing sets of winners and losers. The winners are those that will benefit from cleaner sources of energy, reduced emissions from the removal of fossil fuels, and the employment and innovation opportunities that accompany this transition. The losers are those that will bear the burdens, or lack access to the opportunities. This paper reviews the current state of understanding—based on a rapidly growing body of academic and policy literature—about the potential adverse consequences of the energy transition for specific communities and socio-economic groups on the frontlines of the transition. It reviews evidence about just transition policies and programs, primarily from cases in the Global North, and draws conclusions about what insights are still needed to understand the justice and equity dimensions of the transition, and to ensure that no one is left behind.

Submission by Woodwell Climate Research Center for the mapping of how the scientific community is addressing research needs and gaps identified by Parties under the SBSTA

April 15, 2026

Introduction

Woodwell Climate Research Center (Woodwell) appreciates the invitation by the secretariat to submit information on how our work is addressing research needs and gaps identified by Parties under the Subsidiary Body for Scientific and Technical Advice (SBSTA) since June 2005. This submission outlines how Woodwell's research is generating knowledge and applications relevant to the following research needs and gaps identified by the secretariat:¹

- A(a): Near term climate change and its prediction;
- A(f): High resolution local and regional climate information, as well as improving the development and application of downscaled regional and sub regional climate models, for understanding risks and implementing climate action;
- B(d): Understanding of complex, cascading and transboundary risks;
- B(e): Climate risks for vulnerable groups such as Indigenous Peoples, local communities, children and youth, people with disabilities and women;
- C(a): Opportunities and challenges of implementing nature-based solutions in land and ocean systems in support of climate adaptation and mitigation;
- C(b): Climate change impacts and risks for the ocean and cryosphere and related ecosystems;
- C(c): Emissions and removals from terrestrial ecosystems, and information on ecosystems with high-carbon reservoirs;
- E(b): Contribution of Indigenous and traditional knowledge towards understanding climate change and its consequences.

For each need/gap considered, this submission identifies relevant areas of Woodwell research, specific projects and science-based tools, as well as a selection of publications. Cross-references have been used throughout this submission to indicate if a research area relates to multiple needs and gaps.

Woodwell as pioneer of climate science

Woodwell, originally founded as the Woods Hole Research Center in 1985, has been a pioneer in climate science for four decades. Our founder, Dr. George Woodwell, was among the first scientists to bring the urgency of climate change to the attention of policymakers, testifying before the U.S. Congress on the dangers of rising greenhouse gas (GHG) levels in 1986. Since the Earth Summit in 1992, Woodwell scientists have generated foundational research on the carbon cycle, terrestrial ecosystems, tipping points, nature-based solutions, and the human dimensions of climate change to inform international climate negotiations and assessments. Our scientists have contributed to successive assessments of the

¹ The references to research needs across this document are in relation to the synthesis of research needs and gaps distributed by the UNFCCC secretariat (titled “*Research and systematic observation (RSO), mapping of research needs: Categories of research needs and gaps identified since SBSTA 22 under RSO, Version March 2025*”).

Intergovernmental Panel on Climate Change (IPCC), developed state-of the art methodologies for emissions accounting, engaged directly with Parties and policymakers across more than 20 countries, and built partnerships with Indigenous communities, governments, and research institutions on six continents.

This continuity of engagement positions Woodwell to respond to the research needs and gaps identified by Parties under the SBSTA. Our current work focuses on the physical science of climate change, regional and local risk assessments, nature-based solutions (NBS), ecosystem carbon dynamics, feedback loops and tipping points, and the co-production of knowledge with Indigenous and local communities. Woodwell has always oriented its science toward action: generating peer-reviewed knowledge, as well as tools, datasets, and partnerships that enable communities, governments, and negotiators to translate science into policy and action. As the international community works to close the gaps identified since SBSTA 22, Woodwell has outlined our experience in the hopes of contributing to a successful mapping.

The research highlighted in this submission does not capture the full scope of Woodwell’s work over the last 40 years. The information is intended to provide an illustrative but concise representation of key research areas, projects and publications and their relevance to the research needs and gaps identified by Parties. Woodwell experts are ready to provide further information to the secretariat and to Parties to help enhance the solutions to the climate crisis.

How research at Woodwell is addressing research needs and gaps identified by Parties

Research need A(a): Near term climate change and its prediction

In relation to research need A(a) (*Near term climate change and its prediction*), Woodwell has extensive experience on connections between Arctic warming and shifting weather patterns. Our work investigates how Arctic amplification, the phenomenon by which the Arctic warms 3-4 times faster than global average, along with other changes in the climate system, are affecting the jet stream by favoring persistent extreme weather regimes, including heatwaves, droughts, heavy precipitation, and winter cold spells. The work focuses on improving the scientific basis for linking climate change to observable weather events, on near-term projections, on how natural climate oscillations (such as El Niño and La Niña) and oceanic heat waves interact with Arctic-driven changes to affect weather patterns, and on whether current climate models capture these dynamics. This expertise is also relevant to research needs outlined by the secretariat in section A(c) (*Advances in climate model simulations, particularly by combining multiple lines of evidence and on a wider range of climate variables to improve parameterization of the physical climate system and understanding of scenarios*) and B (*Adaptation, loss and damage and extreme events*).

A central project related to this research focuses on methods for identifying a “**weather whiplash**”² - abrupt shifts from one persistent large-scale atmospheric circulation pattern (or regime) to a substantially different one. Woodwell scientists use an artificial intelligence (AI) -based pattern recognition tool called **Self-Organizing Maps** to analyze observational data and detect whiplash events historically, evaluate how well climate models reproduce them, and project how their frequency may change under emissions scenarios. This avoids reliance on temperature or precipitation measurements and, therefore, reduces uncertainties from instrument and model deficiencies. The method is currently applied across large sectors of the Northern Hemisphere, with the opportunity to expand its application to other regions.

² www.woodwellclimate.org/project/extreme-weather-and-climate-change/weather-whiplash/

Woodwell experts have also recently launched a research project to **map how GHG - fueled sea surface temperature (SST) anomalies are affecting weather patterns across the Northern Hemisphere**. The project will use AI to compare patterns in SST and winter weather regimes over North America, the North Atlantic and the Pacific Oceans. The outcomes will improve seasonal weather forecasting and help decision-makers prepare for increasingly extreme weather.³

Table 1: examples of publications by Woodwell experts relevant to climate and weather:

Publication	Woodwell authors	DOI/URL
Francis, J.A. et al. 2026: Are stratospheric polar vortex disruptions what they seem? An alternative metric excludes tropospheric influences. <i>Climate Dynamics</i> 64.	Francis, J.A.	doi.org/10.1007/s00382-025-08011-0
Liu, Y. et al. 2025: Changes in atmospheric circulation amplify extreme snowfall fueled by Arctic sea ice loss over high-latitude land. <i>Weather and Climate Extremes</i> 50.	Francis, J.A.	doi.org/10.1016/j.wace.2025.100802
Francis, J.A. 2021: Vapor Storms Are Threatening People and Property. <i>Scientific American</i> , November 2021.	Francis, J.A.	www.scientificamerican.com/article/vapor-storms-are-threatening-people-and-property/
Francis, J.A. 2019: Yes, Climate Change Is Making Severe Weather Worse: recent disasters show how climate change is making winter storms, flooding rains and summer heat waves more extreme. <i>Scientific American</i> , June 2019.	Francis, J.A.	www.scientificamerican.com/article/yes-climate-change-is-making-severe-weather-worse/
Francis, J.A. 2018: Meltdown: the Arctic is breaking climate records, altering weather worldwide. <i>Scientific American</i> , April 2018.	Francis, J.A.	www.scientificamerican.com/article/the-arctic-is-breaking-climate-records-altering-weather-worldwide/

Research need A(f): High resolution local and regional climate information, as well as improving the development and application of downscaled regional and sub regional climate models, for understanding risks and implementing climate action

In relation to research need A(f) (*High resolution local and regional climate information, as well as improving the development and application of downscaled regional and sub regional climate models, for understanding risks and implementing climate action*), Woodwell has extensive experience with Earth system modeling and with modeling of climate extremes, impacts and risks at different scales. Woodwell’s risk experts perform applied climate risk analyses and use those as a basis for comprehensive risk assessments to communities and governments. This expertise is also relevant to research needs in section B of the synthesis provided by the secretariat (*Adaptation, loss and damage and extreme events*).

³ www.woodwellclimate.org/winter-2026-fund-for-climate-solutions-awards-five-new-grants/

Woodwell’s **Just Access** project provides cost-free and science-based risk assessments for communities and governments facing resource constraints. The project has supported 65 communities and 12 countries,⁴ and reached approximately 250 million people. Its outcomes include national climate risk assessments for Ethiopia⁵ and the Democratic Republic of the Congo.⁶ As part of these assessments, Woodwell experts have developed customized models to understand risks and to facilitate action,⁷ and provided capacity-building support to government officials and other stakeholders to enhance ownership and continuity of efforts. For example, Woodwell staff provided training on climate data analysis, Extreme Value Analysis, Google Earth Engine, and satellite-based flood monitoring to Ethiopian government experts, academics, and civil society.

In 2025, Woodwell published the **Climate Risk Viewer**,⁸ a data visualization tool that enables users to explore and compare local, regional and global patterns of specific climate risks modeled for 1.5°C and 2°C temperature increase scenarios. The tool is based on open access and open source data curated and developed by Woodwell risk experts. It includes variables for drought, hot days, lethal heat, annual precipitation, sea level rise, annual temperature, tropical cyclones, warm nights, and wildfires. Woodwell is also working on a new metric - the **accumulated dangerous heat index** - to identify regions where the combination of temperature and humidity causes hazardous heat conditions.

Table 2: examples of publications by Woodwell experts relevant to impacts and risks:

Publication	Woodwell authors	DOI/URL
Dusseau, D. et al. 2026: Validation and comparison of U.S. loss estimates from catastrophe flood models. In: Journal of Catastrophe Risk and Resilience 4.	Dusseau, D., Schwalm, C., Zobel, Z.	journalofcrr.com/research/04-01-dusseau-et-al/
Law, B.E. et al. 2025: Anthropogenic climate change contributes to wildfire particulate matter and related mortality in the United States. In: Communications Earth & Environment 6(336).	Byrne, D., Schwalm, C.	www.nature.com/articles/s43247-025-02314-0
Dusseau, D. et al. 2026: Inequity in action: U.S. rural counties subsidize flood insurance discounts. In: One Earth 9(1).	Dusseau, D., McGlinchey, D., Schwalm, C.	doi.org/10.1016/j.oneear.2025.101561
Dusseau, D., et. al. 2023: DiluviumDEM: Enhanced accuracy in global coastal digital elevation models. In: Remote Sensing of Environment 298, 113812, ISSN 0034-4257.	Dusseau, D., Schwalm, C., Zobel, Z.	doi.org/10.1016/j.rse.2023.113812
Carter M. Powis et al. 2023: Observational and model evidence together support wide-spread exposure to noncompensable heat under continued global warming. Sci. Adv. 9, eadg9297.	Byrne, D., Gassert, K.N., Lute, A.C., Schwalm, C., Zobel, Z.	www.science.org/doi/10.1126/sciadv.adg9297

⁴ www.woodwellclimate.org/project/just-access/

⁵ www.woodwellclimate.org/climate-risk-assessment-ethiopia/

⁶ www.woodwellclimate.org/risk-to-resilience-drc/

⁷ These include e.g. customized models for precipitation, drought, streamflow, flooding, sewage, drainage, as well as for health impacts of air pollution from wildfires (see, for example, the risk assessment for the city of Rio Branco, Brazil, at www.woodwellclimate.org/climate-risk-assessment-rio-branco-brazil/).

⁸ www.woodwellclimate.org/project/climate-risk-viewer/

Research need B(d): Understanding of complex, cascading and transboundary risks

In relation to research need B(b) (*Understanding of complex, cascading and transboundary risks*), Woodwell collaborates with other research organizations, intergovernmental bodies, and private sector partners to produce interdisciplinary and collaborative research on transboundary, security and economic risks of climate change.

With the United Nations Environment Programme, Woodwell experts supported the project **Transformational Change in Sustainable Forest Management in Transboundary Landscapes of the Congo Basin** (part of Congo Basin Sustainable Landscapes Programme of the 7th replenishment of the Global Environment Facility) by analyzing climate impacts in four transboundary landscapes and evaluating they threaten endangered wildlife and the capacity of forests to store carbon.⁹ Another project, a collaboration with the Converging Risks Lab and the Council on Strategic Risks, studied the **abrupt environmental shifts in the Arctic**, such as permafrost thaw and sea ice loss, as well as the associated changes in human activities, especially resource extraction, marine traffic and military activities.¹⁰

Since 2018, Woodwell risk scientists have **collaborated with private sector partners** to integrate climate risk with the financial sector. Woodwell works with Wellington Management to provide climate data, models and analyses to integrate climate risk into asset management and financial markets. The collaboration has resulted in a tool for mapping climate risks at asset and portfolio levels, and in the first-ever guidelines for corporate disclosure of physical climate risk in 2019.¹¹ Woodwell also partnered with McKinsey and Co. to provide scientific backing for global climate risk reports, including physical risk and response assessments in Asia, the United States, the Mediterranean, and the European Union.¹²

Research need B(e): Climate risks for vulnerable groups such as Indigenous Peoples, local communities, children and youth, people with disabilities and women

Woodwell collaborates with Indigenous and local communities to map climate risks for those communities, in particular across the Amazon and the Arctic.

In the Amazon, Woodwell experts have led the establishment of a **network of cost-effective air quality sensors** in the Brazilian and Peruvian Amazon to generate ground-level data to support community health policies¹³, documented the impacts of droughts and fires on the Xingu Indigenous Territory in 2001-2020, and are now working to publish latest observations from the sensor network for drought and non-drought periods throughout 2023-2025, indicating how drought-driven fire activity causes periods of hazardous air pollution for Amazonians.

⁹ The results are captured in Naegele, A. and Bush, G. 2025: Climate Analysis and Policy Recommendations on Incorporating Climate Change Considerations into Integrated Land Use Management Plans in the Congo Basin (www.congolandscape.org/node/1032).

¹⁰ The results are reflected in Guy, K., Naegele, A., Baillargeon, N., Holland, M., Schwalm, C.R. and Churchill, C. 2021: Temperatures and tensions rise: Security and climate risk in the Arctic (www.woodwellclimate.org/wp-content/uploads/2023/09/Global_Risk_and_Security_Arctic_Case_Study.pdf).

¹¹ www.woodwellclimate.org/project/woodwell-wellington/

¹² www.woodwellclimate.org/a-productive-first-year-of-work-with-mckinsey-company

¹³ <https://www.woodwellclimate.org/amazon-air-quality-monitoring/>

In the Arctic, Woodwell tracks how rapid warming is threatening Indigenous livelihoods and community safety. The work maps e.g. how permafrost thaw is destabilizing roads, buildings, and critical infrastructure, how Sámi reindeer herders in Norway face unpredictable grazing conditions as changing precipitation and temperature patterns disrupt centuries-old migration routes, and how the decline in Chinook Salmon populations in the Arctic-Yukon-Kuskokwim region of Alaska threatens Indigenous communities whose way of life and food security are dependent on healthy salmon populations.¹⁴

Information on Woodwell’s work with communities to co-produce and apply Indigenous and traditional knowledge for climate action is reflected in the context of research need E(b) below (*Contribution of Indigenous and traditional knowledge towards understanding climate change and its consequences*).

Table 3: examples of publications by Woodwell experts on impacts on Indigenous communities:

Publication	Woodwell authors	DOI/URL
Santos de Lima, L. et. al. 2024: Severe droughts reduce river navigability and isolate communities in the Brazilian Amazon. <i>Communications Earth & Environment</i> 5.	Macedo, M.N.	doi.org/10.1038/s43247-024-01530-4
Feddern, M.L. et. al. 2023: Kings of the North: Bridging Disciplines to Understand the Effects of Changing Climate on Chinook Salmon in the Arctic–Yukon–Kuskokwim Region, <i>Fisheries</i> 48(8), 331–343.	Woods, B.	doi.org/10.1002/fsh.10923
Silvério, D.V. et al. 2022: Intensification of fire regimes and forest loss in the Território Indígena do Xingu. <i>Environmental Research Letters</i> 17.	Macedo, M.N.	iopscience.iop.org/article/10.1088/1748-9326/ac5713
Oliveira, H.F.M. et al. 2025: Expand air quality monitoring of smoke emissions and exposure in Amazonia to safeguard human health. <i>Discov Environ</i> 3, 171.	Macedo, M.N.	doi.org/10.1007/s44274-025-00340-5

Research need C(a): Opportunities and challenges of implementing NBS in land and ocean systems in support of climate adaptation and mitigation

In relation to research need C(a) (*Opportunities and challenges of implementing NBS in land and ocean systems in support of climate adaptation and mitigation*), Woodwell experts have deep expertise on the potential of NBS to keep the world on track towards the temperature limits of the Paris Agreement, and on best practices in implementing NBS. This work focuses in particular on the role of soils in mitigation, the potential for solutions in the nexus of forests and agriculture, as well as the application of fire management practices as a NBS.

¹⁴ See <https://permafrost.woodwellclimate.org/adaptation-strategies/> and <https://storymaps.arcgis.com/stories/a4aa7e22d8874960a4de347cabe0ff5c>

Table 4: examples of publications by Woodwell experts relevant on NBS in general:

Publication	Woodwell authors	DOI/URL
Roe, S. et al. 2021: Land-based measures to mitigate climate change: Potential and feasibility by country. In: <i>Global Change Biology</i> 27(33).	Rivard, C., Sanderman, J.	doi.org/10.1111/gcb .15873
Roe, S. et al. 2019: Contribution of the land sector to a 1.5°C world. In: <i>Nature Climate Change</i> 9, 817-828.	Sanderman, J.	doi.org/10.1038/s41 558-019-0591-9
Griscom, B.W. et al. 2017: Natural climate solutions. In: <i>PNAS</i> 114(44).	Houghton, R.A., Sanderman, J.	doi.org/10.1073/pna s.1710465114

Soils as an NBS

Woodwell’s research covers the role of soils in mitigation, including processes that add, remove and transform carbon in soils, complexity of soil carbon reservoirs, modeling of soil carbon dynamics, and how soil carbon could be integrated into carbon markets. Woodwell scientists have conducted global assessments of the potential and feasibility of land-based mitigation measures, developed methods for monitoring climate benefits of land management strategies on working lands, and optimizing soil carbon measurements through soil spectroscopy and other tools.

Woodwell’s research project **Land as a Natural Climate Solution**¹⁵ estimates the global potential for increasing carbon storage in different land systems, including the size of potential storage, its locations, and the actions that can be taken to implement these natural climate solutions. The project has produced a global spatial dataset of current, potential, and unrealized potential carbon storage in forests, other woody ecosystems, and associated soils, as well as a framework for prioritizing on-the-ground actions related to the restoration, improved management, and maintenance of carbon stocks in these systems. Woodwell also works closely with agricultural and environmental leaders to identify and close key information gaps to enable effective consideration of soils in carbon markets.¹⁶

Rangelands, which cover more than a quarter of global ice-free land surface and hold ca. 30 per cent of global soil carbon, provide a major underused opportunity for NBSs. Woodwell’s **Carbon Monitoring in Rangelands Program** addresses the near-total absence of affordable and accurate data on land health and carbon stocks in grazing lands. The program developed **RangeSTAR (Range System for Tracking and Reporting Carbon)**, a remote sensing and process-based modeling tool that integrates satellite imagery with weather, soil and vegetation data to make high-resolution, spatiotemporal estimates of rangeland productivity, soil organic carbon, and ecosystem carbon fluxes. RangeSTAR is designed to support monitoring, measurement, reporting, and verification of carbon across grazing lands in the United States, with the goal of expansion to other regions. It helps stakeholders such as ranchers, tribal agencies and policymakers seeking to engage with carbon markets and conservation programs.

¹⁵ www.woodwellclimate.org/project/land-as-a-natural-climate-solution/

¹⁶ www.woodwellclimate.org/project/taking-stock-of-soil-carbon/

Woodwell also leads several soil spectroscopy projects to enhance soil carbon measurements. **Soil.Spectroscopy** is a project that brings together scientists and technical experts to enable wider and more efficient use of soil spectroscopy for e.g. global carbon cycle modeling.¹⁷ **Soils Revealed** provides interactive maps of global soil carbon change and local mitigation potential.¹⁸

Table 5: examples of publications by Woodwell experts on soil carbon:

Publication	Woodwell authors	DOI/URL
Sanderman, J. et al. 2025: Application of a Handheld Near Infrared Spectrophotometer to Farm-Scale Soil Carbon Monitoring. In: European Journal of Soil Science.	Partida, C., Safanelli, J.L., Sanderman, J.	doi.org/10.1111/ejss.70053
Xia, Y. et al. 2025: Coupling Remote Sensing With a Process Model for the Simulation of Rangeland Carbon Dynamics. In: Journal of Advances in Modeling Earth Systems.	Hernandez, H., Mullen, A.L., Rivard, C., Sanderman, J., Watts, J.D., Xia, Y.	doi.org/10.1029/2024MS004342
Oldfield, E.E. et al. 2023: Greenhouse gas mitigation on croplands: clarifying the debate on knowns, unknowns and risks to move forward with effective management interventions. In: Carbon Management 15(1).	RoyChowdhury, T., Sanderman, J.	doi.org/10.1080/17583004.2024.2365896
Sanderman, J. et al. 2017: Soil carbon debt of 12,000 years of human land use. In: Sustainability Science 114(36).	Fiske, G.J., Sanderman, J.	doi.org/10.1073/pnas.1706103114

Incentivizing NBS for tropical forests and agriculture

Woodwell experts also study the opportunities and challenges for NBS in context of tropical forests and agriculture, with particular focus on the protection of standing forests, regenerative agriculture as well as alignment of economic incentives to protect forests (including markets mechanisms such as the Paris Agreement Crediting Mechanism and jurisdictional REDD-plus). This work is also relevant to research needs A(f) (*High resolution local and regional climate information, as well as improving the development and application of downscaled regional and sub regional climate models, for understanding risks and implementing climate action*) and C(c) (*Emissions and removals from terrestrial ecosystems, and information on ecosystems with high-carbon reservoirs*) identified in the synthesis by the secretariat.

In the Amazon, the **Global Assessment from Local Observations (GALO)** project conducts field research at farms to explore the dynamics of agriculture and the environment, with focus on standing forests, climate stability, and carbon-rich landscapes as foundations for regenerative agriculture across the Cerrado and Amazonia regions. Woodwell scientists focus on four interconnected dimensions of NBS: climate regulations, water quality and availability, emission reduction and sequestration, and biodiversity protection. The project conducts sampling of water, biodiversity, and above- and below-ground carbon across farm fields, forests, and buffer zones between them, generating insights into how agricultural management affects ecosystem functions and soil carbon storage. GALO also assesses the economic and

¹⁷ soilspectroscopy.org/

¹⁸ www.woodwellclimate.org/project/soils-revealed/

social costs and benefits of climate-resilient agriculture and viability of NBS for farmers and communities in Brazil and other tropical regions. By overlaying global climate projections with local land-use dynamics, GALO produces high-resolution, place-based climate information that is essential for adaptation and that global models alone cannot provide.¹⁹

Woodwell partnered with the Amazon Environmental Research Institute (IPAM) to design and launch **CONSERV** - a mechanism designed to mobilize and allocate funds from performance-based financial mechanisms to farmers to forgo their legal right to deforest their lands in the Mato Grosso province of Brazil. CONSERV locks at-risk lands into conservation contracts and creates an asset for farmers to protect, rather than a barrier to economic activities. Woodwell and IPAM engaged with 22 farms and three municipalities, surveyed their willingness to participate, leveraged knowledge to identify, contract, and pay landowners to set aside their remaining forests for conservation, and set up a monitoring framework.²⁰

Woodwell has collaborated since 2011 with national and provincial governments and stakeholders in the DRC through the **Project Équateur** to enhance investment in conservation and regeneration of forests and biodiversity, to improve livelihoods, and to advance development through research, education, and capacity building. Focus is i.a. on forest governance and management, equitable incentives and low-input food production, connecting producers to markets, standards for high-integrity carbon credits, performance-based mechanisms to finance sustainable forest landscape management, and monitoring and evaluating land sector emissions. The project is helping to protect 643,000 km² of primary forests and improve food security and livelihoods for more than 6 million subsistence farms.²¹

Woodwell experts are also actively engaged in efforts to make operational the Tropical Forests Forever Facility (TFFF) launched at COP 30. Woodwell is currently designing tools that can help prioritize and optimize activities TFFF support. For example, Woodwell’s new **Landscape Capital Index (LCI)** is a data tool to enable identifying optimal locations for implementing NBS. The LCI is currently being built into a publicly available web-based tool.²²

Table 6: examples of publications by Woodwell experts on deforestation:²³

Publication	Woodwell authors	DOI/URL
De Clippele, A. et al. 2024: Aquatic and Soil CO ₂ Emissions from forested wetlands of Congo's Cuvette Centrale. In: Biogeosciences, 22, 3011–3027.	Bush, G., Zambo, J.	doi.org/10.5194/bg-22-3011-2025

¹⁹ www.woodwellclimate.org/project/galo/

²⁰ www.woodwellclimate.org/project/conserv/

²¹ www.woodwellclimate.org/project/projet-equateur/

²² www.woodwellclimate.org/ncs-and-the-voluntary-carbon-market/

²³ See also:

- Seymour, F., Wolosin, M. and Gray, E. 2022: Not Just Carbon: Capturing All the Benefits of Forests for Stabilizing the Climate from Local to Global Scales. World Resources Institute. <https://doi.org/10.46830/wrirpt.19.00004>

- Bush, G., Ruzigandekwe F. & Flores, M. (2024). “The economic impact of shifting to climate-smart agricultural and conservation practices in the Bwindi Ecosystem: A Targeted Scenario Analysis. Technical Report, Vanishing Treasures Project, GRASP-UNEP, Nairobi.

http://www.woodwellclimate.org/wp-content/uploads/2026/02/Bwindi-TSA-case-study_10222024.pdf.

Bush, G. et al. 2024: Evaluating the costs of primary forest conservation in the Democratic Republic of Congo, implications for policy and practice. In: Journal of Environmental Management 352, 119975.	Bush, G.	doi.org/10.1016/j.jenvman.2023.119975
Stabile, M.C.C. et al. 2022: Slowing Deforestation in the Brazilian Amazon: Avoiding Legal Deforestation by Compensating Farmers and Ranchers. Frontiers in Forests and Global Change 4.	Bush, G.	doi.org/10.3389/ffgc.2021.635638
Rattis, L. et al. 2021: Climatic limit for agriculture in Brazil. In: Nat. Clim. Chang. 11, 1098–1104.	Coe, M.T., Macedo, M.N., Rattis, L.	doi.org/10.1038/s41558-021-01214-3
Lawrence, D. et al. 2022: The Unseen Effects of Deforestation: Biophysical Effects on Climate. In: Front. For. Glob. Change, Sec. Forest Disturbance 5.	Coe, M.T., Walker, W.	doi.org/10.3389/ffgc.2022.756115
Coe, M.T. et al. 2017: The Forests of the Amazon and Cerrado Moderate Regional Climate Are the Key to the Future. In: Tropical Conservation Science 10.	Brando, P.M., Coe, M.T., Deegan, L.A., Macedo M.N., Neill, C.	journals.sagepub.com/doi/10.1177/1940082917720671

Fire management as a NBS for climate change mitigation and adaptation

Woodwell experts also focus on fire management strategies, their cost-effectiveness, and how those can provide mitigation solutions. While fire is often an intrinsic ecological process, observed changes in fire regimes – characterized by increasing frequency, extent and intensity – are exceeding historical variability, challenging ecosystem resilience, and emitting increasing levels of carbon into the atmosphere. This is particularly the case for forest, peatland and permafrost systems.

Woodwell research has documented how many national and regional approaches remain heavily oriented toward suppression or blanket fire bans, despite evidence that such approaches are insufficient under increasingly flammable conditions and can contribute to fuel accumulation and more severe fires. Based on these findings, our work focuses on how various fire management strategies, including targeted early suppression, prescribed and cultural burning and fuel treatments, can provide powerful tools to reduce fire-related GHG emissions, how fire management can shift from a focus on reactive suppression towards integrated fire management, and how the socio-ecological and cultural context in which fires occur can be recognized and integrated into responses.

Woodwell’s project on **Changing Boreal Fire Regimes** focused, i.a. on the potential use of fire management strategies for mitigation in Arctic-boreal systems.²⁴ Woodwell provides expertise on modeling and community engagement in context of boreal and tropical ecosystems for the **AI Collaborative on Wildfires**,²⁵ a Google.org strategic initiative that aims to deploy AI in support of wildfire management in line with the launch of Google’s FireSat tool. Woodwell experts also work on integrated fire management practices in the Amazon and Brazilian Cerrado, collaborate with **Indigenous**

²⁴ www.woodwellclimate.org/project/changing-boreal-fire-regimes/

²⁵ <https://blog.google/company-news/outreach-and-initiatives/google-org/ai-collaboratives-wildfires-food-security/>

fire brigades, and consider how Indigenous practices can help respond to **wildland fires in the Arctic** (see section on research need E(b) (*Contribution of Indigenous and traditional knowledge towards understanding climate change and its consequences*) below).

Table 7: examples of publications by Woodwell experts on fire management:

Publication	Woodwell authors	DOI/URL
Menor, I.O. et al. 2025: Integrated fire management as an adaptation and mitigation strategy to altered fire regimes. <i>Communications Earth & Environment</i> 6.	Machado, M.S.	doi.org/10.1038/s43247-025-02165-9
Machado, M. et al. 2024: Emergency policies are not enough to resolve Amazonia’s fire crises. <i>Nature Communications Earth & Environment</i> 5.	Brando, P.M., Machado, M.	www.nature.com/articles/s43247-024-01344-4
Machado, M.S. et al. 2025: Experimental assessment of forest flammability after selective logging in the Brazilian Amazon. <i>Commun Earth Environ</i> 6, 696.	Machado, M.S., Macedo, M.N.	https://doi.org/10.1038/s43247-025-02688-1
Elder, M. et al. 2022: The costs and benefits of fire management for carbon mitigation in Alaska through 2100, <i>Environ. Res. Lett.</i> 17, 105001.	Frumhoff, P.C., Potter, S., Rogers, B.M.	doi.org/10.1088/1748-9326/ac8e85
Phillips, C.A. et al. 2022: Escalating carbon emissions from North American boreal forest wildfires and the climate mitigation potential of fire management, <i>Science Advances</i> 8, eabl7161.	Cooperdock, S., Frumhoff, P.C., Rogers, B.M.	doi.org/10.1126/sciadv.abl7161
Rogers, B.M. et al. 2020: Focus on changing fire regimes: interactions with climate, ecosystems, and society, <i>Environmental Research Letters</i> 15(3).	Rogers, B.M.	iopscience.iop.org/article/10.1088/1748-9326/ab6d3a/meta

Research need C(b): Climate change impacts and risks for the ocean and cryosphere and related ecosystems

Woodwell experts have conducted extensive research into climate impacts on the cryosphere. The **Permafrost Pathways** project,²⁶ launched in 2022 as a collaboration with the Arctic Initiative at Harvard Kennedy School, and the Alaska Institute for Justice focuses on a wide range of impacts related to Arctic permafrost thaw. Woodwell’s work on impacts on Indigenous and local communities in the Arctic is reflected in relation to research need B(e) above.

Woodwell’s **Permafrost Discovery Gateway**²⁷ (PDG) tool is a free online platform designed to support knowledge generation about the changing Arctic cryosphere. The platform provides automated monthly monitoring of permafrost thaw during the snow-free season using satellite imagery at multiple resolutions, and hosts a suite of pan-Arctic geospatial data products mapping retrogressive thaw slumps, wildfire

²⁶ permafrost.woodwellclimate.org

²⁷ www.woodwellclimate.org/project/permafrost-discovery-gateway/

areas, coastal erosion, ice-wedge polygons, and surface water change. By making this information open to researchers, planners, policymakers, educators and the public, the PDG enables users to better understand permafrost thaw dynamics, assess associated climate feedbacks and infrastructure risks, and develop evidence-based responses.

Table 8: examples of publications by Woodwell experts relevant to cryosphere impacts:

Publication	Woodwell authors	DOI/URL
Manos, E. et al. 2025: Permafrost thaw-related infrastructure damage costs in Alaska are projected to double under medium and high emission scenarios. <i>Communications Earth & Environment</i> 6(221).	Liljedahl, A.K.	doi.org/10.1038/s43247-025-02191-7
Watts, J.D. et al. 2025: Regional hotspots of change in northern high latitudes informed by observations from space. <i>Geophysical Research Letters</i> 52, e2023GL108081.	Arndt, K.A., Burrell, A., Fiske, G., Natali, S.M., Potter, S., Rogers, B.M., Virkkala, A-M., Watts, J.D.	doi.org/10.1029/2023GL108081
Natali, S.M. et al. 2022: Incorporating permafrost into climate mitigation and adaptation policy. <i>Environmental Research Letters</i> , 17, 091001.	Holdren, J.P., Natali, S.M., Rogers, B.M., Treharne, R.	doi.org/10.1088/1748-9326/ac8c5a
Webb, E.E. et al. 2022: Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. <i>Nature Climate Change</i> 12, 841–846.	Liljedahl, A.K.	doi.org/10.1038/s41558-022-01455-w
Wolken, G.J. et al. 2021: Glacier and Permafrost Hazards. In: Moon, T.A., Druckenmiller, M.L. and Thoman, R.L. (Eds.), <i>Arctic Report Card 2021</i> . NOAA.	Fiske, G., Liljedahl, A.K., Natali, S.M.	doi.org/10.25923/b7c7-6431

Research need C(c): Emissions and removals from terrestrial ecosystems, and information on ecosystems with high-carbon reservoirs

On research need C(c) (*Emissions and removals from terrestrial ecosystems, and information on ecosystems with high-carbon reservoirs*), our scientists are studying and quantifying i.a. GHG emissions from warming ecosystems, in particular thawing permafrost, boreal wildfires and warming wetlands, as well as the dynamics and impacts of those emissions on e.g. the global carbon budget. This work is also relevant to research needs D(a) (*GHG emissions by sources, removals by source and all reservoirs*) and D(f) (*science-based GHG reporting methodologies used, inter alia, for carbon accounting frameworks*) of the synthesis provided by the secretariat.

The **Permafrost Pathways** project (see footnote 26 above), is coordinating a comprehensive monitoring network to improve tracking and modeling of Arctic permafrost and carbon fluxes, and fostering partnerships with local leaders and national policymakers to harness the data to support local adaptation and global mitigation efforts. In terms of emissions from fires, Woodwell leads the project **Changing Boreal Fire Regimes**, which focuses on the changing fire regimes in boreal forests, as well as the impact

of that change on associated phenomena such as permafrost thaw, on carbon emissions.²⁸ Woodwell is also a partner of the **warming-induced emissions model intercomparison project (WIEMIP)**, launched in 2025 to enhance estimates of warming-induced emissions.²⁹

Woodwell’s **Boreal Biosequester** project is exploring the methane-removing potential of methanotrophs - microbes that live on surface areas of boreal forests, including on soils, tree bark and leaves - and considering how those microbes could be harnessed to remove methane from the atmosphere.³⁰ Woodwell’s research also highlighted significant and growing gaps in the global methane monitoring systems (see e.g. Watts et al. 2026 in table below).

Table 9: examples of publications by Woodwell experts relevant to ecosystem emissions:

Publication	Woodwell authors	DOI/URL
Watts, J.D. et al. 2026: A global methane observation system to track climate feedbacks for verifiable climate impact. In: Science, Vol 391, Issue 6792, pp. 1324-1327.	Arndt, K.A., Natali, S.M., Watts, J.D.	www.science.org/doi/10.1126/science.aef0459
Schaedel, C. et al. 2026: Permafrost and wildfire carbon emissions indicate need for additional action to keep Paris Agreement temperature goals within reach. In: Communications Earth & Environment.	MacDonald, E., Natali, S.M., Rogers, B.M., Schaedel, C., Smith, T., Treharne, R.	doi.org/10.1038/s43247-026-03189-5
Buma, B. et al. 2026: Policy solutions to better assess progress toward Paris goals given warming-induced ecosystem emissions, which shorten timelines by 2-5 years. In: One Earth, 101571.	Frumhoff, P., Goldberg, M., Natali, S.M., Rogers, B.M., Schaedel, C., Treharne, R.	doi.org/10.1016/j.oneear.2025.101571
Virkkala et al. 2025: Wildfires offset the increasing but spatially heterogeneous Arctic-boreal CO2 uptake. Nat. Clim. Chang. 15, 188–195.	Arndt, K.A., Burrell, A., Natali, S.M., Potter, S., Rogers, B.M., Virkkala, A., Wargowsky, I., Watts, J.D.	doi.org/10.1038/s41558-024-02234-5
Goldstein, A. et al. 2020: Protecting irrecoverable carbon in Earth’s ecosystems. In: Nature Climate Change 10, 287-295.	Sanderman, J.	doi.org/10.1038/s41558-020-0738-8

Research need E(b): Contribution of Indigenous and traditional knowledge towards understanding climate change and its consequences

With reference to research need E(b) (*Contribution of Indigenous and traditional knowledge towards understanding climate change and its consequences*), Woodwell recognizes Indigenous and traditional knowledge as essential to understanding climate change and its impacts. Across the Arctic Circumpolar North, Amazon, Cerrado and Mongolian Taiga, Woodwell researchers co-produce knowledge with Indigenous communities, integrating place-based observation with scientific methods to understand how

²⁸ www.woodwellclimate.org/project/changing-boreal-fire-regimes/

²⁹ www.sparkclimate.org/warming-induced-emissions/wie-mip

³⁰ www.woodwellclimate.org/project/boreal-biosequester/

climate change is reshaping ecosystems and lives. This information is also relevant to research needs outlined in section B(e) of the synthesis provided by the secretariat (*Climate risks for vulnerable groups such as Indigenous Peoples, local communities, children and youth, people with disabilities and women*).

The **Permafrost Pathways** project (see footnote 26 above) works with Alaskan Native communities to integrate Indigenous knowledge with carbon flux monitoring, ecosystem modeling, and satellite-based mapping to understand how permafrost thaw, flooding, and erosion transform Arctic landscapes.³¹ Community members serve as Tribal Liaisons, contributing on-the-ground observations that inform scientific outputs, such as a co-produced flood model that incorporates sensor data and local knowledge of sinking ground. The project also builds geographic information system (GIS) capacity in communities, enabling partners to map impacts, document place names in Native languages, and represent their territories in policy settings. This approach has contributed to a comprehensive Arctic-boreal carbon flux database, and demonstrated how more than one-third of the Arctic-boreal region has shifted from a carbon sink to a source.³² Our experts have also highlighted the importance of the Indigenous Gwich'in cultural burning for Arctic wildfire management. The practice uses "cool" spring fires to clear dead vegetation, promote the growth of nutritious plants for wildlife, and create natural fire breaks for the summer.³³

In Brazil, Woodwell's **work with Indigenous fire brigades**³⁴ applies co-production to wildfire management and research. In partnership with IPAM, Woodwell has led GIS capacity-building workshops for Indigenous fire brigades across Brazil, equipping them with spatial analysis tools for documenting fire patterns, mapping their territories, and engaging with government agencies on fire management policy. Indigenous participants bring irreplaceable knowledge of traditional burning calendars and landscape dynamics that climate change is disrupting. Building on this foundation, Woodwell is expanding its community-driven climate hazard monitoring across the Amazon by training community fellows in GIS, participatory mapping, and satellite data to establish a community-governed **Amazon Threat Data Hub**.

Woodwell's research has also demonstrated that **Indigenous stewardship of land in the Brazilian Amazon**³⁵ is among the most effective strategies for maintaining forest carbon stocks and ecosystem health, with direct implications for mitigation policies. Analyzing remote sensing data across land tenure types between 2003 and 2019, Woodwell scientists found that lands outside Indigenous territories and protected natural areas accounted for approximately 70 per cent of total carbon losses despite comprising less than half the total land area, while Indigenous territories kept emissions consistently low, performing as effectively as government protected areas (see Walker, W.S. et al., 2020 in table below). Woodwell experts have shared these results at UNFCCC side events, highlighting that stronger Indigenous land rights, including permanent land titles, is a high-impact climate strategy aligned with climate justice.

In Norway, Woodwell geospatial analysts and the International Centre for Reindeer Husbandry co-produced a map³⁶ with Sámi collaborators to document how reindeer herds navigate a landscape fractured by climate change and industry, blending satellite imagery with traditional knowledge of seasonal grazing grounds and migration routes. Woodwell hosted 18 Indigenous youth leaders from the circumpolar North for a day of science, mapping, and policy programming, equipping young Indigenous

³¹ permafrost.woodwellclimate.org

³² Moon, T.A., Druckenmiller, M.L., Thoman, R.L. (Eds) 2024: Arctic Report Card. doi.org/10.25923/b7c7-6431.

³³ wildfiretoday.com/cultural-burning-wildfires-in-the-arctic/

³⁴ www.woodwellclimate.org/brigadistas-indigenous-womens-fire-brigades-gis/.

³⁵ www.woodwellclimate.org/powerful-and-vulnerable-indigenous-communities-are-key-to-protecting-the-amazon/

³⁶ www.maps.com/uncertainty-arrives-in-the-arctic/

leaders with GIS and mapping tools to document climate impacts in their communities and advocate for traditional ways of life.³⁷ In Mongolia, Woodwell has worked in **collaboration with Dukha reindeer herding communities** to co-produce maps of migratory routes, seasonal camp locations, and land-cover change, combining Indigenous spatial knowledge with geospatial data to document how rapid warming, permafrost thaw, and land-use restrictions are threatening traditional livelihoods. The project will expand the co-production approach by training Dukha herders in GIS map storytelling tools and systematically mapping land-use changes affecting Indigenous grazing lands.

Table 10: examples of publications by Woodwell experts relevant to Indigenous knowledge:

Publication	Woodwell authors	DOI/URL
Webb, H. et al. 2025: A review of abrupt permafrost thaw: definitions, usage, and a proposed conceptual framework. <i>Current Climate Change Reports</i> 11(7).	Natali, S.M., Schaedel, C., Virkkala, A-M.	link.springer.com/article/10.1007/s40641-025-00204-3
Walker, W.S. et al. 2020: The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas, <i>Proc. Natl. Acad. Sci. U.S.A.</i> 117 (6) 3015-3025.	Gorelik, S.R., Macedo, M.N., Walker, W.S.	doi.org/10.1073/pnas.1913321117
Bronen et al. 2019: Usteq: integrating indigenous knowledge and social and physical sciences to coproduce knowledge and support community-based adaptation. <i>Polar Geography</i> 43(2-3).	Natali, S.M.	doi.org/10.1080/1088937X.2019.1679271

About Woodwell Climate Research Center

Originally founded as the Woods Hole Research Center in 1985, Woodwell’s world-leading science helps individuals, communities, corporations, and nations understand the realities of climate change, recognize the impact it is having everywhere on our planet, and embrace the urgent action needed to safeguard the future of life on Earth. We work with partners, stakeholders, and government officials in more than 20 countries across six continents, from the Arctic to the Amazon. Woodwell’s researchers conduct science for solutions at the nexus of climate, people, and NBS that are urgently needed to propel us toward a more equitable, healthy, and sustainable world. Together with our global network of partners, we generate breakthrough insights into the risks we face and the just, effective solutions we can develop.

³⁷

permafrost.woodwellclimate.org/permafrost-pathways-hosts-arctic-youth-commemorates-partnership-with-international-centre-for-reindeer-husbandry/



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SBSTA input: WCRP

The below input is *only a small sample of examples* WCRP would like to highlight. For a full history please check the reports and website of WCRP (<https://www.wcrp-climate.org/>)

A. Understanding Climate Change, Climate Data and Scenario Development and Use

Sub-topics

Near-term climate change and its prediction: e.g. EPESC and GC-NTCP

Examples: WCRP's Grand Challenge on Near Term Prediction (GC-NTCP) and the Explaining and Predicting Earth System Change (EPESC) Lighthouse Activity

1. GC-NTCP:

Summary description: The Grand Challenge on Near-Term Climate Prediction supported research and development to improve multi-year to decadal climate predictions and their utility to decision makers. It aimed to support the development of organizational and technical processes for future routine provision of decadal prediction services that can assist stakeholders and decision-makers.

Timeline: 2016-2022

Geographic scope: Global

Relevant outputs and links: <https://www.wcrp-climate.org/gc-near-term-climate-prediction>

The GC-NTCP's main final product was the Annual to Decadal Climate Update: <https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/seasonal-forecast/annual-to-decadal-update-faqs>

Partnerships and collaborations: Many, led by UK Met Office

Capacity-building activities: N/A

2. EPESC:

Summary description: Design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning, and prediction of Earth System change on global and regional scales, with a focus on multi-annual to decadal timescales. Has three Working Groups:

- Working Group 1: Observing and Modelling of Earth System Change

- Working Group 2: Integrated Attribution, Prediction and Projection
- Working Group 3: Assessment of Current and Future Hazards

Timeline: 2021- onwards (noting LHAs have a lifetime of ~10 years)

Geographic scope: Global

Relevant outputs and links: <https://www.wcrp-climate.org/epesc>

See also: <https://www.wcrp-climate.org/epesc-documents>

Capacity-building activities: Various, focused on Early Career and engaging Global South scientists.

Advances in scenario development and use, including scenarios limiting warming in 2100 to 1.5°C relative to pre-industrial levels e.g. CMIP:

The Coupled Model Intercomparison Project (CMIP)

Summary description: CMIP is a project of the World Climate Research Programme, providing climate projections to understand past, present and future climate changes. Members of the **CMIP Core Panel** designed and are currently implementing **CMIP Phase 7 (CMIP7)**. **Task teams** have been created to bring in expertise from across the climate science community, each tackling a different component supporting delivery. The data output for **CMIP phase 6 (CMIP6)** is available on the **Earth System Grid Federation (ESGF)**, with CMIP7 data expected to emerge from the end of May 2026.

Timeline: 1995 onwards

Geographic scope: Global, but with regional components e.g. downscaling via CORDEX (<https://cordex.org/>)

Relevant outputs and links:

Main: <https://wcrp-cmip.org/>

CMIP 7: <https://wcrp-cmip.org/cmip-phases/cmip7/>

Fresh eyes on CMIP: <https://wcrp-cmip.org/cmip7-task-teams/fresh-eyes-on-cmip>

Model outputs, climate forcing datasets (input4MIPs) and model-compatible observational datasets (obs4MIPs) are made publicly available. Specific outputs are many but include projections out to 2100 and beyond assessed by IPCC.

Partnerships and collaborations: Many, including IPCC, modelling centres, Model Intercomparison Projects, infrastructure providers (Earth System Grid Federation)

Capacity-building activities: Many, including “Fresh eyes on CMIP”, community workshops (e.g., CMIP 2026) etc.

Advances in climate model simulations, including combining multiple lines of evidence and expanding climate variables to improve parameterization of the climate system e.g., ESMO:

Earth System Modeling and Observation (ESMO)

Summary description: [ESMO](#) is a WCRP Core Project aimed at advancing climate model simulations by coordinating and integrating modelling, data assimilation, and observations across WCRP and other research communities. It supports improved coupled and high-resolution modelling, model evaluation, decadal prediction, and the use of multiple lines of evidence to strengthen climate parameterization and prediction. It also promotes emerging approaches such as Km-Scale modelling, AI/ML, and climate emulators, helping bridge research and operational climate.

Timeline: From 2023 onwards.

Geographic scope: Global model intercomparison efforts with modelling centers.

Relevant outputs and links: CMIP7 protocol development, decadal prediction contributions, and activities on climate model development, verification, and emerging technologies [Projects and Panels — ESMO Website - \(CMIP Phase 7 \(CMIP7\) - Coupled Model Intercomparison Project, Decadal Climate Prediction Project \(DCPP\) — ESMO Website\)](#).

Partnerships and collaborations: Works across ESMO working groups, in collaboration with other research communities and a strong link with WMO’s research and climate services.

Capacity-building activities: Various particularly engaging ECR and underrepresented regions, for instance the [WCRP School on Climate Prediction Across Timescales](#), workshops and [systematic model evaluation](#) activities.

Addressing sensitivities of climate simulations to varying scenarios and parameterizations: e.g. ESMO

Earth System Modelling and Observations

Summary description: ESMO supports the development and assessment of climate simulations that explore sensitivity to emissions scenarios, model structure, and parameterizations through the Working Group on Coupled Modeling (WGCM), which is leading the WCRP Grand Challenge on "Clouds, Circulation and Climate Sensitivity". Another key contribution is strengthening the evidence base for carbon-cycle and climate metrics such as Transient Climate Response to cumulative carbon Emissions (TCRE) Assessment (TCRE) and Zero Emissions Commitment (ZEC), helping explain how climate responds to cumulative emissions and what warming may continue after net zero. This work helps improve the robustness of climate projections and the interpretation of uncertainty in model-based assessments

Timeline: Launched in 2023 onwards, with TCRE/ZEC assessment activities advancing through 2024–2025 onwards.

Geographic scope: Global coverage

Relevant outputs and links: International climate assessment, carbon budgets, and regional global climate response analysis reports.

- [Working Group on Coupled Modelling \(WGCM\) - Overview](#)
- [WCRP Grand Challenge- White Paper on Clouds, Circulation and Climate Sensitivity](#)
- [WCRP Transient Climate Response to cumulative carbon Emissions \(TCRE\) Assessment](#)

Partnerships and collaborations: Global links to the scientific modelling communities with assessment-oriented groups.

Capacity-building activities: Workshops, meetings etc.

Addressing uncertainties identified in assessments of the Intergovernmental Panel on Climate Change: e.g. Tipping points of SLCs, GPEX

Many of WCRP’s activities feed into this- here are just a couple of examples.

Summary description: Tipping point activity of WCRP’s Safe Landing Climates Lighthouse Activity

The Safe Landing Climates Lighthouse Activity is an exploration of the routes to “safe landing” spaces for human and natural systems. It explores future pathways that avoid dangerous climate change while at the same time contributing to the United Nations Sustainable Development Goals (SDGs), including those of climate action, zero hunger, clean water and sanitation, good health and well-being, affordable and clean energy, and healthy ecosystems above and below water. The relevant time scale is multi-decadal to millennial.

High-impact climate events, tipping points, and irreversible regional impacts assessment: WCRP is finalising an authoritative review paper that will systematically assess our understanding of threshold breaching, irreversibility, and tipping in the climate system. The paper will also provide key recommendations for how Earth systems models can be improved to better understand these processes and identify potential early warnings. This review paper will contribute to the Seventh Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and we are working actively with the IPCC as these topics will be important across IPCC working groups (particularly WGI Chapter 8, “Abrupt changes, low-likelihood high impact events and critical thresholds, including tipping points, in the Earth system.” Consensus building and a solid knowledge base will be important contributions to the IPCC process.

Timeline: The tipping points activity started in earnest in 2024. The assessment will be finalised later this year (2026)

Geographic scope: Global

Relevant outputs and links: <https://www.wcrp-climate.org/slc-activities/tpa>

Partnerships and collaborations: IPCC and many others

Capacity-building activities: Not directly for Tipping Points activity, but many across Safe Landing Climates

Summary description: Global Precipitation Experiment

The Global Precipitation EXperiment ([GPEX](#)), a WCRP Lighthouse Activity, works on addressing key uncertainties highlighted in IPCC assessments related to precipitation processes, extremes, and their response to climate change. It focuses on improving understanding and prediction of high-impact precipitation systems (atmospheric rivers, monsoons, mesoscale convective systems, tropical cyclones), which remain a major source of uncertainty in projections of climate impacts and risks.

GPEX directly contributes to reducing uncertainties through:

- Bringing together coordinated field campaigns to better observe poorly constrained processes (e.g., orographic precipitation, convective extremes, high-mountain regions)
- Development of reference datasets and benchmarking frameworks across observations, reanalyses, and models
- Advancing process-based model evaluation and km-scale and AI-enabled prediction systems
- Strengthening the science-to-services link, translating process understanding into improved forecasts and risk information

These activities will help respond to gaps in:

- Representation of precipitation extremes in models
- Observational constraints, especially in data-sparse regions
- Attribution of changes in high-impact events
- Quantification and communication of uncertainties

Timeline:

- Launched: End of 2023
- Science plan published in 2025 (<https://journals.ametsoc.org/view/journals/bams/106/2/BAMS-D-23-0242.1.xml>)
- Implementation phase: 2025–2027 (workshop, Scientific Steering Group actions, papers toward AR7)
- Years of Precipitation (YoP): 2028–2030 (coordinated global field campaigns and experiments)
- Legacy phase: Post-2030 (sustained datasets, modelling advances, services uptake)

Geographic scope:

Global, with emphasis on:

- Data-sparse and high-uncertainty regions, example- high mountains
- High-impact regions for extremes: monsoon regions, tropical cyclone basins, mid-latitude storm tracks
- Expansion toward Southern Hemisphere

Relevant outputs and links:

- Peer-reviewed contributions (precipitation drivers, model evaluation, monsoon precipitation)
- Benchmarking frameworks for precipitation datasets and models
- Potential case studies linking observations, modelling and societal framework
- Global inventory of field campaigns and coordinated YoP activities

Partnerships and collaborations:

GPEX brings together a broad range of international partners, including WCRP core projects (GEWEX, CLIVAR, ESMO), WMO programmes (WWRP, Hydrology and Cryosphere), space agencies (e.g., JAXA, NASA), National Meteorological and Hydrological Services (NMHSs), operational centres, as well as regional institutions and universities across Asia, Africa, and South America. GPEX acts as a coordination platform for linking observations, modelling, and services across communities.

Capacity-building activities:

Through its Working Group 4, GPEX drives capacity-building activities including EMCR engagement, regional initiatives such as South Asia AWS networks and Africa data hubs, support for data access and FAIR practices, co-development of tools with stakeholders, and strengthening science-to-services pathways for impact-based forecasting, with a focus on vulnerable regions.

High-resolution local and regional climate information, including advances in downscaled regional and sub-regional climate models: CORDEX, DE

1. Coordinated Regional Downscaling EXperiment (CORDEX)

Summary description: CORDEX provides high-resolution regional, and sub-regional climate information through coordinated downscaled climate simulations. It improves the realism and usefulness of climate projections from the Coupled Model Intercomparison Project (CMIP) through updated regional downscaling frameworks and preparation for future model intercomparison phases, particularly for regions where global models are too coarse for decision-making.

Timeline: Launched 2015 onwards

Geographic scope: Global, with regional domains covering most regional downscaled projections.

Relevant outputs and links:

- [Regional climate model projection datasets](#),
- [CORDEX-CORE simulations](#),
- [flagship pilot studies](#), and
- updated [CORDEX-CMIP guidance and data archives](#).

Partnerships and collaborations: CORDEX works through the WCRP network with modelling centres, regional scientific groups coordinated by the regional point of contacts (POCs), and national and international climate institutions.

Capacity-building activities: CORDEX supports regional modelling capacity, shared Empirical Statistical Downscaling (ESD) and dynamical downscaling protocols, training, and collaborative studies that help build expertise in downscaling and climate services at regional and national levels.

2. Digital Earths (DE)

Summary description: [Digital Earths](#) Advances high-resolution Earth System information by combining km-scale modelling, data fusion, and AI/ML methods. Fostering climate data assimilation and data-driven modeling (ML/AI, exploring ML-based DA and coupled spin-up, and maintaining a catalogue of hybrid AI-climate models. This advances beyond "weather generators" to climate-aware systems. Its work supports more realistic local and regional climate information, including digital twin approaches that extend beyond the physical climate system, to enhances better data integration for optimal climate monitoring, reanalysis, and predictions useful for sectoral applications.

Timeline: Launched in 2021

Geographic scope: Global coverage, with applications across regions, cities, and climate-sensitive areas worldwide.

Relevant outputs and links:

- <https://www.wcrp-climate.org/digital-earths>
- <https://www.wcrp-esmo.org/activities/wcrp-global-km-scale-hackathon-2025>
- <https://destine.ecmwf.int/news/destination-earth-team-advances-climate-digital-twin-science-at-global-km-scale-hackathon>
- <https://github.com/tbeucler/HybridESM>
- <https://www.wcrp-climate.org/de-working-groups/de-wg-data-fusion-climate>

Partnerships and collaborations: Works across WCRP communities and with external partners on modelling, observations, AI/ML, and digital twin development.

Capacity-building activities: Supports international hackathons, webinars, workshops, and collaborative coding exercises that build skills in high-resolution modelling, AI/ML, and data integration with a huge involvement from the ECRs.

Advances and gaps in attribution science, including regional and national attribution studies and attribution of monsoon pattern changes: e.g. EPESC, GPEX

CLIVAR-GEWEX Monsoons Panel & Explaining and Predicting Earth System Change Light House Activity

Summary description:

The CLIVAR–GEWEX Monsoons Panel coordinates international research on monsoon systems, providing a scientific basis for understanding variability, trends, and changes in monsoon patterns. It contributes to advancing attribution science by synthesizing observations and modelling across regions, while identifying key gaps in understanding monsoon responses to climate variability and change.

The EPESC Light House Activity advances attribution science by building an integrated capability to explain and predict multi-annual decadal climate change. It focuses on process-based detection and attribution, improved model and reanalysis evaluation, and operational attribution statements to support WMO forecasts (e.g. Global Annual to Decadal Climate Update) and State of the Climate reports.

Timeline:

CLIVAR–GEWEX Monsoons Panel is an ongoing WCRP panel with continuous activities aligned with WCRP’s other activities.

EPESC is a WCRP LHA launched in 2021 onwards

Geographic scope:

Global, covering major monsoon systems: Asian-Australian, African, and American monsoons.

Relevant outputs and links:

- Panel activities, reports, and coordinated research initiatives

<https://www.clivar.org/clivar-panels/monsoons>

- [Explaining and Predicting Earth System Change](#)
- [EPESC workshops & relevant publications](#)

Partnerships and collaborations:

CLIVAR–GEWEX Monsoons Panel is jointly coordinated under CLIVAR and GEWEX, with strong links to broader WCRP activities, modelling communities. Also works closely with WMO programmes such as WWRP.

EPESC works across WCRP and with modelling, observation, and forecasting communities, including collaboration relevant to WMO Expert Teams across the globe.

Capacity-building activities:

Supports regional research communities through coordination of workshops, and integration of scientists across monsoon regions, including engagement of early-career researchers.

EPESC supports, international workshops, webinars and training activities with emphasis on the ECRs and Global-South science experts.

B. Adaptation, Loss and Damage and Extreme Events

Sub-topics

Evolution and dynamics of extreme events, including early warning systems and climate services: e.g. GEP and EPESC

Explaining and Predicting Earth System Change and Global Extremes Platform

Summary description:

EPESC and the Global Extremes Platform (GEP) advance the science and operational use of event attribution for weather and climate extremes. EPESC-WG3 focuses on quantifying current likelihoods of extremes, understanding how hazards are changing, linking them to external drivers, and translating results into actionable risk information. GEP complements this by building upon and integrating activities on weather and climate extremes across WCRP through strengthening operational attribution, improving comparability across methods, and developing guidance for rapid and routine event attribution in climate services.

Timeline:

EPESC is a WCRP LHA launched in 2021 onwards

GEP launched in 2021 onwards

Geographic scope: EPESC and GEP work on a global scale with research and operational partners directly linked to service delivery communities.

Relevant outputs and links:

- [Global Extremes Indices data portal](#)
- [Working Group 3 - Assessment of Current and Future Hazards](#)
- [GEP Working Group on Event Attribution](#)
- [Annual assessment of Weather and Climate Extremes \(AWCE\)](#)

Partnerships and collaborations: EPESC works across WCRP communities and with operational and research partners. GEP brings together attribution scientists and operational practitioners and is closely linked to WCRP and service-focused communities.

Capacity-building activities:

GEP is developing technical guidance, evaluation approaches, and training-related materials. EPESC and GEP also support community exchange on methods, uncertainty communication, and best practice for operational attribution.

[Assessing adaptation progress and impacts of adaptation actions on reducing risks
Climate impacts across 1.5°C warming scenarios at local and regional levels](#)

Understanding complex, cascading and transboundary climate risks Tipping Points? See Tipping Point and Safe Landing Climates already mentioned above

[Climate risks for vulnerable groups, including Indigenous Peoples, local communities, children, youth, persons with disabilities and women](#)

C. Ecosystems and Nature-Based Solutions

Sub-topics

[Opportunities and challenges of implementing nature-based solutions in land and ocean systems](#)

[Climate impacts and risks for the ocean and cryosphere and related ecosystems](#)

Emissions and removals from terrestrial ecosystems and ecosystems with high-carbon reservoirs

Vulnerability of natural and human ecosystems, including interactions and potential tipping points, and strengthening ecosystem resilience

D. Mitigation, Technologies and Greenhouse Gas Emissions and Reporting

Sub-topics

Greenhouse gas emissions by sources and removals by sinks and reservoirs Opportunities, risks and costs associated with carbon dioxide removal (CDR) technologies and options Research on Climate Intervention (R-CI)

Summary description:

The WCRP Research on Climate Intervention (R-CI) Lighthouse Activity intends to advance understanding of climate interventions, defined as deliberate large-scale manipulations of the Earth system to counteract anthropogenic climate change. This includes both carbon dioxide removal (CDR) and solar radiation modification (SRM). R-CI aims to explore potential future scenarios that include climate intervention approaches and provide an objective assessment of their potential Earth system risks, opportunities, uncertainties, and knowledge gaps, recognising the significant scientific, technical, societal, and governance challenges associated with their implementation.

Timeline:

Ongoing WCRP Lighthouse Activity (since ~2024)

Geographic scope:

Global

Relevant outputs and links:

- <https://www.wcrp-climate.org/ci-overview>
- Hurrell JW, Haywood JM, Lawrence PJ, Lennard CJ and Oschlies A (2024) Climate intervention research in the World Climate Research Programme: a perspective. *Front. Clim.* 6:1505860. doi: 10.3389/fclim.2024.1505860
- Oschlies A, Bach LT, Fennel K, Gattuso J-P and Mengis N (2025) Perspectives and challenges of marine carbon dioxide removal. *Front. Clim.* 6:1506181. doi: 10.3389/fclim.2024.1506181

Partnerships and collaborations:

Implemented across WCRP core projects and scientific communities.

Capacity-building activities:

Intends to foster rigorous, transparent, and globally inclusive research, and promote best practices in climate intervention research.

Role of CDR in achieving the goals of the Paris Agreement and links with sustainable development e.g. R-CI (see above)

Modelling sustainable development in mitigation pathways, including equity and justice considerations

Implications of different emission metric choices for climate policy

Science-based greenhouse gas reporting methodologies used in carbon accounting frameworks

E. Cross-Cutting Research Areas

Sub-topics

Synergies and trade-offs between mitigation, adaptation and the United Nations Sustainable Development Goals, including equity considerations

Contribution of Indigenous and traditional knowledge to understanding climate change and its impacts

Other research activities supporting work under the United Nations Framework

Convention on Climate Change and the Paris Agreement, including activities under the Nairobi Work Programme

As a follow-up, while [redacted] and I tried to be succinct in this initial response, we appreciate that each of the questions asked are complex and could be responded to much more comprehensively and quantitatively with reference to specific papers if desired. For example, in answer to question 1, one of the ways that CMIP has tried to convey a synthesis of how models have improved across generations of CMIP models is through "portrait plots" like Figure 6 of [Bock et al., 2020](#), where the transition from red to blue is used to illustrate the decrease in model error compared to observations for a suite of different metrics. For question 2, we would point to the ScenarioMIP documentation of [Van Vuuren et al., 2026](#). For the climate risks of question 3, we would probably have to first need to have the particular risk specified, and for the uncertainties of question 4 start with [Hawkins and Sutton, 2011](#) for the general contextualization of sources of uncertainty and the [IPCC AR6 WG1 description in Chapter 4](#) on projections in general before iterating on the particular uncertainties wanting to be characterized. Please let us know if more information is desired.

1. Major advancements to CMIP over the last 20 years include developments in climate models towards increased complexity (for example, including aerosols and their cloud interactions, atmospheric chemistry, and the full carbon cycle), higher resolution allowing representation of extremes and more regional detail, improved process and interactions representation through both direct simulation or improved parameterisation (including AI), and better connection to the downscaling and impacts communities. One recent major advance is the ability to produce CMIP projections as CO₂ emissions driven (rather than concentration driven), allowing the uncertainty in committed warming to be assessed.
2. Economic dimensions are included in CMIP projections via scenarios developed by the Integrated Assessment Modelling Community through ScenarioMIP. For the latest round, we have ensured that all voices can be heard in the process of scenario development via an open review process for proposed scenarios and a large, diverse advisory group. The process for scenario development and its outcome was endorsed by the WCRP Joint Scientific Committee. CMIP has also accommodated other national scenarios such as SSP245com through encouraging the community to establish [Policy-aligned MIP \(PoMIP\)](#) and registering as a [CMIP Community MIP](#).

3. Climate risks such as tipping points and extremes are emergent properties of climate models driven by scenarios. These risks are not handled directly within CMIP but rather facilitated through establishment of design protocols and infrastructure to support open community access and analysis through the published literature, national and international assessments, and the growing fields of non-profit and industry efforts. In the case of tipping points, the [TipMIP](#) idealised scenarios are designed to push models to greater limits to induce tipping points.

4. While uncertainties are formally quantified not by CMIP itself but the users of CMIP output through their analysis, uncertainty quantification is a key component of CMIP experimental design through characterization of structural uncertainty across models, scenario uncertainty across forcings, and internal variability across ensemble members within individual models. For example, the critical role of both large ensembles from the same models to characterize statistics of extremes and perturbed parameter ensembles to characterize structural uncertainty was introduced through CMIP6. However, CMIP has also recently established a [Responsible Data Use \(RDU\) Task Team](#) with [WCRP Regional Information for Society](#) core project which seeks to provide advice on uncertainty. For example, the RDU TT recently worked with CMIP to produce [best guidance](#) for the use of the [Rapid Evaluation Framework](#) - a free to use, online tool which summarises key climate metrics as the data is uploaded to be stored on the Earth System Grid Federation.

**WMO OMM**

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Invitation to submit scientific research information about needs identified under the Research and Systematic Observation (RSO) agenda since 2005

Submission from WMO

WMO welcomes the initiative of the Chair of the UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) to prepare an information note mapping progress made in addressing research gaps identified under the agenda item on Research and Systematic Observation (RSO) since United Nations Framework Convention on Climate Change (UNFCCC) SBSTA 22 in June 2005.

In response to the request contained in Decision FCCC/SBSTA/2025/L.5 adopted at the sixty-second session of SBSTA in June 2025, WMO is pleased to contribute information on research and scientific activities undertaken by the meteorological and climate science community since 2005 that address research needs and gaps identified by Parties. These contributions will support the preparation of the Chair's information note to be presented at the eighteenth meeting of the Research Dialogue (RD) during the June 2026 session of the Subsidiary Bodies.

Information Note

Through this submission, WMO highlights progress made by the global research community in advancing climate science and responding to the research priorities identified by Parties under the RSO agenda.

The information is presented in the sections below in accordance with the guidance provided by the SBSTA Chair. For each topic, the submission includes the title and description of the research activity, its objectives, methodology and key findings or expected outcomes, the timeline of the work, and its geographic scope. Where relevant, the entries also provide links to outputs such as publications, datasets or project pages, and highlight partnerships, research networks and collaborative initiatives involved. In addition, information is included on capacity-building efforts, particularly those aimed at strengthening research and institutional capacity in developing countries.

Research Topics

A. UNDERSTANDING CLIMATE CHANGE, CLIMATE DATA AND SCENARIO DEVELOPMENT AND USE

a. NEAR-TERM CLIMATE CHANGE PREDICTION

1. The World Climate Research Programme (WCRP) Grand Challenge on Near-Term Climate Prediction (GC-NTCP)

Summary description: The Grand Challenge on Near-Term Climate Prediction supported research and development to improve multi-year to decadal climate predictions and their utility to decision makers. It aimed to support the development of organizational and technical processes for future routine provision of decadal prediction services that can assist stakeholders and decision-makers.

Timeline: 2016 – 2022.

Geographic scope: Global.

Relevant outputs and links: <https://www.wcrp-climate.org/gc-near-term-climate-prediction>.

The GC-NTCP's main final product was the Annual to Decadal Climate Update: <https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/seasonal-forecast/annual-to-decadal-update-faqs>.

Partnerships and collaborations: Many, led by UK Met Office.

Capacity-building activities: N/A

2. The WCRP Explaining and Predicting Earth System Change (EPESC) Lighthouse Activity

Summary description: Design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning, and prediction of Earth System change on global and regional scales, with a focus on multi-annual to decadal timescales. Has three Working Groups:

- Working Group 1: [Observing and Modelling of Earth System Change](#)
- Working Group 2: [Integrated Attribution, Prediction and Projection](#)
- Working Group 3: [Assessment of Current and Future Hazards](#)

Timeline: 2021 – onwards (noting LHAs have a lifetime of ~10 years).

Geographic scope: Global.

Relevant outputs and links: <https://www.wcrp-climate.org/epesc>.

See also: <https://www.wcrp-climate.org/epesc-documents>.

Capacity-building activities: Various, focused on Early Career and engaging Global South scientists.

b. ADVANCES IN SCENARIO DEVELOPMENT AND USE, INCLUDING SCENARIOS LIMITING WARMING IN 2100 TO 1.5°C RELATIVE TO PRE-INDUSTRIAL LEVELS

1. The WCRP Coupled Model Intercomparison Project (CMIP)

Summary description: CMIP is a project of the World Climate Research Programme (WCRP), providing climate projections to understand past, present and future climate changes. Members of the [CMIP Core Panel](#) designed and are currently implementing [CMIP Phase 7 \(CMIP7\)](#). [Task teams](#) have been created to bring in expertise from across the climate science community, each tackling a different component supporting delivery. The data output for [CMIP phase 6 \(CMIP6\)](#) is available on the [Earth System Grid Federation \(ESGF\)](#), with CMIP7 data expected to emerge from the end of May 2026.

Timeline: 1995 onwards.

Geographic scope: Global, but with regional components for example downscaling via CORDEX (<https://cordex.org/>).

Relevant outputs and links:

- Main: <https://wcrp-cmip.org/>
- CMIP 7: <https://wcrp-cmip.org/cmip-phases/cmip7/>
- Fresh eyes on CMIP: <https://wcrp-cmip.org/cmip7-task-teams/fresh-eyes-on-cmip>
- Model outputs, [climate forcing datasets](#) (input4MIPs) and model-compatible observational datasets ([obs4MIPs](#)) are made publicly available. Specific outputs are many but include projections out to 2100 and beyond assessed by Intergovernmental Panel on Climate Change (IPCC)

Partnerships and collaborations: Many, including IPCC, modelling centres, Model Intercomparison Projects, infrastructure providers ([Earth System Grid Federation](#)).

Capacity-building activities: Many, including “Fresh eyes on CMIP”, community workshops (for instance [CMIP 2026](#)).

c. ADVANCES IN CLIMATE MODEL SIMULATIONS, INCLUDING COMBINING MULTIPLE LINES OF EVIDENCE AND EXPANDING CLIMATE VARIABLES TO IMPROVE PARAMETERIZATION OF THE CLIMATE SYSTEM

1. The WCRP Earth System Modelling and Observations (ESMO) Core Project

Summary description: [ESMO](#) is a WCRP Core Project aimed at advancing climate model simulations by coordinating and integrating modelling, data assimilation, and observations across WCRP and other research communities. It supports improved coupled and high-resolution modelling, model evaluation, decadal prediction, and the use of multiple lines of evidence to strengthen climate parameterization and prediction. It also promotes emerging approaches such as Km-Scale modelling, AI/ML, and climate emulators, helping bridge research and operational climate.

Timeline: From 2023 onwards.

Geographic scope: Global model intercomparison efforts with modelling centres.

Relevant outputs and links:

- CMIP7 protocol development, decadal prediction contributions, and activities on climate model development, verification, and emerging technologies [Projects and Panels ESMO Website](#) – (CMIP Phase 7 (CMIP7) - [Coupled Model Intercomparison Project](#), [Decadal Climate Prediction Project \(DCPP\)](#) – [ESMO Website](#)).

Partnerships and collaborations: Works across ESMO working groups, in collaboration with other research communities and a strong link with WMO research and climate services.

Capacity-building activities: Various particularly engaging ECR and underrepresented regions, for instance the [WCRP School on Climate Prediction Across Timescales](#), workshops and [systematic model evaluation](#) activities.

d. ADDRESSING SENSITIVITIES OF CLIMATE SIMULATIONS TO VARYING SCENARIOS AND PARAMETERIZATIONS

1. *The WCRP Earth System Modelling and Observations (ESMO) Core Project*

Summary description: ESMO supports the development and assessment of climate simulations that explore sensitivity to emissions scenarios, model structure, and parameterizations through the Working Group on Coupled Modelling (WGCM), which is leading the WCRP Grand Challenge on “Clouds, Circulation and Climate Sensitivity”. Another key contribution is strengthening the evidence base for carbon-cycle and climate metrics such as Transient Climate Response to cumulative carbon Emissions (TCRE) Assessment (TCRE) and Zero Emissions Commitment (ZEC), helping explain how climate responds to cumulative emissions and what warming may continue after net zero. This work helps improve the robustness of climate projections and the interpretation of uncertainty in model-based assessments

Timeline: Launched in 2023 onwards, with TCRE/ZEC assessment activities advancing through 2024 – 2025 onwards.

Geographic scope: Global coverage.

Relevant outputs and links: International climate assessment, carbon budgets, and regional global climate response analysis reports.

- [Working Group on Coupled Modelling \(WGCM\) - Overview](#)
- [WCRP Grand Challenge- White Paper on Clouds, Circulation and Climate Sensitivity](#)
- [WCRP Transient Climate Response to cumulative carbon Emissions \(TCRE\) Assessment](#)

Partnerships and collaborations: Global links to the scientific modelling communities with assessment-oriented groups.

Capacity-building activities: Workshops and meetings.

e. ADDRESSING UNCERTAINTIES IDENTIFIED IN ASSESSMENTS OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

1. WCRP's Safe Landing Climates Lighthouse Activity

Summary description: The Safe Landing Climates Lighthouse Activity is an exploration of the routes to "safe landing" spaces for human and natural systems. It explores future pathways that avoid dangerous climate change while at the same time contributing to the United Nations Sustainable Development Goals (SDGs), including those of climate action, zero hunger, clean water and sanitation, good health and well-being, affordable and clean energy, and healthy ecosystems above and below water. The relevant time scale is multi-decadal to millennial.

2. High-impact climate events, tipping points, and irreversible regional impacts assessment

Summary description: WCRP is finalizing an authoritative review paper that will systematically assess our understanding of threshold breaching, irreversibility, and tipping in the climate system. The paper will also provide key recommendations for how Earth systems models can be improved to better understand these processes and identify potential early warnings. This review paper will contribute to the Seventh Assessment Report of the IPCC, and we are working actively with the IPCC as these topics will be important across IPCC working groups (particularly) WGI Chapter 8, "Abrupt changes, low-likelihood high impact events and critical thresholds, including tipping points, in the Earth system". Consensus building and a solid knowledge base will be important contributions to the IPCC process.

Timeline: The tipping points activity started in earnest in 2024. The assessment will be finalized later this year (2026).

Geographic scope: Global.

Relevant outputs and links: <https://www.wcrp-climate.org/slc-activities/tpa>

Partnerships and collaborations: IPCC and many others.

Capacity-building activities: Not directly for Tipping Points activity, but many across Safe Landing Climates.

3. WCRP's Global Precipitation Experiment

Summary description: The Global Precipitation EXperiment ([GPEX](#)), a WCRP Lighthouse Activity, works on addressing key uncertainties highlighted in IPCC assessments related to precipitation processes, extremes, and their response to climate change. It focuses on improving understanding and prediction of high-impact precipitation systems (atmospheric rivers, monsoons, mesoscale convective systems, tropical cyclones), which remain a major source of uncertainty in projections of climate impacts and risks.

GPEX directly contributes to reducing uncertainties through:

- Bringing together coordinated field campaigns to better observe poorly constrained processes (such as orographic precipitation, convective extremes, high-mountain regions)
- Development of reference datasets and benchmarking frameworks across observations, reanalyses, and models
- Advancing process-based model evaluation and km-scale and AI-enabled prediction systems
- Strengthening the science-to-services link, translating process understanding into improved forecasts and risk information

These activities will help respond to gaps in:

- Representation of precipitation extremes in models
- Observational constraints, especially in data-sparse regions
- Attribution of changes in high-impact events
- Quantification and communication of uncertainties

Timeline:

- Launched: End of 2023
- Science plan published in 2025 (<https://journals.ametsoc.org/view/journals/bams/106/2/BAMS-D-23-0242.1.xml>)
- Implementation phase: 2025 – 2027 (workshop, Scientific Steering Group actions, papers toward AR7)
- Years of Precipitation (YoP): 2028 – 2030 (coordinated global field campaigns and experiments)
- Legacy phase: Post-2030 (sustained datasets, modelling advances, services uptake)

Geographic scope: Global, with emphasis on:

- Data-sparse and high-uncertainty regions, example – high mountains
- High-impact regions for extremes: monsoon regions, tropical cyclone basins, mid-latitude storm tracks
- Expansion toward Southern Hemisphere

Relevant outputs and links:

- Peer-reviewed contributions (precipitation drivers, model evaluation, monsoon precipitation)

- Benchmarking frameworks for precipitation datasets and models
- Potential case studies linking observations, modelling and societal framework
- Global inventory of field campaigns and coordinated YoP activities

Partnerships and collaborations: GPEX brings together a broad range of international partners, including WCRP core projects (GEWEX, CLIVAR, ESMO), WMO programmes (WWRP, Hydrology and Cryosphere), space agencies (for example JAXA, NASA), National Meteorological and Hydrological Services (NMHSs), operational centres, as well as regional institutions and universities across Asia, Africa, and South America. GPEX acts as a coordination platform for linking observations, modelling, and services across communities.

Capacity-building activities: Through its Working Group 4, GPEX drives capacity-building activities including EMCR engagement, regional initiatives such as South Asia AWS networks and Africa data hubs, support for data access and FAIR practices, co-development of tools with stakeholders, and strengthening science-to-services pathways for impact-based forecasting, with a focus on vulnerable regions.

f. HIGH-RESOLUTION LOCAL AND REGIONAL CLIMATE INFORMATION, INCLUDING ADVANCES IN DOWNSCALED REGIONAL AND SUB-REGIONAL CLIMATE MODELS

1. WCRP's Coordinated Regional Downscaling EXperiment (CORDEX)

Summary description: [CORDEX](#) provides high-resolution regional, and sub-regional climate information through coordinated downscaled climate simulations. It improves the realism and usefulness of climate projections from the Coupled Model Intercomparison Project (CMIP) through updated regional downscaling frameworks and preparation for future model intercomparison phases, particularly for regions where global models are too coarse for decision-making.

Timeline: Launched 2015 onwards.

Geographic scope: Global, with regional domains covering most regional downscaled projections.

Relevant outputs and links:

- Regional climate model projection datasets - How to access CORDEX-CMIP5 data
- [CORDEX-CORE simulations](#)
- [Flagship pilot studies](#)
- Updated [CORDEX-CMIP guidance and data archives](#)

Partnerships and collaborations: CORDEX works through the WCRP network with modelling centres, regional scientific groups coordinated by the regional point of contacts (POCs), and national and international climate institutions.

Capacity-building activities: CORDEX supports regional modelling capacity, shared Empirical Statistical Downscaling (ESD) and dynamical downscaling protocols, training, and collaborative studies that help build expertise in downscaling and climate services at regional and national levels.

2. WCRP's Digital Earths (DE) Lighthouse Activity

Summary description: [Digital Earths](#) Advances high-resolution Earth System information by combining km-scale modelling, data fusion, and Artificial Intelligence (AI) and Machine Learning (ML) methods. Fostering climate data assimilation and data-driven modelling (ML/AI, exploring ML-based DA and coupled spin-up, and maintaining a catalogue of hybrid AI-climate models. This advances beyond "weather generators" to climate-aware systems. Its work supports more realistic local and regional climate information, including digital twin approaches that extend beyond the physical climate system, to enhances better data integration for optimal climate monitoring, reanalysis, and predictions useful for sectoral applications.

Timeline: Launched in 2021

Geographic scope: Global coverage, with applications across regions, cities, and climate-sensitive areas worldwide.

Relevant outputs and links:

- <https://www.wcrp-climate.org/digital-earths>
- <https://www.wcrp-esmo.org/activities/wcrp-global-km-scale-hackathon-2025>
- <https://destine.ecmwf.int/news/destination-earth-team-advances-climate-digital-twin-science-at-global-km-scale-hackathon>
- <https://github.com/tbeucler/HybridESM>
- <https://www.wcrp-climate.org/de-working-groups/de-wg-data-fusion-climate>

Partnerships and collaborations: Works across WCRP communities and with external partners on modelling, observations, AI/ML, and digital twin development.

Capacity-building activities: Supports international hackathons, webinars, workshops, and collaborative coding exercises that build skills in high-resolution modelling, AI/ML, and data integration with a huge involvement from the ECRs.

g. ADVANCES AND GAPS IN ATTRIBUTION SCIENCE, INCLUDING REGIONAL AND NATIONAL ATTRIBUTION STUDIES AND ATTRIBUTION OF MONSOON PATTERN CHANGES

1. WCRP's CLIVAR-GEWEX Monsoons Panel & Explaining and Predicting Earth System Change Light House Activity (LHA)

Summary description: The CLIVAR – GEWEX Monsoons Panel coordinates international research on monsoon systems, providing a scientific basis for understanding variability, trends, and changes in monsoon patterns. It contributes to advancing attribution science by synthesizing observations and modelling across

regions, while identifying key gaps in understanding monsoon responses to climate variability and change.

The EPESC Light House Activity advances attribution science by building an integrated capability to explain and predict multi-annual decadal climate change. It focuses on process-based detection and attribution, improved model and reanalysis evaluation, and operational attribution statements to support WMO forecasts (for instance Global Annual to Decadal Climate Update) and State of the Climate reports.

Timeline: CLIVAR – GEWEX Monsoons Panel is an ongoing WCRP panel with continuous activities aligned with WCRP’s other activities. EPESC is a WCRP LHA launched in 2021 onwards.

Geographic scope: Global, covering major monsoon systems: Asian-Australian, African, and American monsoons.

Relevant outputs and links:

- <https://www.clivar.org/clivar-panels/monsoons>
- [Explaining and Predicting Earth System Change](#)
- [EPESC workshops & relevant publications](#)

Partnerships and collaborations: CLIVAR – GEWEX Monsoons Panel is jointly coordinated under CLIVAR and GEWEX, with strong links to broader WCRP activities, modelling communities. Also works closely with WMO programmes such as WWRP.

EPESC works across WCRP and with modelling, observation, and forecasting communities, including collaboration relevant to WMO Expert Teams across the globe.

Capacity-building activities: Supports regional research communities through coordination of workshops, and integration of scientists across monsoon regions, including engagement of early-career researchers.

EPESC supports, international workshops, webinars and training activities with emphasis on the ECRs and Global-South science experts.

B. ADAPTATION, LOSS AND DAMAGE AND EXTREME EVENTS

a. EVOLUTION AND DYNAMICS OF EXTREME EVENTS, INCLUDING EARLY WARNING SYSTEMS AND CLIMATE SERVICES

1. WCRP’s Explaining and Predicting Earth System Change Lighthouse (EPESC), and the Global Extremes Platform (GEP)

Summary description: EPESC and the Global Extremes Platform (GEP) advance the science and operational use of event attribution for weather and climate extremes. EPESC-WG3 focuses on quantifying current likelihoods of extremes, understanding how hazards are changing, linking them to external drivers, and

translating results into actionable risk information. GEP complements this by building upon and integrating activities on weather and climate extremes across WCRP through strengthening operational attribution, improving comparability across methods, and developing guidance for rapid and routine event attribution in climate services.

Timeline:

EPESC is a WCRP LHA launched in 2021 onwards.

GEP launched in 2021 onwards.

Geographic scope: EPESC and GEP work on a global scale with research and operational partners directly linked to service delivery communities.

Relevant outputs and links:

- [Global Extremes Indices data portal](#)
- [Working Group 3 - Assessment of Current and Future Hazards](#)
- [GEP Working Group on Event Attribution](#)
- [Annual assessment of Weather and Climate Extremes \(AWCE\)](#)

Partnerships and collaborations: EPESC works across WCRP communities and with operational and research partners. GEP brings together attribution scientists and operational practitioners and is closely linked to WCRP and service-focused communities.

Capacity-building activities: GEP is developing technical guidance, evaluation approaches, and training-related materials. EPESC and GEP also support community exchange on methods, uncertainty communication, and best practice for operational attribution.

2. WMOs activities related to extreme heat

Summary description: WMO conducts various initiatives related to extreme heat including its impacts on sectors like health and agriculture. It is not purely research but rather a combination of activities needed to better understand impacts, vulnerabilities, risk and adaptation actions.

Timeline: Ongoing.

Geographic scope: Global.

Relevant outputs and links:

- [FAO-WMO Extreme Heat and Agriculture Report](#) (to be published on 22 April) - Highlights report can be found [here](#).
- [WHO – WMO Joint Climate and Health Programme](#)
- [WHO-WMO Joint Programme of Work: 2019–2022 Highlights Report – ClimaHealth](#)

- [Heat Health Risks | Global Heat Health Information Network](#)

Partnerships and collaborations: This is done jointly with organizations such as the Food and Agriculture Organization (FAO) and the World Health Organization (WHO), as well as in the framework of WMO programmes such as the Integrated Drought Management Programme (IDMP) and the Global Heat Health Information Network (GHHIN).

Capacity-building activities: various capacity building activities are undertaken including trainings for service providers, trainings for sector representatives, institutional support in NMHSs and Regional Climate Centres (RCCs), documenting case studies and good practices, and more.

3. *WMO activities related to climate science information for climate action, including National Adaptation Plans and Nationally Determined Contributions*

Summary description: The WMO initiative on Developing Climate Science Information for Climate Action aims to strengthen the scientific basis for climate action by providing countries with methodologies, tools and data to integrate climate science into policy, investment and project design. The initiative addresses the growing need for reliable climate information to guide adaptation and mitigation decisions, particularly for developing countries seeking access to climate finance. The approach promotes the use of the best available climate data, projections and indicators to identify climate risks, assess vulnerabilities and select effective climate actions for National Adaptation Plans (NAPs), Nationally Determined Contributions (NDCs). The initiative also contributes to strengthening national climate services and supports reporting and implementation under international frameworks such as the Paris Agreement. A key element is the Climate Information Platform (CIP) developed by WMO, WCRP, the Green Climate Fund (GCF) and the Swedish Hydrometeorology Service (SMHI) provides access to climate data, indicators and visualization tools derived from global and regional climate models and observational datasets. These tools support evidence-based climate adaptation planning, risk assessment and the development of climate finance proposals.

Timeline: 2018 – Ongoing.

Geographic scope: Global.

The initiative supports countries worldwide, with particular emphasis on:

- Developing countries
- Least Developed Countries (LDCs)
- Small Island Developing States (SIDS)

It also strengthens national and regional climate service systems through institutions such as NMHSs and RCCs.

Relevant outputs:

- Methodology for [Developing the Climate Science Information for Climate Action](#) (WMO-No. 1287)
- [Climate Information Platform](#) (CIP) providing site-specific climate indicators

and data

- Tools for calculating climate indices (such as [Climpact](#))
- Climate indicators and datasets derived from global climate model initiatives such as Coupled Model Intercomparison Project (CMIP) and World Climate Research Programme (WCRP)

Links:

- <https://wmo.int/media/news/climate-science-information-climate-action>
- <https://climateinformation.org>
- <https://climpact-sci.org/>

Partnerships and collaborations: The initiative involves collaboration among several international and scientific institutions, including:

- World Meteorological Organization
- Green Climate Fund
- Swedish Meteorological and Hydrological Institute (developer of the CIP)
- Intergovernmental Panel on Climate Change (scientific assessment framework)
- National Meteorological and Hydrological Services (NMHSs)
- Regional Climate Centres and climate research institutions
- Academic institutions

Capacity building activities: WMO implements a range of capacity-building activities under the Climate Science Information for Climate Action initiative to strengthen countries' ability to apply climate science in policy and climate finance planning. Through regional and national training workshops, technical courses, and global knowledge-sharing forums organized, national and international experts and decision-makers are trained to access, analyze and interpret climate data, climate projections and indices using tools such as the CIP and Climpact. These trainings support NMHSs, government ministries and climate finance institutions in integrating climate science into NDCs, NAPs and climate investment proposals, thereby improving the scientific basis of adaptation planning and funding applications, particularly in developing countries.

b. UNDERSTANDING COMPLEX, CASCADING AND TRANSBOUNDARY CLIMATE RISKS

1. WMO activities related to drought monitoring and early warning

Summary description: WMO conducts various activities related to drought monitoring and early warning mostly in the framework of the IDMP.

Timeline: Ongoing.

Geographic scope: Global.

Relevant outputs and links:

- [Baseline Assessment of Drought Impact Monitoring](#) (WMO-No. 1355)

Partnerships and collaborations: This is done jointly with various organizations, mostly in the framework of the IDMP.

Capacity-building activities: various capacity building activities are undertaken including trainings for service providers, trainings for sector representatives, institutional support in NMHSs and RCCs, documenting case studies and good practices, and more.

C. MITIGATION, TECHNOLOGIES AND GREENHOUSE GAS EMISSIONS AND REPORTING

a. ROLE OF CDR IN ACHIEVING THE GOALS OF THE PARIS AGREEMENT AND LINKS WITH SUSTAINABLE DEVELOPMENT

1. *The WCRP Research on Climate Intervention (R-CI) Lighthouse Activity*

Summary description: The WCRP Research on Climate Intervention (R-CI) Lighthouse Activity intends to advance understanding of climate interventions, defined as deliberate large-scale manipulations of the Earth system to counteract anthropogenic climate change. This includes both carbon dioxide removal (CDR) and solar radiation modification (SRM). R-CI aims to explore potential future scenarios that include climate intervention approaches and provide an objective assessment of their potential Earth system risks, opportunities, uncertainties, and knowledge gaps, recognizing the significant scientific, technical, societal, and governance challenges associated with their implementation.

Timeline: Ongoing WCRP Lighthouse Activity (since ~2024).

Geographic scope: Global.

Relevant outputs and links:

- <https://www.wcrp-climate.org/ci-overview>
- Hurrell JW, Haywood JM, Lawrence PJ, Lennard CJ and Oschlies A (2024) Climate intervention research in the WCRP: a perspective. *Front. Clim.* 6:1505860. doi: 10.3389/fclim.2024.1505860
- Oschlies A, Bach LT, Fennel K, Gattuso J-P and Mengis N (2025) Perspectives and challenges of marine carbon dioxide removal. *Front. Clim.* 6:1506181. doi: 10.3389/fclim.2024.1506181

Partnerships and collaborations: Implemented across WCRP core projects and scientific communities.

Capacity-building activities: Intends to foster rigorous, transparent, and globally inclusive research, and promote best practices in climate intervention research.