European Commission

The Next Frontier for Climate Change Science

Insights from the authors of the IPCC 6th Assessment Report on knowledge gaps and priorities for research

Independent Expert Report

Research and Innovation

The Next Frontier for Climate Change Science:
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European Commission
Directorate B — Healthy Planet
Unit B.3 — Climate & Planetary Boundaries

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The Next Frontier for Climate Change Science

Insights from the authors ofthe IPCC 6th Assessment Report on knowledge gaps and priorities for research

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Directorate-General for Research and Innovation
Healthy Planet

2024

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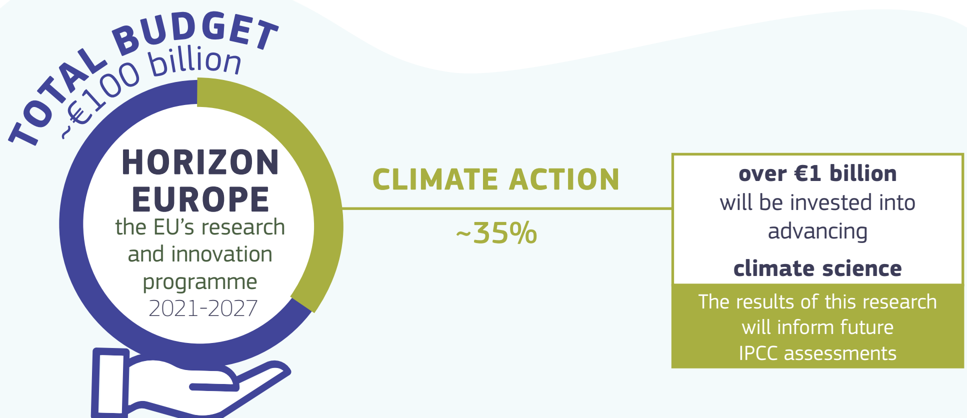
INTRODUCTION

2023 is now confirmed as the warmest year on record. This period was marked by unparalleled temperature anomalies and witnessed a disturbing escalation in the frequency and magnitude of devastating climate impacts. In Europe, Slovenia was hit by the worst-ever floods on record with a month's worth of rain falling in less than a day; Spain, Portugal and Greece experienced extreme heat and were badly scarred by wildfires and Switzerland recorded a new altitude record for the freezing point of well above 5,000 meters. Many parts of the Middle East saw temperatures of above 50°C. The global ocean witnessed unprecedented sea surface temperature anomalies, fuelling numerous typhoons, cyclones, and hurricanes. In parallel, global GHG emissions and atmospheric concentrations of carbon dioxide (CO_2) also hit new highs, putting the world on track for a temperature rise far above the goals of the Paris Agreement, underscoring the urgent need to step up adaptation action, while at the same time making rapid, immediate, and deep economy-wide cuts in greenhouse gas (GHG) emissions.

Accelerating the transition to climate neutrality and resilience is at the heart of the **European Green Deal**. By placing environmental sustainability at the centre of the European policy agenda, this ambitious initiative aims to provide a holistic response not only to global warming, but also to biodiversity, pollution, and resource depletion crises. Informed by science, the implementation of the Green Deal will continuously rely on robust scientific evidence to guide policymakers, businesses, and citizens in the massive transformations ahead.

By helping us understand how the climate system works, how it will change over time and how the impacts of climate change will materialise, climate science is fundamental for enabling informed decisions about how to reduce emissions and how to adapt to a warmer, more unpredictable, and more inhospitable world. The work of the **Intergovernmental Panel on Climate Change (IPCC)** is an example of how instrumental science is for shaping effective policies and mobilising action. The IPCC reports not only represent an essential source of information about climate change, but they also help to forge consensus among governments and play a central role in international climate diplomacy.



The journey towards sustainability calls for a major research and innovation effort not only to provide a robust scientific basis to guide the transition process, but also to assess, develop, deploy, and scale up the solutions and to nurture the behavioural change and political will on which the transition hinges. **Horizon Europe**, the European Union's (EU) current research and innovation (R&I) funding programme, acknowledging the importance of the R&I contribution to fighting climate change, earmarks at least 35% of its nearly EUR 100 billion budget to climate action, out of which over EUR 1 billion will be invested in climate science.

It is the role of Directorate-General for Research and Innovation (DG RTD) to maximise the impact of the programme by financing activities that are scientifically, socially and politically relevant and by focusing the available funding on the most critical areas. In the domain of climate science this means addressing knowledge gaps and advancing our understanding on how the climate system works, how it is influenced by climate change, what options we have to pursue ambitious mitigation and adaptation action, and how to mobilise society towards transformative change.

To inform the design of future calls on climate science, DG RTD has assembled a group of leading European scientists involved in the IPPC 6th assessment cycle, to identify the most pressing research themes in climate change arising from the latest IPPC reports. This document compiles a synthesis of independent recommendations spanning the physical climate science, impacts and risks, adaptation, and mitigation, while promoting multi-disciplinarity and synergies between the various themes. The report is structured by key themes ("clusters"), many of which tackle the topics assessed by the different IPCC Working Groups and address cross-cutting or particularly pressing policy issues such as equity and justice, losses, and damages[1], overshoot of temperature targets, transitions in the land sector, limits to adaptation or climate intervention. As a result, this compilation represents a precious resource for shaping a more strategic approach towards EU investment in climate research under Horizon Europe and beyond.

"Investing in climate science is investing in our future by securing the necessary knowledge to shape the climate action that is required.

This report, building on state-of-art scientific expertise, is invaluable for maximising the impact of EU-funded R&I and for generating the evidence-base for guiding the implementation of the European Green Deal."

Marc Lemaître,
Director-General for Research and Innovation (DG RTD)

1. "Losses and damages" refer broadly to harm from observed impacts and projected risks whereas "Loss and Damage" refers to political debate under the UNFCCC, which is to address loss and damage associated with impacts of climate change in developing countries that are particularly vulnerable to the adverse effects of climate change. In the research context of this report, unless specified otherwise, we primary focus on "losses and damages".

The Intergovernmental Panel on Climate Change (IPCC)

The IPCC, to which many of the world's leading climate scientists contribute, plays a unique role within climate science and in informing policy decisions. First convened in 1988 by the United Nations Environment Programme and the World Meteorological Organisation, the IPCC is tasked to provide policymakers with regular (*circa* every 5-7 years), comprehensive, and authoritative assessments of the scientific basis of climate change and its impacts as well as available human response options, building on the research and technical work of thousands of scientists, and increasingly also practitioners, worldwide. The IPCC does not carry out any research of its own and the authors work *pro bono* to provide an expert assessment of the published literature.

The Panel's work has been instrumental in establishing unequivocally the link between human activity and climate change. With each successive assessment cycle, reports have seen an increased confidence in the findings, based on continuous progress in climate science, including modeling, process understanding, observations, and empirical studies, and have provided the knowledge basis for reinforced warnings and calls for action. The IPCC reports thus represent an essential source of information for the implementation of the Paris Agreement.

The latest IPCC 6th Assessment Report (AR6), consists of three special reports on global warming of 1.5°C[2]; climate change and land[3]; and the ocean and cryosphere in a changing climate[4], and a three-part "climate report": the first instalment, on the physical science of climate change[5], was published in August 2021, delivering the starkest warning so far, and described by the United Nations Secretary-General António Guterres as a "code red for humanity". The second part, approved in February 2022 and focusing on impacts, adaptation and vulnerability[6] warns that any further delay in climate action "will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all". The third report[7] that came out in April 2022 is centred on mitigation and highlights how the world must take deep and rapid cuts in emissions to keep global warming in check.

Finally, the Synthesis Report[8] concluding the 6th assessment cycle was adopted in March 2023 and summarises the main messages from across the entire AR6.

2. https://www.ipcc.ch/sr15/
3. https://www.ipcc.ch/srccl/
4. https://www.ipcc.ch/srocc/
5. https://www.ipcc.ch/report/ar6/wg1/
6. https://www.ipcc.ch/report/ar6/wg2/
7. https://www.ipcc.ch/report/ar6/wg3/
8. AR6 Synthesis Report: Climate Change 2023 (ipcc.ch)

HOW TO READ THIS DOCUMENT

This document is a comprehensive although non-exhaustive summary of independent expert recommendations on research priorities in climate science, inspired by, but not limited to, IPCC authors' experience in contributing to the 6th assessment cycle. It means to provide inspiration for Directorate-General R&I and other funding bodies in the identification and selection of research priorities.

The research gaps, presented in a form of one-pagers, have been grouped together around common areas to form 11 thematic clusters. Each one pager briefly describes the nature of the research gaps and its policy relevance and signals how the thematic is pertinent for the three IPCC Working Groups (Earth system science (WGI); Impact, risks and adaptation (WGII); Mitigation (WGIII)). The order of presentation is random, with no prioritisation between or within Clusters.

For each research gap the relevance for five cross-cutting policy issues as set out in the Horizon Europe legal basis is flag(s)ged to signal that the gap has high potential for tackling these horizontal priorities. The five flag(s) categories include:

- international cooperation (see below)
- digitalisation and artificial intelligence (AI) (e.g., where advanced computing and digital technologies, incl. machine learning, sensors, and satellites, can enable advances in climate research)
- ecosystems and biodiversity (e.g. climate-biodiversity nexus, including NBS for mitigation and adaptation)
- social sciences and humanities (e.g., where human behaviour, policy, governance, economics etc. are at stake)
- gender (e.g., where distributional aspects are discussed)

It should be clarified that whereas international cooperation on any topic addressing climate change might seem by default applicable given the global nature of the problem at stake, in the report we apply a more restrictive approach by flag(s)ging only topics where participation of non-EU countries as essential members of research consortia would be necessary for successfully tackling the specific research issue at stake. By extension, an absence of such a flag(s) does not mean that international cooperation would not be needed or welcome to address the gap in question.

By design, the fiches within clusters are closely interrelated. In addition, where strong thematic links exist between research gaps across the different clusters, these have been signaled by means of cross-references to facilitate the readability of the report.

CLUSTER 1:

EARTH SYSTEM PROCESSES, CLIMATE FEEDBACKS AND CLIMATE SENSITIVITY

The latest IPCC report concludes that: human activities have unequivocally caused widespread and rapid changes in all components of the Earth system. The pace and scale of the observed changes across the climate system are unprecedented over many thousands to millions of years, with recent intensification of these trends. Advancements in comprehending the Earth system are imperative to assess how the climate may change in the future, to understand the regional implications, and to formulate effective strategies for both adaptation and mitigation action. Research on multiple lines of evidence will be key for narrowing uncertainties in estimates of key variables such as climate sensitivity, Earth system feedbacks, and biogeochemical cycles.

Observations and paleoclimate records together with climate models are all essential tools to advance our understanding of the changing climate. Progress is required to secure high quality stable and sustained observational measurements over multiple decades, to increase the quality and exploitation of reanalyses, and to develop integrated composite products that bring added value and address data and knowledge gaps. Past climatic changes can provide uniquely valuable context - enhanced and extended paleoclimate records are needed to help us understand how the components of the climate system work, how unusual present and future conditions are and what the committed climate change is, particularly in the slowly responding ocean and cryosphere.

Better understanding of key processes and feedbacks in the climate system and our ability to model and observe them is necessary to understand past and current changes in the climate system, and to explore future scenarios. For example, near-surface fluxes between the ocean and atmosphere are still not well known with broad ranging implications, including for quantifying global surface temperature changes. Another fundamental source of uncertainty in climate sensitivity and for estimating carbon budgets are cloud feedbacks.

Core challenges persist in the development and utilisation of diverse datasets, arising particularly from in-situ observations, satellite products, paleoclimate proxies, modeling exercises, and other research activities that generate data as part of their deliverables. Collaborative efforts are essential to improve the development, use and interoperability of these datasets, addressing issues related to heterogeneity, sustainability, and curation. Such improvements would also benefit the Copernicus Climate Change Service and other similar products.

> **“Advancements in comprehending the Earth system are imperative to assess how the climate may change in the future, to understand the regional implications, and to formulate effective strategies for both adaptation and mitigation action.”**

Tracking progress in stabilising global temperatures is critical for guiding climate policy and requires the ability to accurately assess and monitor natural and human caused sources and sinks of GHGs, the related processes and feedbacks as well as the carbon budgets. As net zero targets are becoming increasingly prominent in the EU and international policymaking, we also need to better understand how the Earth system will respond to a state of net zero CO_2/GHG emissions. This knowledge will be critical for defining the future emission reduction efforts under the Paris Agreement.

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1.1 Understanding and quantifying near-surface fluxes of heat, moisture and momentum

■ Earth system science ☐ Impacts, risks and adaptation ☐ Mitigation

There are substantial gaps in our observational and theoretical understanding of near-surface fluxes, with broad ranging implications for the quantification of key processes and their future projections in climate models. This is the case over both the ocean and land surface, with sparse direct measurements of near-surface fluxes, particularly over the ocean. The related key processes are parameterised in climate models, often based on similar assumptions. There are major opportunities for progress in measuring these fluxes. For example, large-scale wind farm facilities include high quality meteorological instrumentation that can augment sparse measurement capabilities. Higher resolution models may also allow for key processes to be explicitly modelled rather than be parameterised.

A critical knowledge gap is how the relationship between sea-surface temperatures (SST) and marine air temperatures (MAT) has evolved and will continue to evolve in a warming climate. It is critical to reconcile these observations to understand and improve early estimates of observed changes. Climate model simulations consistently suggest that MATs should be warming faster than SSTs. However, all models parametrise the processes at this scale and all parameterisations are based upon the same similarity theory, leaving open the possibility of a common systematic bias in the simulations. Observationally-based estimates, for which MAT-based estimates are considerably less mature than their SST-equivalents, suggest the opposite behaviour – that SST warms more than MAT in the long term. Theoretical understanding of the expected spatio-temporal behaviour is overall lacking, leading to uncertainties in long-term surface temperature change estimates.

Policy relevance

Surface flux exchanges are a key part of the meteorological and climatic conditions at the surface where we live and work, and their better understanding will substantially improve regional projections and help to address overall model biases. Changes in surface fluxes will directly affect human health and comfort, bio-spheric health, and agricultural production amongst others.

Flag(s)

Digitalisation/AI

Related fiche(s)

5.5

1.2 Assessing feedback mechanisms in the climate system and their dependence on climate state

■ Earth system science ☐ Impacts, risks and adaptation ☐ Mitigation

Climate feedback mechanisms in the Earth system need to be well understood to robustly quantify Earth's climate sensitivity to increasing temperatures. While many of the feedbacks have reduced uncertainties over recent years thanks to scientific progress and are now assessed with high confidence, others remain uncertain. This is particularly the case for cloud feedback mechanisms, for which a strong dependence on climate state and patterns of warming have been identified. Whilst there has been progress in understanding marine low-cloud feedbacks, historically a major contributor to the total cloud feedback uncertainty, other cloud regimes remain major sources of uncertainty, for example the climate feedback resulting from the amount of tropical high-clouds.

Furthermore, climate models still have considerable biases in climatological temperature and cloud macroscopic properties, in particular over land and over the Southern Ocean. There are confounding issues, on the one hand between the number of different cloud regimes in the climate system and the challenge of representing these in climate models and, on the other hand, the need for a consistent treatment of clouds in models. Observational campaigns necessarily focus on one specific cloud type, while climate modeling is geared at representing different cloud processes and regimes, and their aggregate effects across scales. Research strategies for how to propagate process understanding from individual cloud regimes into demonstrated climate modeling improvements across multiple cloud regimes would be highly valuable.

The reduction of uncertainties related to cloud feedbacks since IPCC 5th assessment cycle has contributed to the reduced uncertainty of the assessed equilibrium climate sensitivity (ECS) in the latest IPCC report. However, the assessment also noted a distinct possibility of a warming climate increasing the strength of these feedbacks. This means that the upper end estimates of the likely ECS range are weakly constrained. More research is also needed into how future changes of SST patterns could determine the "effective" climate sensitivity, with implications for the assessment of ECS.

Policy relevance

Assessments of the Earth climate sensitivity are of great relevance for understanding how the climate will respond to increasing warming, as well as for estimating the remaining carbon budgets in the context of meeting the goals of the Paris Agreement. Improvements in the understanding of cloud processes are also central for better representing the water cycle in climate models, which, in turn, enables more accurate assessment of future changes in precipitation.

Flag(s)

Digitalisation/AI

Related fiche(s)

5.3, 6.3

1.3 Quantifying the methane budget and monitoring progress on methane reductions

■ Earth system science □ Impacts, risks and adaptation ■ Mitigation

Methane is the second largest contributor to global warming. Its atmospheric concentration has increased by around 170% since pre-industrial times. Owing to its relatively short lifetime, changes in methane concentration exhibit substantial inter-annual to multi-decadal variations. The global methane cycle remains relatively poorly understood with challenges in determining the causes of many year-to-year and even longer timescale variations, including the role of natural variability, feedbacks, and permafrost thawing.

There is a substantial opportunity to reduce uncertainty in critical aspects of the global methane cycle, such as better monitoring and quantifying anthropogenic emissions from diffuse sources which are thus far poorly quantified. This will support the development of policy-relevant indicators of the magnitude and speed of climate and methane cycle interactions that may, in turn, reinforce human-caused warming. Accordingly, there is a need to develop a European-wide methane assessment capacity, building on advances in modeling and observation of the methane cycle and on improved cooperation and communication between the relevant scientific communities.

Policy relevance

A better understanding, monitoring, and modeling of atmospheric chemical processes will result in improved science base for methane cycle analysis, enhancing the quality of emission inventories reported to the United Nations Framework Convention on Climate Change (UNFCCC). This will be critical for verifying national and regional contributions towards the Global Methane Pledge agreed at the COP26 in Glasgow, led by the United States and the EU and for forming a robust policy advice.

Flag(s)

International cooperation

Digitalisation/AI

Related fiche(s)

2.3

1.4 Better understanding early instrumental period changes

■ Earth system science ☐ Impacts, risks and adaptation ☐ Mitigation

There is a rich history of observing weather and climate globally, particularly over Europe. However, much of this data exists solely in hard copy or image form and thus is presently unexploitable. It is likely that as much data exists for the period prior to 1950 as is currently in digital form. These “unknown knowns” from the observations can be resolved through their rescue and integration into national, regional, and global holdings.

There are efforts underway to rescue data across Europe, but scaling up is needed using novel approaches such as classroom-based exercises while taking care to address the quality and homogeneity of the early observations. This could be extended to also rescue data from Africa based upon the recently recovered fiche and film records from the African Centre of Meteorological Application for Development effort led by the Belgian meteorological service, as well as efforts to digitise comprehensively European records. Once digitised, these data could be analysed to form both new and extended observational datasets of a broad range of essential climate variables. It would also provide an improved observational constraint to reanalysis products at global and regional scales.

Policy relevance

Longer-term and higher quality datasets on retrieved past observations and records will enable greater insights into past significant climatic events. It will increase climate literacy through participatory learning techniques across countries and offers significant potential to strengthen international cooperation, in particular with Africa.

Flag(s)

International cooperation

Digitalisation/AI

Related fiche(s)

2.4, 3.7

1.5 Understanding how the Earth system components will respond to a state of net zero emissions

■ Earth system science ☐ Impacts, risks and adaptation ■ Mitigation

Net zero targets are being used to guide climate policy in the coming decades and as such, they are taking an increasingly prominent place in national and international climate debates. At present, however, it is unclear how exactly the Earth system will respond to a state of net zero CO_2 or GHG emissions.

The latest IPCC report assessed the "zero emissions commitment" (ZEC) of CO_2, which is the additional warming projected to occur after a net zero CO_2 emissions state is achieved and maintained, with a best estimate of zero additional warming, but with an uncertainty range of up to 15% of further warming. Much of the evidence underpinning this ZEC assessment has an incomplete representation of potentially important Earth system feedbacks with climate modeling tools most often showing a slight cooling after net zero CO_2 emissions are reached.

Research is needed to better constrain, quantify, and identify key contributing factors of ZEC uncertainty and to improve modeling tools to allow applying new ZEC insights to mitigation analysis. Progress is also necessary on enhanced understanding of global warming and other committed changes in a net zero world, including improved representation of processes that drive future ocean heat uptake, carbon uptake in land and ocean, and in atmospheric physical feedback processes. Additional aspects come into play when net zero GHG is considered and are equally important to research, including the need for net negative CO_2 emissions.

Policy relevance

Furthering the understanding of the Earth system response to declining and net zero emissions of CO_2 and other GHGs is critical for understanding the emission reduction efforts, as well as the role of CO_2 removal, required to meet the Paris Agreement.

Flag(s)

Digitalisation/AI

Biodiversity/ Ecosystem

Related fiche(s)

3.1, 3.5

CLUSTER 2:

CHANGES IN THE CLIMATE SYSTEM, INCLUDING ABRUPT AND IRREVERSIBLE CHANGE

Although the origin and magnitude of Earth's warming are now firmly established, major uncertainties persist about the resulting consequences and their effects on regional climate. Changes in both atmospheric and ocean circulation need to be better understood and represented more accurately in climate models. This includes the causes, rate and consequences of past changes - for example, the Atlantic Meridional Overturning Circulation (AMOC) collapsed abruptly during the last glacial period, but our ability to determine the likelihood of such collapse under increasing global warming remains limited. The European climate, in particular precipitation patterns, is strongly affected by variations in atmospheric circulation, mid-latitudes trends and changes in the AMOC. Yet, present climate models still grapple with uncertainties regarding whether precipitation will locally increase or decrease with additional warming. This underscores the need for advancements in our understanding of atmospheric circulation changes in a warming climate, including the impacts of Arctic amplification on global warming in mid-latitudes.

The increasing pace of climate change combined with insufficient progress in reducing emissions escalates the need to better understand the emergence of novel conditions, including the probability and quantification of abrupt, high-impact, large-scale and potentially irreversible changes. Notably, despite recent progress and ongoing efforts, uncertainties persist so as to the likelihood, timing and amplitude of the thresholds beyond which tipping points may occur. Understanding these changes and the related processes is crucial for long-term climate action planning, including adaptation efforts.

The response of the cryosphere, most notably ice sheets and permafrost, can be both abrupt and irreversible, and lead to committed long-term changes in the future. Thawing in the cryosphere can amplify global or regional climate feedbacks - for example, large meltwater fluxes into the North Atlantic from Greenland have the potential to affect the deep ocean circulation (AMOC). High uncertainty exists regarding the response of the Antarctic Ice Sheet, but also regarding carbon release from permafrost thaw since the related processes are generally not represented in climate models. Therefore, the understanding of all these complex processes and their monitoring must be significantly advanced.

> **"The increasing pace of climate change combined with insufficient progress in reducing emissions escalates the need to better understand the emergence of novel conditions, including the probability and quantification of abrupt, highimpact, large-scale and potentially irreversible changes."**

More research is also needed on proxy reconstructions that provide valuable historical climate information extending beyond the period for which we have direct records. These reconstructions help scientists understand past climate variations and patterns, which is essential for estimating natural climate variability, calibrating climate models, identifying climate trends or contextualising recent changes. Targeted efforts are needed on prior warm periods in the paleoclimatic record to better understand how the climate was behaving globally and regionally in a multi-millennial context. This will inform our understanding in terms of both the novelty of the current climate system state and the rate of ongoing climate change.

2.1 Modeling atmospheric circulation and precipitation changes in a warming climate

■ Earth system science ☐ Impacts, risks and adaptation ☐ Mitigation

Future changes in atmospheric circulation and the resulting precipitation changes are subject to substantial knowledge gaps. There are structural and systematic uncertainties in representing changes in the 21st century atmospheric circulation changes in the North Atlantic/European sector and there remains substantial uncertainty in assessing the interactions between climate change and in particular Arctic warming, and mid-latitude variability. There are contrasting lines of evidence that cannot yet be reconciled on the linkages between the Arctic warming and the mid-latitude atmospheric circulation. Furthermore, climate models agree only in a few regions on how (in which direction) trends in mean precipitation will change during this century. Hence, based on the current generation of climate models, we do not know for most regions whether mean precipitation will increase or decrease, let alone knowledge of more sophisticated climate indicators related to precipitation.

Strong arguments can be made that these substantial uncertainties can be reduced through a decisive increase in spatial resolution and hence quality of the climate models used. Progress will require flexible experimentation with the recently developed very-high-resolution coupled climate models increasingly feasible in the context of the upcoming European exascale High Performance Computing efforts.

Policy relevance

Reducing uncertainties in predicting atmospheric circulation and precipitation changes is vital for informed policymaking across sectors to enhance resilience, sustainability, and preparedness in the face of a changing climate, via a shift to higher-resolution climate models.

Flag(s)

Digitalisation/AI

Related fiche(s)

5.3, 8.4

2.2 Representing the Atlantic Meridional Overturning Circulation (AMOC) in climate models

■ Earth system science ☐ Impacts, risks and adaptation ☐ Mitigation

Our current knowledge on the AMOC is insufficient. The best assessment is that the AMOC will weaken in the future, but we do not know by how much and for how long, nor how much this weakening depends on the mix and rate of future GHG emissions. It is generally understood that the AMOC collapsed abruptly during the last glacial period, but the likelihood of collapse this century under global warming is currently assessed as a low likelihood outcome with considerable uncertainty. While proxy records indicate that the AMOC was relatively stable during the past 8000 years, there is some evidence, but low confidence, of a decline during the 20th century. To what extent observed change is due to natural variability or human-caused change remains uncertain.

These knowledge gaps highlight the critical importance of continuous high-quality monitoring, yet the future of subpolar AMOC measurements is unclear. A systematic exploration of reducing the dependency upon short-term funding support of subpolar observations by individual entities and teams is needed to ensure long-term continuous monitoring. There is also a need for systematic exploration of physical, chemical, and perhaps biological proxies of recent AMOC changes.

The magnitude and mechanisms of AMOC internal variability show inconsistent behaviour across existing climate models and remain underestimated despite most recent model development. The observations in the subpolar North Atlantic show that the importance of Labrador Sea deep convection for AMOC variability is substantially overestimated in standard climate models. This suggests that coupled climate models must be run at much higher spatial resolution than is currently standard to simulate air-sea interactions in the water-mass formation regions and to properly assess the impact of future changes. Flexible experimentation with recently developed very-high-resolution climate models is needed for the assessment of likeliness of future collapse.

Policy relevance

AMOC changes influence regional ocean changes in the North Atlantic/European realm and have far-reaching effects on precipitation patterns. A complete AMOC collapse would fundamentally alter the North Atlantic regional climate with broad ranging impacts for Europe and beyond. Better understanding the likelihood and warning signs of an AMOC collapse is critical for robust policies for building climate resilience.

Flag(s)

Digitalisation/AI

2.3 Identifying abrupt, irreversible, and committed changes in the cryosphere

■ Earth system science ☐ Impacts, risks and adaptation ☐ Mitigation

The climatic responses of cryospheric elements like ice sheets and permafrost can be both abrupt and irreversible, lead to committed long-term changes, and contribute to global or regional climate feedbacks. However, despite recent progress, large uncertainties remain on the likelihood, timing, and amplitude of abrupt and irreversible changes in the cryosphere. This is also the case for the amplitude of committed future changes in the context of stabilising global temperatures at a given warming level.

There is an urgent need to improve our capabilities to observe, model and identify signs of destabilisation of the Antarctic and Greenland Ice Sheets to constrain uncertainties in projections of global sea level rise.

The Greenland Ice Sheet could be subject to abrupt changes in a warmer climate, however, there is low agreement including on the processes determining the evolution of surface mass balance (meltwater formation, storage, and drainage at the surface and below), and their potential interaction with ice dynamics. The West and East Antarctic ice sheets are considered to be susceptible to develop instabilities linked to critical thresholds. However, there are large uncertainties in modeling marine instability due to warming oceans, subsurface melting, and ice shelf fractures, impacting future ice-mass projections.

Conflicting observations and limited accessibility hinder accurate modeling. Permafrost thawing with global warming will decrease the frozen soil volume, releasing carbon, yet the timing and extent of carbon dioxide versus methane release remain uncertain. Inadequate representation of processes like abrupt thaw and limited observational data in climate models contribute to this uncertainty. Variability in surface conditions complicates understanding and modeling carbon pools, while some models overlook the existing permafrost carbon pool crucial for estimating its feedback.

Policy relevance

Ice-sheet melt has direct implications on the global scale due to the influence on global mean sea level. Abrupt changes can lead to accelerated changes; committed and irreversible changes with long-term effects, including on regional climate. Having a better understanding of how such changes might and will occur will help design the necessary adaptation responses, with a greater knowledge of implied impacts for ecosystems and populations, both relevant for region-specific policies and for international cooperation.

Flag(s)

International cooperation

Digitalisation/AI

Related fiche(s)

1.3, 3.1, 5.5, 5.6.

2.4 Extending high-resolution proxy reconstructions with a focus on the mid-Holocene

■ Earth system science ☐ Impacts, risks and adaptation ☐ Mitigation

Proxy reconstructions of past climate with a yearly temporal resolution only reach back to the Common Era at global and hemispheric scales. Further back in time the reconstructions become progressively sparser in time, at decadal, centennial, and then even millennial temporal scales. This limits how our rapidly changing climate state can be compared with earlier periods, and thus the quantification of both the unusualness of the current state of the climate system, and the rate of ongoing climate change in a multi-millennial context. There is considerable potential to extend back in time high resolution proxy reconstructions through a combination of reanalysis of existing proxy records and the development of new and improved techniques.

A focus on the mid-Holocene thermal maximum period is particularly valuable as a comparison to current climate. During that epoch, the global surface temperature maximum – driven by seasonal insolation changes from orbital variations – may have reached sustained temperatures above pre-industrial levels, potentially only surpassed in the most recent decade. However, there is considerable ambiguity over the synchronicity of reconstructed changes and incomplete knowledge of implied changes in other climatic variables.

Improving the temporal resolution of reconstructions around the last interglacial peak, when the climate was warmer than today, with a higher global sea level and smaller ice sheets, but with much lower CO_2 concentrations in the atmosphere, is important to help answer to what degree climate change experienced in the coming decades is unique in the context of the current interglacial. The currently available reconstructions for this last warm period around 125,000 years ago are at solely centennial to multi-centennial resolution.

Policy relevance

This enables a longer-term view of changes, which is important to exploit existing proxies and undertake targeted additional studies. Improving our knowledge about the past periods similar to today's in terms of climatic and non-climatic aspects will aid planning and decision-making across scales with a greater granularity.

Flag(s)

Digitalisation/AI

Related fiche(s)

1.4, 3.7.

CLUSTER 3:

RISKS AND VULNERABILITY ACROSS TIME AND SPACE

The latest IPCC assessment finds that dangerous climate risks will occur at lower warming levels and earlier than assessed in previous reports. With additional warming, risks are becoming increasingly intense, complex and more difficult to manage. In addition, societal systems and their economies are more and more exposed to compounding risks arising from multiple climate hazards occurring together and concurring with a range of other, non-climatic factors such as land use and habitat destruction. Transboundary and trans-sectoral risks related to, for example, global supply chains, financial markets, non-linear socioeconomic responses, or loss of ecosystem services, can significantly amplify losses, as has been dramatically illustrated by the recent COVID-19 pandemic.

The dynamics of compounding and cascading risks are still poorly understood and require further investigation to inform pathways for building societal resilience in the long term. The propagation of risks and their interactions with adaptation and mitigation options should be analysed from a more holistic perspective. More evidence is needed to characterise and quantify the development and transmission pathways of risks for specific systems under different scenarios of future climatic, adaptation, mitigation, and societal development pathways.

Reducing the vulnerability of ecosystems and people to climate hazards also requires more and better data on climate-related risks, with a commitment to widespread accessibility, as pursued by the Risk Data Hub and ClimateAdapt initiatives. Equally important is the development of robust methodologies and frameworks for the quantification of risk sensitivity. This involves addressing the characterisation, monitoring and quantification of the many nonlinear interactions involved. These advances are pivotal for evaluating the effectiveness of mitigation, adaptation, and risk reduction strategies.

Adaptation also needs to be better characterised under a variety of future scenarios, with new data and knowledge on the response of both human and natural systems to adaptation options. Research should explore how the adaptation potential of societies for risk reduction varies with local and temporal context, depending on the dynamics of human vulnerability and exposure to climate change and extreme events, their interaction and interdependence with ecosystem vulnerability, and with other non-climatic factors and hazards. A comprehensive approach is required to inform adaptation strategies that are not only incremental but also transformative to build lasting resilience embedded in broader development policies.

> **“With additional warming, risks are becoming increasingly intense, complex and more difficult to manage”**

With global warming likely to exceed 1.5°C in this century given the slow pace of progress on reducing GHG emissions, there is an increasing interest in the exploration of overshoot scenarios with a subsequent decline in global temperatures. In fact, the majority of emission scenarios limiting global warming to 1.5°C by 2100 analysed in the latest IPCC assessment involve a temperature overshoot. There is an urgent need to better understand risks associated with such scenarios, including exploration of climate and Earth system feedbacks, the feasibility and impacts of large-scale carbon dioxide removal (CDR) that would be needed to bring the temperatures back down, and the wider implications for mitigation and adaptation strategies.

3.1 Understanding future global climate risks for individual systems, sectors and for compound risks

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Climate risks intensify with rising temperatures, especially affecting vulnerable groups and systems. As temperatures rise, managing impacts becomes more challenging due to complex interactions between multiple hazards and other threats. The ability to minimise risks varies by location and depends on adaptation efforts.

Research is needed to better understand the development of risks over time for different possible future climate and mitigation scenarios, the surpassing of temperature dependent adaptation limits for ecosystems and human systems, and what effective response options can be deployed both for human society and communities, and also in terms of constraints on individual actors. Developing robust projections of future compounding global climate risks requires further basic research about mechanisms and underlying causes and effects concerning 1) the vulnerability of species, biodiversity, ecosystems, dependent humans and societies at regional scale at different warming levels; 2) the occurrence, including "when" and "why", of biological tipping points (ecosystems) and tipping points for societal functioning, and; 3) the limits to adaptation (evolutionary adaptation) of species, ecosystems and of dependent societies with various economic backgrounds.

Furthermore, IPCC reports include an iconic representation of rising climate risk as a function of temperature rise – figures called "burning embers". These represent the relationship between risk development and degree of global warming. It would be valuable to develop approaches that would enable visualisations akin to the burning embers, with and without adaptation, for various development pathways, and including consideration of regional risks and also embracing other indicators of climate change beyond the warming levels alone (such as temperature humidity combinations, extreme events including drought and flood, sea level rise, ocean oxygen loss and acidification).

Policy relevance

Expanded risk-scenarios, including compound risks and nature's and societies' capacities to respond, will enable policymakers to make robust decisions about mitigation, adaptation and climate resilient development.

Flag(s)

Digitalisation/AI

Biodiversity/Ecosystems

SSH

Related fiche(s)

1.5, 2.3, 4.2, 6.3.

3.2 Understanding the dynamics of exposure and human vulnerability at regional and local scales

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

In assessing climate risk, both exposure and vulnerability, as well as their interlinkages, need to be taken into account. Notably, vulnerability and exposure cannot be considered as static, and their variability in both space and time needs better understanding and assessment.

Despite changes in exposure, present studies tend to assess exposure to heat stress based on static information, without accounting for daily mobility and other population dynamics. For example, during the day, increased heat stress exposure can be experienced outside of the place of residence, as well as during any commute. The development of adaptation and early warning systems in the context of extreme events would benefit significantly from more sophisticated understanding and treatment of daily, weekly and monthly dynamics of population movements in terms of exposure. A comprehensive and improved consideration of population dynamics requires updated methodologies, advanced modeling, and planning tools.

Changes in vulnerability, in turn, are especially induced by evolving socio-demographic and socio-economic structures or framework conditions. Better understanding of the associated dynamics is a pressing research need given the potentially significant implications for adaptation responses in the context of mitigation action, as well as the broader equity and justice dimensions. Today, 3.6 billion people are already considered highly vulnerable to climate change due to overlapping challenges and effects of compound risks. But how will their adaptation capacity and limits change depending on the progress on poverty reduction, equity, justice, resource distributions and mitigation? Research is needed to elucidate these questions by providing more insights into issues such as vulnerability of human society at regional and local scales; interactions between heat stress, human thermal performance and levels of societal functioning; the environmental criteria for human well-being and health, but also for ecosystem health and biodiversity; trajectories that integrate human into ecosystem and planetary health through climate resilient development; the gender dimension of vulnerability and adaptive capacity.

Policy relevance

More accurately representing societal and ecosystem vulnerability and exposure in time and space, will allow for better tailoring of early warning systems (of direct relevance for the World Meteorological Organisation (WMO) "Early Warnings for All" initiative), risk management strategies and other adaptation measures at different levels of mitigation, significantly improving their effectiveness and helping to avoid maladaptation.

Flag(s)

SSH

International cooperation

Biodiversity/ Ecosystems

Gender

Related fiche(s)

4.3, 4.6, 9.3.

3.3 Cascading, compound and transboundary risks and adaptation

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Cascading and compound risks of climate change are potentially very damaging to economies and societies, including across sectors and international borders. The latest IPCC report has found that increasing transboundary risks are projected across the food, energy, and water sectors as impacts from more frequent and severe weather and climate extremes increasingly propagate through supply chains, financial markets, and natural resource flows, and may also increasingly interact with impacts from other crises such as pandemics.

While the conceptual understanding of cascading and compound risks and adaptation has improved, systems-wide research quantifying how commodity and trade networks, the financial system, natural resource flows (e.g. rivers and watersheds) and the movement of people and species propagate impacts and risks across sectors, regions and borders has only recently started to emerge. Substantially more evidence is needed to understand risk transmission pathways. Several gaps remain also for specific compound risks, for instance how the interaction of multiple risks across sectors may result in displacement, migration, or immobility of people both within and from outside Europe. Finally, while there is generally good conceptual understanding of how adaptation can reduce risks at the source, research is needed to identify the effectiveness of different adaptation options in reducing these cascading, compound, and transboundary risks across different levels of mitigation action.

Policy relevance

Most European adaptation strategies are still heavily focused on sectoral, regional, and national risks and thereby underestimate the true costs and disruption of climate change. This research will inform cross-sectoral, cross-boundary and better coordinated international adaptation responses to diverse combinations of climatic and non-climatic risks. It will also contribute to understanding adaptation limits and the requirements for transformational rather than incremental adaptation.

Flag(s)

International cooperation

SSH

Biodiversity/ Ecosystems

Related fiche(s)

4.1, 4.2, 8.3.

3.4 Evaluating the intrinsic risks of climate change responses

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

The way we respond to climate change can itself generate new risks. The IPCC defines risk as "the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems", encompassing risks from both potential impacts of climate change and human responses to it. These may include: 1) maladaptation (and/or trade-offs between adaptation to various increasing hazards, e.g., adaptation to increasing extreme precipitation leading to a higher vulnerability to drought); 2) mitigation options that unintentionally increase physical climate risk or other crises like pollution or biodiversity loss (e.g., biofuel production competing with food security, driving land use change and limiting options for more effective mitigation).

With the scale of implementation of responses required, such risks will become increasingly likely and potentially severe, hence also constraining future options for climate action. A core research priority is to develop a systematic inventory of such risks, and, where possible, their quantification. Accordingly, research is needed to strengthen the methodological toolbox for complex climate risk assessment, to increase public understanding and policy awareness of such risks, and to quantify the most important complex risk feedbacks, particularly when it may result in significant constraints on options for climate action. In this context, monitoring and evaluation of the effectiveness of mitigation and adaptation measures, policies, and actions is needed on a local, regional, and national scale.

Policy relevance

In-depth understanding of side-effects associated with climate action can help eliminate the response options that are ineffective or even counterproductive and identify the most effective solutions for both mitigation and adaptation.

Flag(s)

Digitalisation/AI

Biodiversity/Ecosystems

SSH

Related fiche(s)

4.1, 6.1, 8.1, 8.2, 10.4.

3.5 Advancing knowledge on risks from overshooting 1.5°C and options to bring temperatures back down

Earth system science | Impacts, risks and adaptation | Mitigation

The latest IPCC reports conclude that global warming of 1.5°C is likely to be reached early in the 2030s. Yet there is limited understanding of the implications of exceeding a level of global warming of 1.5°C and the extent to which a reversal in global surface temperatures can be achieved. This includes characterising the physical and social risks associated with exceedance and return below a specified level of global warming, including a better understanding of carbon cycle feedbacks and of the socio-economic, technical, and institutional feasibility of drawing down temperatures by removing CO_2 from the atmosphere, requiring new modeling frameworks. This would include systematic approaches to modeling risks of different durations and magnitudes of overshoot, including fast and slow onset processes, low-likelihood high-impact events, and the risk of irreversible impacts.

A better understanding of overshoot and (ir)reversibility of its long-term impacts beyond 2100 need to be considered to account for the slowly varying components of the climate and natural systems in the light of the consequences on the well-being of future generations. While many hazards decrease with lower temperatures, vulnerability and exposure are not linearly related to global surface temperatures and will depend on impacts that occur during an overshoot period and on adaptation measures implemented and their cost. Irreversible impacts and ineffective adaptation may lead to a situation where impacts remain high even once temperatures return to lower levels.

The feasibility and sustainability of a globally attainable level of CDR also needs to be better understood, considering carbon cycle feedbacks and land and ocean impacts, together with an improved representation of CDR options and their implementation barriers in global mitigation pathways. The potential for stepping up near-term action (including governance and institutional barriers) needs to be explored, to understand how much further temperatures could be reversed, at what costs and how this would limit residual climate risks.

Policy relevance

Every increment of global warming has major implications for global and regional climate and related risks in the coming decades. Both mitigation and adaptation policies will benefit from assessing the potential for enhanced near-term mitigation, long-term CDR and the associated impacts, risks and feasibility of returning temperatures to lower levels.

Flag(s)

SSH

Biodiversity/ Ecosystems

Related fiche(s)

1.5, 4.1, 8.5.

3.6 Exploring societal resilience in a volatile world amplified by climate change

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

The causes, risks, and consequences of climate change are well established. Addressing the climate challenge is also increasingly seen as a key enabling factor to achieve other societal objectives that are part of a broader sustainable development agenda, and vice versa. It is therefore clear that societal choices about how to respond to the climate change challenge are intricately interlinked with our wider societal system. A key knowledge gap, however, is how other crises can amplify climate risk or are exacerbated by climate impacts or adaptation and mitigation responses, when they occur simultaneously or in short succession. This state, where disparate crises can interact such that the overall impact far exceeds the sum of each part is called a poly-crisis. Interlinked crises that were identified in expert elicitations include environmental (climate change, biodiversity and ecosystem collapse, natural resource crisis), societal (public health and pandemics, cost of living, mis- and disinformation), technological (breakdown of critical infrastructure), economic and geopolitical crises (armed conflicts).

Illustrative examples of the interactions between different crises that need to be better understood in the context of adaptation are the role of non-climate crises in changing exposure and vulnerability patterns that affect loss and damage, including through the impact of multiple crises on biodiversity and access to environmental services. A crisis that increases vulnerability presents an additional driver of risk and further exacerbates the impacts of climate shocks. Adaptation options that exist otherwise may not be available under these conditions. Compound and cascading risk assessments and analyses of multi-dimensional climate risk in areas of high vulnerability (and often limited data) are needed. In the context of mitigation, the interactions and linkages between different crises need to be better understood in how the transformations required to reach a net zero world change society's vulnerability and exposure to critical infrastructure, geopolitical or other risks. It is equally important to address how climate (mitigation and adaptation) policies can create synergies and trade-offs in addressing other crises, and vice versa.

Policy relevance

Current research and research tools are not equipped to explore the interdisciplinary questions that must be answered to understand complex and cascading multi-dimensional climate risks, their interaction with societal vulnerability and exposure, as well as potential societal solutions. However, a better understanding of these risks at different spatial and temporal scales is crucial to ensure a resilient future society through informed decision-making.

Flag(s)

Gender

SSH

Related fiche(s)

4.4, 5.1, 9.3, 10.2, 10.6.

3.7 Utilising paleo records of past impacts of climate changes to refine future scenarios

☐ Earth system science ■ Impacts, risks and adaptation ☐ Mitigation

The unfolding climatic changes are not unique and there have been equivalents in the prehistoric past. Although climatic changes of the last 2.5 million years have largely been driven by astronomical cycles, there are examples from the more distant past when large releases of GHGs caused global ecological crises and even mass extinctions. The rich record of ecosystem responses in the deep past is currently poorly integrated in the assessment of climate risks and vulnerabilities. The study of past warming periods can help assess the vulnerability of groups of species and ecosystems, identifying those which may be most vulnerable to global warming in the long run, including where the impacts of climate change are expected to be most severe and which climatic thresholds may lead to mass extinctions.

The latest IPCC report includes a better coverage of paleontological records of impacts than before, but due to lack of targeted research few statements could be made with high confidence. Exploring climate impacts in the geological past can reveal climate change impacts with no confounding human impacts such as habitat destruction, pollution and overexploitation that are the main sources of modern biodiversity decline. Another advantage is that ecosystem states can be compared for different stages of past climate-induced crises – before, during, and after. A key challenge to compare these past impacts with current climate change is the different timescales over which such comparisons can be made. Bridging the gap requires a combined effort to find mechanisms that are scale-independent and to use modeling and simulations. Regarding models, the most widely used approaches to predicting biodiversity losses due to climate change are species distribution models. Simulations are needed to interpolate longer term observations of climate impacts to shorter time scales. Challenges also exist with reference to the spatio-temporal link between warming and biological responses.

Policy relevance

Deepening the understanding of species and ecosystems' vulnerability to climate change based on multiple lines of evidence, including paleo records, is critical for refining conservation planning and directing it towards species and ecosystems that are likely to be most impacted under projected warming scenarios.

Flag(s)

Biodiversity/ Ecosystems

Digitalisation/AI

Related fiche(s)

1.4, 2.4.

CLUSTER 4:

ADAPTATION: EFFECTIVENESS, PATHWAYS AND LIMITS, LOSSES AND DAMAGES

Widespread adverse impacts, including related losses and damages to people and nature, are already occurring in countries and regions hit by climate hazards, affecting disproportionately vulnerable communities and ecosystems. Impacts will escalate with every increment of global warming, making the case for adaptation increasingly urgent. The IPCC cautions, however, that there are limits to how much adaptation can reduce climate risks - as climate change progresses, human and natural systems increasingly face adaptation limits, where adaptive measures become ineffective in reducing risk and safeguarding against harmful consequences. There is also a need to learn from the increasing evidence of maladaptation across sectors and regions that creates lock-in of vulnerability and makes exposure and risks more difficult and costly to manage.

In addition to the continued benefits of incremental adaptation, the IPCC report introduces a paradigm shift towards transformational adaptation that builds resilience in the long term in synergy with sustainable development, helping to overcome soft adaptation limits. Sustainable development for all is also the foundation of the concept of climate resilient development, integrating adaptation with mitigation action to deliver benefits for human well-being and health of the planet. However, important barriers that undermine adaptive capacity remain to be overcome, including in Europe, to accelerate, monitor and assess the development and implementation of effective and transformative adaptation actions. Examples of such barriers include missing data, inadequate institutional and governance arrangements or gaps in our capacity to assess climate risk and the effectiveness of adaptation strategies. The links between risk preparedness and response, including early warning, climate resilient reconstruction, grey and nature-based solutions (NBS) for adaptation and sustainable development also need to be strengthened, and incorporated into the EU core policies such as the Common Agricultural Policy and the Water Framework Directive.

Understanding the role of human activities through climate attribution becomes increasingly important for informed risk management and policy development and is key to progress in strengthening the preparedness for extremes, reducing losses and damages. It is important to clarify here the distinction between "losses and damages" and "Loss and Damage" - the IPCC uses the former to refer broadly to adverse (observed) impacts and (projected) risks whereas the latter is linked to political debate under the UNFCCC on addressing climate-related destruction in developing countries in the context of the Warsaw International Mechanism. In the research context of this report, the primary focus is on the wider notion of "losses and damages", with the potential to inform the "Loss and Damage" policy and legal dimensions. Advances are needed in our understanding and quantification of losses and damages, including cross-cutting issues related to climate justice and responsibility, distributional aspects, and stakeholder engagement, as well as non-economic aspects such as ecosystem functions, culture and heritage. The potential legal implications of Loss and Damage under the UNFCCC, as well as at other scales (e.g., local and national) and other legal regimes, also need to be further explored.

> **"Human and natural systems increasingly face adaptation limits, where adaptive measures become ineffective in reducing risk and safeguarding against harmful consequences."**

Filling these gaps will secure more and better data on climate-related losses and damages, help validate effective adaptation options and provide state-of-art knowledge on adaptation best-practises, strengthening repositories such as Climate-ADAPT.

4.1 Understanding adaptation effectiveness and limits at different degrees of warming

■ Earth system science ■ Impacts, risks and adaptation □ Mitigation

Despite a notable increase in evaluations of the implementation and effectiveness of adaptation in the latest IPCC report, the assessment primarily focused on responses to past or present climatic conditions and did not consider increasing temperatures. However, most adaptation options to the four key risks in Europe (heat, drought, flooding, water scarcity) depend on water and land, the availability of which will be diminished with increasing global warming. The current adaptation implementation gap is therefore likely to increase with higher warming, but quantification is missing.

The latest IPCC report also found increasing evidence for hard limits to adaptation being surpassed already at current warming levels. Such hard limits are related to biological tolerance thresholds, including human physiological limits (such as under hot and wet conditions) and biological physiological limits leading to species mass mortality and degradation of ocean, aquatic, and terrestrial ecosystems. With further warming, it is expected that context-specific hard limits will increasingly be encountered due to biogeophysical constraints, e.g. on water availability, carbon storage and biomass production. However, the scientific evidence underpinning the identification of such hard limits remains limited, facilitating lock-in effects, maladaptation, and negative mitigation responses.

Better knowledge about adaptation feasibility and limits and effectiveness of adaptation for different global warming levels and socio-economic contexts is necessary. Advancements are needed in assessing possible adaptation responses to numerous climatic impact-drivers across a comprehensive range of warming levels, sectors (energy, agriculture, building, transport, industry, ecosystems…), and regions, but also in better including adaptation in climate impact and Integrated Assessment Models (IAMs). Regions of particular interest for exploration of adaptation limits include those affected by the loss of high mountain cryosphere for water availability, small islands and low-lying areas and coasts (changing profiles of coastal hazards including salinisation), and the Mediterranean region (biogeophysical constraints e.g., on greening due to limited water availability).

Policy relevance

This knowledge is highly relevant for informing the development of comprehensive, context-specific, and effective adaptation strategies, including evaluation of adaptation options in light of limitations, feasibility, and effectiveness, and how to avoid maladaptation.

Flag(s)

Biodiversity/ Ecosystems

Related fiche(s)

3.1, 3.3, 3.4, 3.5, 5.2, 8.2, 10.4.

4.2 Probing the limits of nature-based solutions under different climate-change scenarios

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Nature-based solutions (NBS) are clearly preferable over grey solutions, both by virtue of their co-benefits to biodiversity and human health, and also because they sometimes are simply better climate mitigation and adaptation solutions. However, the latest IPCC report suggests that while NBS as well as most water-related adaptation options are effective, they are vulnerable to climate change impacts and their effectiveness may drop with increasing global warming. Effectiveness and full exploitation of the potential of NBS therefore relies on ambitious emissions reductions.

As the limits to NBS depend on context and intended benefit, there is need for a more rigorous assessment of their feasibility for climate resilience and mitigation at different levels of warming, at different timescales, and across a wide range of regions and sectors, addressing questions such as when, where and for whom these options can be most effective. Research is needed on the benefits and costs of NBS in different settings (e.g., coastal, terrestrial) and for different purposes (e.g., mitigation, adaptation, biodiversity conservation) under different warming scenarios and to identify best-practice pathways towards design and implementation in different socio-economic contexts. In addition, more effort is needed to quantify the efficacy of NBS for adaptation (as has been done for mitigation) at various warming levels, and including co-benefits for mitigation and biodiversity.

Policy relevance

Understanding how NBS will respond to a warming climate and how their potential will be impacted will inform the timely development of resilient climate strategies (combining adaptation and mitigation dimensions) that are robust against various warming levels and promote implementation of climate resilient NBS in the broader sustainable development context.

Flag(s)

SSH

Biodiversity/ Ecosystems

Related fiche(s)

3.1, 3.2, 5.4.

4.3 Considering population response and coastal adaptation strategies in the face of rising sea levels

■ Earth system science ■ Impacts, risks and adaptation □ Mitigation

Understanding and predicting coastal change is severely limited by incomplete or insufficiently tested models, incomplete understanding of nearshore wave processes and unreliable satellite-derived shoreline estimates. Calibration to local scales is generally needed. A coupled approach promises a better handle on both data and model reliability for sandy open coasts, at scales from municipalities to regions and continents. Whether this can be extended to mud/mangrove coasts that comprise a very substantial part of the global coastlines is an open question. A universal approach would be useful to assess long-term strategies of erosion prevention and coastline management.

Shortcomings also remain in how national to continental scale assessments of future coastal risk can support long-term coastal adaptation pathways. First, they lack consideration of human population dynamics and of the interactions between decisions at different scales. While national level socio-economic development has generally been included in the assessments, these mostly do not take into account subnational spatial and temporal patterns of human development, such as urbanisation and migration. Furthermore, assessments generally do not link higher level adaptation decisions (e.g., to protect or retreat) with decisions associated with population development.

Assessments have generally not included decision-making frameworks that fit the dynamic and adaptive nature of coastal pathways. Adaptation pathway analysis is a helpful tool but lacks integration with modeling frameworks. Generally, there is a need to move from static approaches (cost-benefit analysis) to dynamic and adaptive approaches that consider the spatial and temporal patterns of sea-level rise and socio-economic development. Research should develop a relocatable workflow for assessment of past and future coastal evolution at a timescale of decades under global and local scenarios of coastal and urban development and climate change. We also need to learn more about social acceptability and population responses to coastal adaptation as part of broader adaptation pathways across various contexts.

Policy relevance

The outcomes will serve to better appraise the effectiveness and efficiency of coastal adaptation policy options that take into account the essential development dynamics and are tailored for different contexts. Improved coastal change projections will inform risk assessment and shape policies such as coastal management plans and zoning.

Flag(s)

Digitalisation/AI

SSH

Gender

Related fiche(s)

3.2, 5.1, 5.5, 5.6, 10.2.

4.4 Advancing climate science relevant for loss and damage

Earth system science | Impacts, risks and adaptation | Mitigation

There is an urgent need for a more systemic and, where possible, quantified assessment of current and future losses and damages. This includes the extent to which future losses and damages can be avoided by mitigation and adaptation and at what costs, as well as limits to adaptation. This calls for updated assessments of observed impacts, including their attribution to climate change, associated limits to adaptation, and adaptation options and constraints. Second, it requires progress in modeling of future losses and damages in relation to mitigation, adaptation, and development pathways, linking to research on wider climate risk assessment.

Research needs range from basic climate research and advances in the interplay between natural variability and human-induced global climate change (both in the recent past and in the near-term future), to research focused on responses, to inform how impacts are shaped by the interactions between local responses with human-induced exacerbation of climate hazards. Detection and attribution of climate-specific losses and damages can be enabled by delivering datasets and enhanced methods to separate influences of climate trends (including in extreme events) from trends in exposure and vulnerability, both in observed datasets and in model scenarios.

Combining the methodologies of attribution and emergence could help better inform when and where unprecedented conditions potentially leading to major losses and damages are expected to occur (including using initialised predictions and scenario-based projections).

Policy relevance

Advancements in attribution science can inform and improve the effectiveness of early warning and humanitarian strategic planning in a changing climate, country- and region-specific planning for both adaptation and management of residual risk, including in the context of the UNFCCC Santiago Network on loss and damage, as well as mitigation choices.

Flag(s)

International cooperation

Digitalisation/AI

Gender

SSH

Biodiversity/ Ecosystems

Related fiche(s)

3.6, 9.1, 9.2.

4.5 Integrating climate resilience in post-extreme events reconstruction

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Strengthening the integration of climate resilience and adaptation into reconstruction and loss and damage programmes is needed, including in the context of climate resilient development. In most cases loss and reconstruction funds primarily provide funding for the rebuilding of what has been there before. Improvements towards climate resilience, in different phases of reconstruction, are often underfunded or not part of the funding schemes (private insurance as well as state funding schemes). New data, methods and tools are needed to improve the consideration of climate resilience within different phases and sectors of reconstruction after extreme events, considering differences in climatic hazards, but also in vulnerability and exposure of people, infrastructures, and services.

In addition to the integration of climate resilience and adaptation into reconstruction programmes, there is also the need to better understand synergies and trade-offs between adaptation and mitigation actions. For example, synergies can be strengthened when improving climate resilience with new green/blue infrastructures in cities, but specific insulation materials for houses to reduce energy consumption might increase loss and damage once the house gets flooded.

Policy relevance

Building climate resilience into reconstruction and loss and damage programmes enhances preparedness and adaptive capacity in synergy with sustainable development. It also contributes to sound financial management in the face of non-linear risks associated with future climate change and supports improved definition of adaptation and resilience goals, and cooperation formats.

Flag(s)

International cooperation

Gender

SSH

Related fiche(s)

6.1, 9.2, 9.3, 10.6.

4.6 Linking early warning to long-term adaptation

■ Earth system science ■ Impacts, risks and adaptation □ Mitigation

With the impacts of extreme climate events becoming a highly political issue, there is a growing interest in examining the role of early warning to protect lives and assets and to support wider adaptation efforts. However, there has so far been little systematic exploration of the extent to which early warning systems link to adaptation planning, including issues such as how information about exposure and vulnerability can be useful across timescales, whether it is shared across institutions and if limits to adaptation emerge when considering response to an early warning of an unprecedented extreme event.

Case-study based assessments are needed to investigate the adequacy of early warning systems in a changing climate, and how they can be improved to enhance preparedness to future events. The assessments should identify the limitations of such systems - for example, with the short lead-time between warning and extreme weather event (typically a few hours or days notice), people may be able to move out of harm's way, but many assets will still be lost, with no time for more structural adaptation such as changes in land use planning, construction of protective infrastructure or public awareness raising. The outcomes should underpin the design of better early warning systems and point to areas where other adaptation solutions are necessary.

Policy relevance

Results will serve to strengthen the coherence between short-term disaster risk management, longer-term disaster risk reduction, and more systemic climate change adaptation as called for by the Cancun Agreement and the Sendai Framework for Disaster Risk Reduction. At the global level, the outcomes will support the efforts on addressing "Loss and Damage", including under the UNFCCC, where early warning systems have been suggested as a key mechanism, and encompassing the "Early Warnings for All" initiative of the WMO.

Flag(s)

International cooperation

Gender

Digitalisation/AI

SSH

Biodiversity/ Ecosystems

Related fiche(s)

3.2, 9.1, 9.2.

CLUSTER 5:

WATER, BIODIVERSITY, NATURE-BASED SOLUTIONS AND THE COASTAL ENVIRONMENT IN A CHANGING CLIMATE

Water is a dual force in the fight against climate change, acting as both a source of hazards through floods, droughts, and extreme weather events, and a vital component of both adaptation and mitigation responses. As highlighted at the 2023 United Nations Water Conference, "Water is a dealmaker for the Sustainable Development Goals, and for the health and prosperity of people and planet. But our progress on water related goals and targets remains alarmingly off track". Indeed, the world is already facing an unprecedented water crisis, with global freshwater demand predicted to exceed supply by 40% by 2030. The latest IPCC report warns that continued warming is poised to further disrupt the global water cycle, impacting its variability, monsoon precipitation, river flows, seasons as well as very wet and very dry extremes. The IPCC report warns that increases in frequency, intensity, and severity of droughts, floods, and heatwaves, combined with sea-level rise will expose millions of people to acute water and food insecurity with a high risk of triggering conflicts, political instability, and refugee crises.

Water and food security greatly depend on functioning freshwater ecosystems in streams, rivers, lakes, and wetlands, which are vital for sustainable development, climate resilience and as carbon sinks. In 2022, the Convention on Biological Diversity (CBD) emphasised their crucial role by establishing targets that specifically focus on the conservation, restoration, and sustainable management of inland waters. However, the latest IPCC report shows that freshwater ecosystems are under threat from climate induced changes in the hydrological cycle. With additional global warming, ecosystems may reach or surpass hard adaptation limits.

Around 10% of the world's population – close to 1 billion people – resides in low-lying coastal areas hosting significant infrastructure, economic and ecosystem assets that are at significant risk from sea-level rise, storms, and storm surges, but also from saltwater intrusion into coastal ecosystems, increased water temperatures and ocean acidification. Whereas many coastal cities and settlements are already experiencing severe climate impacts, the latest IPCC report warns that coastal climatic impact-drivers – sea-level rise, coastal flooding, and coastal erosion - are projected to increase by mid-century. Coastal flood damage alone is projected to increase at least tenfold by the end of the 21st century.

> “Continued warming is poised to further disrupt the global water cycle, impacting its variability, monsoon precipitation, river flows, seasons as well as very wet and very dry extremes.”

Understanding of the changes in the global water cycle and the interdependencies between climate change, water dynamics, and biodiversity is essential for crafting effective response strategies, which should include nature-based solutions (NBS) among other approaches to support ecosystem adaptation. Strengthening the evidence base regarding the efficacy of NBS in a warming climate is crucial. Ecosystem adaptation must be driven by improved knowledge about the ramifications of management and restoration actions on ecosystem functions, services, and biodiversity. Coastal ecosystems adaptation can be advanced by comprehending and quantifying the future risks and impacts of changing coastal conditions and the effectiveness of related adaptation strategies, not least by combining modeling studies with satellite observations and by expanding comprehensive local to global assessments. Enhancing the resolution and representation of coastal processes is also crucial for actionability at a local scale. All these aspects should be considered as research needs and take into account the needs of the Water Framework Directive in a changing climate, by addressing a variety of issues from water-related extremes (e.g., floods and droughts) to water as a resource (e.g., groundwater, urban water and water reuse) and water in the ecosystems (e.g., marine water and nitrates).

5.1 Projecting climate impacts across natural systems: terrestrial, marine, and freshwater

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

When it comes to risk reduction, our knowledge on how nature-based solutions, in terms of both adaptation and mitigation measures, integrate is limited. To guarantee a liveable future for all, we need to rebuild destroyed or degraded ecosystems for biodiversity and carbon storage. To do so successfully, we need improved projections of future possible impacts and to develop adaptation pathways across ecosystems and dependent societies more comprehensively.

Current research is improving the understanding around which climate-dependent mechanisms are underpinning biodiversity shifts, and which physiological trade-offs and constraints must be considered, explaining species interactions, competitiveness, abundance in relation to environmental parameters, and overall, ecosystem structure and functioning. However, to cover global biodiversity in freshwater or marine environments a significant expansion of modelled scenarios should consider abrupt changes, thresholds and possible tipping points of ecosystems and dependent societies (which are system properties), their (lack of) capacities to adapt and mitigate, as well as the responses of ecosystems and societies to shocks under extremes, and water-related risks associated with adaptation and mitigation responses. Scenario development needs to reflect this integration, considering land, freshwater and ocean “scapes”.

Furthermore, the climate change-biology interface needs further investigation to broaden our understanding regarding evolutionary responses in complex and long-lived marine organisms to identify which changes in ecosystems lead to ecosystem failure.

Policy relevance
A better understanding of climate change related impacts on ecosystems and dependent societies can lead to an improved quality and acceptability of climate policies. Improved understanding of tipping points and limits to adaptation supports the development of adaptation trajectories that are better tailored to ecosystems and societies.

Flag(s)
SSH
Biodiversity/ Ecosystems

Related fiche(s)
3.6, 4.3, 6.3, 9.1.

5.2 Integrating water management and adaptation responses

■ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

In its latest report, the IPCC has underscored that 60% of climate change adaptation measures are intricately tied to water. Furthermore, a multitude of climate impacts are also mediated through water, including but not limited to floods, droughts, and the melting of glaciers, highlighting the importance of improving our understanding of the effectiveness, robustness, and limitations of water-related adaptation strategies.

There is a need to advance integrated water management for adaptation purposes through a context-specific, portfolio-based approach that considers all aspects of the water cycle, from atmospheric rivers, to soil moisture and groundwater storage. This would require a systematic review of observed and projected climate impacts in the hydrological cycle together with identification of water-based adaptation options and limits (at different levels of mitigation and warming) as well as risks of maladaptation. For example, salinisation of coastal aquifers and upstream migration of salt wedge in rivers due to sea-level rise may limit the available adaptation options.

Research should include better understanding of the interaction between water-based adaptation and mitigation options to strengthen their synergies - for example, in water scarce areas some adaptation responses (e.g., desalination) could undermine decarbonisation efforts. There is also a need to explore the interdependencies more thoroughly within water-related sustainable development objectives, notably in the context of the water-energy-food nexus, such as the relationship between soil moisture and land use.

Policy relevance

A more comprehensive understanding of how climate change affects the entire water cycle will enable a portfolio of strategies for better managing water resources, including options for climate-proofing the existing EU water policies, and reinforcing synergies with sectoral adaptation (e.g., energy, agriculture). It will also help avoid maladaptation and support better integration of ecosystem-based adaptation and NBS into water management strategies.

Flag(s)

Biodiversity/ Ecosystems

Related fiche(s)

4.1, 6.1, 6.3.

5.3 Projecting and monitoring soil moisture and ecosystem drought processes to build resilience

Earth system science | Impacts, risks and adaptation | Mitigation

Soil moisture is a crucial regulatory variable affecting water resources, ecosystems, and land-climate feedbacks. Its interaction with other variables such as soil organic carbon plays an important role in determining soil GHG emissions, though quantification of these interactions comes with large uncertainties. Within the water cycle, soil moisture plays a significant role in various natural processes, including plant growth, groundwater recharge, runoff generation, and climate interactions. Accurate monitoring of soil moisture offers therefore significant potential skill for short-term and sub seasonal weather and hydrological forecasting. However, soil moisture initialisation is generally not fully incorporated in forecasting systems. The development of robust initialisation capabilities is crucial, as it sets the initial state of soil moisture in a model or simulation.

Better and extended monitoring systems are needed for soil moisture and environmental drought status combining in-situ measurements, remote sensing, and land surface models, both in Europe and at the global scale. Improvements are necessary in land surface, hydrological and climate models in their representation of soil moisture dynamics and soil moisture-climate feedbacks, including progress on understanding and quantifying the implications for land-carbon sinks in terms of drivers and future trends. The collaboration between relevant research communities (climate science, meteorology, hydrology, ecosystem science, physiology of relevant organisms, agronomy and forestry, soil science, land surface modeling, remote sensing) should be strengthened.

Assessing the soil moisture status and associated ecosystem and atmospheric responses is particularly important in Southern, Central and Western Europe, hosting regions that are projected to be affected by increasing soil moisture deficits with climate change.

Policy relevance

An improved understanding of the evolution of soil moisture and ecosystem drought in a warming climate will provide policymakers with essential information for effective water resource management, drought preparedness, land use planning, and climate change adaptation and mitigation strategies, notably in the agriculture and forestry sectors.

Flag(s)

Digitalisation/AI

SSH

Biodiversity/Ecosystems

Related fiche(s)

1.2, 2.1, 6.3, 8.4, 9.4.

5.4 Strengthening best-practices for freshwater ecosystems, biodiversity and climate response strategies

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Biodiversity is declining globally and one of the most species-rich ecosystems - fresh waters - are being especially threatened. Freshwater vertebrates have faced an average population decline of 84% since 1970. Today, roughly one third of all known freshwater species face the threat of extinction, including one third of all known freshwater fish species. Under future climate change, the pressures on freshwater ecosystems and their species are expected to further increase with habitat loss and barriers to migration routes among major threats. Loss of freshwater biodiversity will directly lead to a decline in ecological functions, threatening the multitude of natural benefits that freshwater biodiversity and ecosystems provide for people.

Nature-based solutions (NBS) have been identified as a cornerstone for protection and restoration of biodiversity and ecosystem services. To fully realise their potential benefits, it is essential that they are deployed in the right places and with the appropriate approaches based on a scientifically robust decision-making framework that integrates interdisciplinary, local, and indigenous knowledge with practical expertise while accounting for uncertainty. For highly context-specific local policy challenges, building of typologies, case studies and their synthesis, as well as knowledge sharing, is critical. However, there is still limited evidence on the effectiveness of NBS adaptation measures, especially for freshwater ecosystems. In addition, despite the fact that participatory (i.e., collaborative) processes are emphasised as part of the development of the EU Water Framework River Basin Management Plans, there is still a considerable lack of consolidated knowledge that defines best practices of collaborative decision-making processes for the development and implementation of freshwater adaptation. Such practices encompass catchment restoration, management, NBS plans, for example at different spatial scales, with different spatial resolutions, and ecological and cultural backgrounds.

Policy relevance

Furthering our understanding of the different elements that comprise the value of freshwater restoration, management, adaptation, and NBS plans and strategies, including when, where, what and how to co-develop, implement, and refine them, will be imperative to mitigate and to adapt to a warmer climate.

Flag(s)

Biodiversity/ Ecosystems

Related fiche(s)

4.2, 9.2, 10.4.

5.5 Improving projections of future coastal change with Earth observations

■ Earth system science ■ Impacts, risks and adaptation □ Mitigation

Coastal climatic impact-drivers (relative sea level change, coastal flooding, coastal erosion) and related impacts are projected to increase almost all over the world by the mid-21st century. Committed sea level rise requires effective local coastal adaptation measures in addition to the global effort to reduce GHG emissions to limit the magnitude and the rate of sea level rise, allowing for more time for coastal responses. Progress is needed in modeling the related processes (e.g., permanent inundation, episodic flooding, coastal erosion) and associated impacts, together with an assessment of risk reduction adaptation measures (e.g., protection structures, NBS, managed retreat, etc.).

While advances have been made in recent years on exploiting the ever-increasing Earth observation (EO) data, high resolution global datasets of coastal type (sandy, muddy, rocky, etc.), nearshore bathymetry and coastal topography are needed for integration with modeling studies to inform adaptation planning at local scales. Research is needed on the one hand to benchmark EO baseline data with model applications to assess changes in climate hazards, impacts, and risks. On the other hand, stakeholder engagement, including the effective involvement of social sciences, is needed to develop adaptation options and strategies for implementation.

Policy relevance

Coastal communities are increasingly at risk from the consequences of sea level rise. The local-scale assessment of risk reduction, enabled through a range of adaptation measures, is highly relevant for tailoring policy formulation, helping allocate resources efficiently, promoting community engagement, enabling data-driven decision-making, building resilience, and reducing vulnerability.

Flag(s)

Digitalisation/AI

SSH

Biodiversity/ Ecosystems

Related fiche(s)

1.1, 2.3, 4.3.

5.6 Multi-scale modeling coastal changes in Arctic regions under warming conditions

■ Earth system science ■ Impacts, risks and adaptation □ Mitigation

Global warming accelerates thawing rates in Arctic regions. Permafrost thaw is occurring in an increased number of areas, exposing the landscape more and more to cyclic frost patterns and prolonged periods of above freezing temperatures. These changing conditions are expected to lead to an expanded exploitation of these areas for socio-economic purposes, a process that has already started. However, the suitability of the coastal zones of such regions for these developments is relatively understudied, in particular, the physical processes that shape these coasts, and their dynamics on various temporal and spatial scales are largely unknown. More research is also needed on the implications of an accelerated warming and erosion of presently frozen floodplains for the release of GHG into the atmosphere.

State of the art morpho-dynamic models can reproduce the medium to long term evolution of unconsolidated coasts consisting of a silty and/or sandy substrate. However, currently no morpho-dynamic model can simulate the evolution of a (partially) frozen coastline under the action of tides, waves, and ice, largely due to a lack of process knowledge. This gap may be filled by leveraging existing datasets of morpho dynamics of Arctic coastal zones, collecting new detailed data on freezing/thawing related dynamics in field and/or lab settings, and by developing suitable parameterisations that can be built into existing coastal morpho-dynamic models.

Policy relevance

Evidence-based decision making is needed to address new developments in the next decades that will likely occur in the warming Arctic including on issues such as suitability for civil construction, increased flood risk for coastal communities due to a larger exposure to coastal hazards and sustainable coastal zone management.

Flag(s)

Digitalisation/AI

SSH

Biodiversity/ Ecosystems

Related fiche(s)

2.3, 4.3.

CLUSTER 6:

TOWARDS MORE COHERENCE IN CLIMATE POLICIES: INTEGRATING IMPACTS–ADAPTATION–MITIGATION

Mitigation and adaptation are two sides of the same coin, but their interactions are inherently complex. The latest IPCC report is clear that progress on mitigation will largely determine the demand for and the effectiveness of adaptation, with limits being reached with increasing warming levels. At the same time, mitigation scenarios themselves must be resilient to changes in climate, particularly the occurrence of extremes. The IPCC stresses that the trends in adverse climate impacts, projected risks and vulnerability increase the urgency to advance climate resilient development that combines deep emissions reductions and climate adaptation together, making the case for coordination and integration of climate policies and actions even stronger. This is also important because approaches focusing on mitigation or adaptation in siloes may produce trade-offs that undermine the overall progress of climate action.

Synergies and trade-offs between adaptation and mitigation vary across sectors, between and within regions and nations, depending on local contexts. For example, certain adaptation actions such as NBS can have positive effects on mitigation through increasing carbon stocks. Climate resilient urban planning also holds great potential for reducing emissions. Conversely, some measures such as (hard) flood protection, desalination or expansion of air conditioning can have negative impact in terms of emissions due to their high energy intensity. Furthermore, some mitigation strategies can be detrimental for adaptation. As an example, densification of the urban structure to reduce emissions from transportation can cause urban heat islands, and large-scale bioenergy production can disrupt ecosystems and erode their adaptation services. Careful balancing between mitigation and adaptation objectives is therefore crucial for effective climate action but needs to overcome a scale challenge as the decisions on adaptation and mitigation are typically taken at different governance levels.

Opportunities also exist to better integrate adaptation and mitigation into broader development strategies in line with the United Nations 2030 Agenda for Sustainable Development, which recognises that ending poverty and delivering on social needs must go hand in hand with tackling climate change and other environmental crises. The latest IPCC report has for the first time comprehensively assessed the interplay between adaptation, mitigation, and sustainable development in terms of synergies and trade-offs. The IPCC concludes that more synergies than conflicts exist, but more integration is needed to deliver climate resilient development. The IPCC also emphasises strong links between climate change and biodiversity loss, stressing that climate related impacts on ecosystems and biodiversity increase vulnerability and may limit our ability to adapt and mitigate. In higher warming scenarios the feasibility, effectiveness, and availability of NBS, agroforestry, bioenergy or bio-based materials may be (severely) constrained.

> “Trends in adverse climate impacts, projected risks and vulnerability increase the urgency to advance climate resilient development that combines deep emissions reductions and climate adaptation together.”

Research is needed to support a more strategic approach to climate action and sustainable development by providing a more complete overview of how adaptation and mitigation interact with each other and with other policy objectives, and by identifying transformative and equitable climate actions with most co-benefits. A better toolbox is needed to support linking policies and actions across different spatial and temporal scales and across sectors, underpinned by an effective monitoring and evaluation. Improving the representation of the interplay between mitigation and adaptation options in a warming world requires better linking mitigation pathways to climate impacts and adaptation. An improved assessment of optimal allocation and vulnerability of land-use to climate change (forest cover, forest type, conservation, agricultural land, food production) is also required.

6.1 Integrating mitigation and adaptation action across scales

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

As the urgency to step up climate action mounts, it is fundamental to adopt a more integrated approach to mitigation and adaptation interventions to maximise their effectiveness. This calls for a much better understanding of synergies and trade-offs between mitigation and adaptation responses. Improved coherence at all scales – from global through national to regional and local - is necessary to tap into potential synergies, to avoid and/or minimise trade-offs while also capturing the links with other Sustainable Development Goals (SDGs).

Research is needed to underpin operationalisation of integrating adaptation and mitigation both from design and tracking perspectives, and evaluation of which approaches are most effective. A significant challenge consists in the different spatial and temporal scales of mitigation and adaptation and in understanding how they interact. More insight is needed on the interaction dynamics within and across specific domains such as, for example, settlements (spatial planning, architectural design, blue/green infrastructure) and land use/agriculture (agroforestry, soil, and wetland management) based on real-life case studies and addressing various dimensions - legal, economic, technological, social (including gender) and environmental. There is also a need to better measure and monitor progress on adaptation effectiveness, which has traditionally been more challenging than tracking mitigation effectiveness. This includes generating comprehensive evidence-gap maps of the evidence on integrated adaptation-mitigation responses as well as a strategic approach to fill existing gaps by high-quality evaluation work.

Finally, research should improve our understanding on how the adaptation-mitigation nexus has (or has not) been built into existing policies and institutions, extracting the lessons learnt and replicable examples of best practice across sectors, ecosystems, countries, and communities.

Policy relevance

Improved understanding of the interplay between mitigation and adaptation will support the development of integrated, economy-wide resilient net zero pathways with clear metrics to evaluate progress from a social, environmental, and economic perspective. It can also increase the cost-effectiveness of actions and make them more attractive to stakeholders.

Flag(s)

Digitalisation/AI

SSH

Gender

Biodiversity/
Ecosystems

Related fiche(s)

3.4, 4.5, 7.2, 8.1, 10.4.

6.2 Bridging the gap from Earth system science to impacts and low-emissions climate resilient scenarios

Earth system science | Impacts, risks and adaptation | Mitigation

Climate resilient low-carbon development requires continuously updated assessments of climate risks, for which an accurate understanding of evolving climate hazards and their uncertainties is key. A central challenge is to accurately capture the changes in global to local climate responses, depending on the emission scenario followed, given a cascade of underlying uncertainties (including in climate sensitivity and effective radiative forcing at the global level, but also those related to local response patterns).

A novel dimension of the latest IPCC report was the assessment of global Earth system emulators to evaluate the climate outcomes of diverse mitigation pathways. This innovation, however, also highlighted important research gaps, notably in translating Earth system knowledge for integration into impact and adaptation assessments.

To tackle these challenges, we must improve the availability of tools, methods, and data to incorporate and emulate the Earth system response and its uncertainties, especially at the regional and local level. The most critical bottlenecks include the scarce data availability for model calibration and validation, limitations in tools to accurately represent complex systems (including high-impact tail risks), as well as integration of cutting-edge Earth system knowledge into adaptation strategies, climate resilience assessments and mitigation pathways. There is a need to bridge scales from global to regional, incorporating feedbacks and processes that are crucial for understanding impacts and the effectiveness of climate policy measures.

Policy relevance

This research will inform risk assessments across a wide range of stakeholders, from academia over decision makers to the private sector and the general public, enabling more effective and more coherent mitigation and adaptation strategies thanks to a comprehensive, holistic, and horizontal approach.

Flag(s)

Digitalisation/AI

Related fiche(s)

3.1, 6.3.

6.3 Investigating the interplay of mitigation and adaptation through integrated scenarios with improved representation of climate impacts

Earth system science　　Impacts, risks and adaptation　　Mitigation

The assumptions underlying integrated assessment models (IAMs) are insufficiently tested against projections of both regional climate changes and climate extremes. Research should investigate existing and develop new low-emissions pathways consistent with the temperature goals of the Paris Agreement that integrate and are resilient to climate impacts, including extreme events, to test their feasibility. This requires IAMs to better represent physical climate change and related extremes, including frequency and magnitude of change as well as a more granular representation of vulnerability, exposure and adaptive capacity that captures differences across populations and ecosystems, as well as adaptation options and how these interact with mitigation pathways. Relating climate change impacts, mitigation and adaptation measures to a broader range of SDGs is also highly desirable.

With respect to climate extremes, there is an urgent need to better understand how they interact with and constrain mitigation pathways - for example, how events such as droughts and wildfires affect afforestation and bioenergy scenarios, including potential indirect consequences for the population, food production, economy, financial systems, and political stability. This requires the development of new approaches for evaluating and interactively computing changes in extremes for emissions scenarios, such as regional climate model emulators, the integration of regional biophysical feedbacks from land use and should have the capability to address low-likelihood/high-impact events.

Given a significant level of uncertainty surrounding the future effects of climate change on land and marine systems (e.g., permafrost thaw, tipping points, increased disturbances, intensified CO_2 fertilisation effect) and, by extension, on their capacity to contribute to mitigation and adaptation, further research into these mechanisms and integration of this knowledge into IAMs is also critical to better understand the potential of climate action measures in the land sector.

Policy relevance

Improving the representation of physical climate change and related extreme events in IAMs is of high relevance to risk-proof mitigation and adaptation pathways, enabling the development of Paris-aligned strategies that are feasible, realistic, and better capture the dynamics between mitigation and adaptation options.

Flag(s)

Digitalisation/AI

Biodiversity/ Ecosystems

Related fiche(s)

1.2, 3.1, 5.1, 5.2, 5.3.

CLUSTER 7:

SECTORAL AND SYSTEMS TRANSITIONS

Rapid and profound transformations are needed in all sectors and regions to reduce emissions and avoid the most serious impacts of climate change. The IPCC has assessed the substantial potential for reducing emissions in systems including urban, energy, buildings, transport, industry and land use through reducing energy demand and transitions to low- or zero-carbon technologies, materials and processes. It found that options to reduce emissions exist, costing less than $100 per tonne of CO_2, and which, cumulatively, could cut global GHG emissions by at least half by 2030. Most notably, the cost of producing renewable electricity has become competitive with fossil fuels in many parts of the world, driving the deployment rates up and placing renewables at the heart of the transformation, next to energy efficiency, electrification, and circularity. The IPCC is also clear on fossil fuels – they must be phased out rapidly. The positive message is that there are many proven policy measures that can deliver deep emission reductions and build climate resilience if scaled up.

The IPCC also found that changes in our lifestyles and new ways of delivering services enabled by the right policies, infrastructure and technologies can reduce global GHG emissions in end-use sectors (buildings, transport, food) by as much as 40-70% by 2050. A better understanding of the transformation of demand-side provisioning systems is necessary to tap into this significant potential. It requires research on key barriers and enabling conditions for a transition towards a shared and circular economy, including better understanding of the interactions between individual behaviour, social norms, technology/service options and available infrastructure, and how they shape consumer preferences.

In addition, there is a need for a more systematic exploration of the role of digitalisation in the transformation towards a net zero future, with particular focus on unlocking demand-side transitions. Notably, the convergence of advances in high resolution spatial data and the rapid progress in AI and machine learning, presents novel opportunities for strategies that not only maximise mitigation benefits but also increase climate resilience by fostering sustainable practices and informed choices at both individual and systemic levels. Examples include analysing consumer behaviour to tailor sustainable interventions, optimising transport, and energy management with co-benefits for flexibility of service provision and access equality, streamlining supply chains for reduced emissions, minimising waste-generation, optimising recycling operations and informing climate risk assessments by mapping areas prone to extreme weather and other climate impacts.

In the context of systemic transitions, cities, as transition hubs, will play a very central role in driving forward the climate agenda. They are home to more than half of the world's population and are responsible for three quarters of the global energy consumption and GHG emissions. Cities are also hotspots of climate impacts with higher average temperatures and more intense heat extremes. Against this backdrop, they are emerging as pivotal actors in both mitigation and adaptation efforts and as key determinants of human well-being. For these reasons, cities are being increasingly recognised as key actors for climate action, with their role to be highlighted in a special report of the new IPCC 7th assessment cycle.

“Rapid and profound transformations are needed in all sectors and regions to reduce emissions and avoid the most serious impacts of climate change.”

7.1 Improving global assessments of urban responses to climate change

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Urban infrastructure plays a crucial role in achieving net zero emissions and enhancing climate resilience. Nonetheless, there is an insufficient understanding of how cities and human settlements can be fully harnessed to expedite these transitions. The uniqueness of each city and its infrastructure, coupled with historically sparse and high-quality data on urban areas, makes meaningful comparisons challenging. We lack rigorous ex-post evaluations of urban climate responses, hindering our ability to understand the effectiveness of policies and their contextual nuances. Given the complexity of large urban agglomerations, there is a pressing need for a stronger focus on the metropolitan scale to discern their mitigation and adaptation options.

Modeling low-carbon and resilient urban planning with AI and the advancement of big spatial data offers new opportunities for research to guide urban form modification in the context of a changing climate: agile, AI-based, high-resolution tools can advance urban design at the scale of individual streets, locations, and buildings to reduce energy demand and emissions in buildings, urban transportation and waste while rendering cities more resilient to climate change and extreme events. Research should build on new sources of data and rapid progress in AI that provides the required granular representations of the complex structures of cities and human settlements. Conceptual advances and most recent developments in AI (in particular, the advent of large-language models) and in evidence synthesis methodologies can gather the vast amount of scientific evidence on cities. Two challenges need to be overcome to leverage AI for urban planning: curating high resolution datasets and developing machine learning algorithms that provide useful insights for cities and municipal actors.

Research in this domain should also address systematisation of critical and sensitive AI-based infrastructures that are key to support vital services and functions to urban systems and analyse how different societal groups (e.g., children, disabled persons, elderly, women, marginalised groups) use them differently. This will help draw conclusions towards urban development and planning that is compatible with Paris-aligned mitigation and adaptation requirements.

Policy relevance

This area of research will generate evidence for municipal decision-makers on most effective strategies and modifications to the existing urban form that would maximise climate benefits, while contributing to more liveable cities that provide a high quality of life to their citizens.

Flag(s)

Digitalisation/AI

SSH

Gender

Related fiche(s)

7.2, 7.4.

7.2 Investigating the contribution of demand-side measures in expediting the shift toward climate neutrality, with a particular focus on the role of digitalisation

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

The latest IPCC report concludes that demand-side measures and new ways of service provision can considerably (40-70% by 2050) reduce global GHG emissions in end use sectors. Digitalisation, driven by revolutionary developments combining AI, deep learning, and large data sets, is already fundamentally transforming consumption and production patterns across scales, creating opportunities, but also risks for climate action. On one hand, it offers considerable potential for limiting growth in energy-demand, but on the other, it also risks inducing energy-intensive practices (e.g., online shopping), not to mention the ICT sector's own emission footprint.

First, a better understanding of the transformation potential of demand-side provisioning systems towards climate-neutrality is necessary and requires research on behavioural, social, and other factors determining uptake of demand-side solutions, with particular focus on the role of digitalisation. Building on that, novel modeling tools need to be developed with a bottom-up representation of demand-side aspects in transition pathways. Key barriers and enabling conditions of shared and circular economy should be included in such a representation, capturing the interactions between individual behaviour, social norms, technology options, and available infrastructure in shaping consumer preferences.

Second, research should comprehensively investigate climate implications of the digital economy and evaluate the role of digitalisation in unlocking demand-side transitions. Progress is needed on identifying effective strategies for proactive climate-focused governance across actors, scales, and contexts, addressing issues of risk, trust, engagement, and access (incl. gender dimension) with an explicit consideration of institutional design. There is also room for progress on data and AI governance for making cities, settlements, and societies more climate resilient, for example, by mapping of heat, precipitation risks and other climate-related risks.

Policy relevance

Better capturing demand-side mitigation measures will widen the option space, enabling acceleration of the transformation towards net zero emissions while minimising trade-offs associated with supply-focused strategies. Careful governance of digitalisation will support climate change mitigation and adaptation efforts, including at municipal and national scale, with a focus on low energy demand, and sustainable, resilient service provisioning systems

Flag(s)

Digitalisation/AI

SSH

Gender

Related fiche(s)

6.1, 7.1, 7.4, 10.4.

7.3 Informing the politics and economics of phasing out fossil fuel infrastructures

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

The anticipated emissions from existing and planned fossil fuel infrastructures are projected to contribute 600-1100 Gt of future CO_2 emissions, exceeding the remaining carbon budgets compatible with limiting warming to 1.5°C. There is hence a strong case for fossil fuel infrastructure phase out - encompassing exploration, production, refining, distribution and end-use, - and making the underlying political strategies an essential element of the transition process.

Research should map the current state of fossil fuel infrastructures both in terms of related CO_2 emissions and their economic value to define economically viable (or unviable) options and limits for phase-out, repurposing and retrofitting to stay in line with the goals of the Paris Agreement. Repurposing for "green" fuels, such as low-carbon hydrogen and synfuels, requires assessing the interplay between energy demand (including green carbohydrates that require high energy input but allow flexible storage/load) and renewable energy availability (including competition with alternative uses, and compatibility with efficient electrification strategies such as heat pumps). The existing evidence on the deployment limits of green fuels in the transition towards net zero should also be considered. It is also crucial to broaden the analysis to the political economy of fossil fuel infrastructures, including common narratives in the media (including social media) and options for circumventing the lobbying structures that work to prevent the phase-out.

Policy relevance

Progress in this area will guide the decisions on which fossil infrastructures should be decommissioned, which should be repurposed or retrofitted with carbon capture and storage, under what kind of timelines, and who should bear the costs in support of overcoming the severe carbon lock-in of the global energy system.

Flag(s)

SSH

7.4 Reducing energy demand and quantifying materials and embodied carbon in the building stock and other infrastructure

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Buildings are responsible - directly and indirectly - for 36% of the energy-related GHG emissions in the EU, thus playing a pivotal role in the transition to reaching net zero emissions. Whereas most European countries continue to invest in energy efficiency and renewable energy sources, it is equally important to place a focus on promoting energy sufficiency (avoidance of energy demand) and transforming the existing built environment in line with the net zero paradigm. More research is needed for innovative solutions that can be easily implemented in the already built environment and support energy sufficiency such as new wall concepts, new window frames, new building materials with more thermal inertia and lower carbon footprint, new insulation systems and integrated nature-based solutions (NBS) for refurbishing. This should be complemented by work on prioritising renovation needs in the built environment. In this context, it is also important that all public buildings in Europe become net zero as soon as possible to convince society to invest in improving their own housing. A better understanding of the interlinkages between a low emission built environment, urban planning and transport systems for people and merchandise is needed to support more integrative strategies.

Embodied energy and embodied carbon in the built environment, including buildings, industrial facilities, roads, and other infrastructure have now also been identified as an essential component of the transition to a net zero emissions. The assessment of embodied energy and carbon emissions relies on the understanding of the quantity of materials used or processed in the production phase per infrastructure type. To address the existing gaps, more work is needed on the classification of infrastructures in the built environment according to the types of buildings. The challenges that need to be overcome include a multitude of different construction types that change with location, age, final use, etc. as well as quantification of infrastructure by type. Then, research should support the clear identification and quantification of the materials used per built environment type (i.e., type of building, type of road), together with the production and/or transformation processes associated with each of them with a view to evaluate the embodied energy and carbon footprint more precisely.

Policy relevance

More reliable emissions data, including embodied carbon, will improve the precision and quality of models that underpin climate policies, supporting a whole-system approach to carbon reductions and allowing for better targeted climate policies. This research will also inform strategies on how to efficiently improve, repurpose and/or retrofit the building stock, based on the Sufficiency, Efficiency, Renewables (SER) framework.

Flag(s)

SSH

Digitalisation/AI

Related fiche(s)

7.1, 7.2.

CLUSTER 8:

LAND USE, AGRICULTURE AND CARBON DIOXIDE REMOVAL

As demonstrated by the IPCC Special Report on Climate Change and Land, sustainable land management offers great potential contribution to mitigation and adaptation action. The land sector has the ability to act both as a source and a sink for emissions, with opportunities to provide biomass, mainly from forestry and residues, as a substitute for carbon intensive products. Globally, emissions from agriculture, forestry, and other land uses (AFOLU) contribute about 22% of total anthropogenic GHG emissions while terrestrial ecosystems sequester more than a third of CO_2 emissions. The largest near-term mitigation potential of the AFOLU sector comes from forests and other natural ecosystems, with land-use management critical for achieving a balance between anthropogenic GHG emissions and removals after 2050. The IPCC warns, however, that land-based mitigation cannot compensate for delayed action in other sectors.

The links between land (-use) and climate are complex. Higher levels of warming will impact the ability of land to store carbon, its productivity (by changing levels of water availability) and the resilience of ecosystems, making the persistence of removals highly uncertain. For example, an increase in droughts, wildfire damage, insect and fungus outbreaks, or permafrost thawing can decrease the role of land as a carbon sink. In turn, adaptive management to these impacts can also alter land mitigation potential. In addition, land also plays an integral role in regulating temperature and precipitation patterns through albedo effects, evapotranspiration, and aerosol loading.

Effective land-use management is also critically important for meeting the biodiversity targets under the Convention on Biodiversity (CBD) and plays a crucial role in achieving several of the Sustainable Development Goals (SDGs), including those on ending hunger (SDG 2), clean water (SDG 6), clean energy (SDG 7), and life on land (SDG 15). While many options offer co-benefits for adaptation, food security, biodiversity, health and livelihoods, there are also trade-offs and indirect land-use effects. Competition with food production is of particular concern. Therefore, exploring options to alleviate competition for land should be prioritised, such as reducing meat consumption and moving to more plant-based, balanced diets, reducing food waste, managing discarded products, and exploring innovative food and feed sources (e.g., insects, grass-based protein feeds, etc).

Policies targeting land-use need to be synergistic with other policy objectives in the areas of climate, food security, biodiversity, and health. A better understanding of the multidimensional land-climate-biodiversity-food-health nexus is necessary to effectively manage the underlying synergies and tensions. Research should identify sustainable land-use management practices and define what institutions, strategies and policies are needed at global, national, and regional levels. This requires a more in-depth understanding of the underlying dynamics in mitigation pathways, including improvements in sectoral models and integrated assessment models (IAMs) to better reflect the diversity of priorities related to land and biomass use options and investigation of the political economy of large-scale land and biomass use. Research should also support enhancing the consistency between global models and national GHG inventories under the UNFCCC on human-caused CO_2 emissions and removals for the land sector to better evaluate the efficacy of land-based mitigation, particularly for the forestry sector.

> **"A better understanding of the multidimensional and-climate-biodiversity-food-health nexus is necessary to effectively manage the underlying synergies and tensions."**

Mitigation pathways compatible with achieving the Paris Agreement assessed in the latest IPCC report include carbon dioxide removal (CDR) at scale in addition to accelerating near-term emission reductions, to achieve net zero CO_2, and to move into net negative emissions thereafter towards net zero GHG emissions. Land-based approaches such as reforestation, afforestation, soil, and forest management, dominate today's removals options, but novel technologies like direct air capture and storage (DACCS) or bioenergy combined with carbon capture and storage (BECCS), biochar, and enhanced weathering are also emerging. More is needed to explore CDR scaling as resolved by mitigation scenarios and the development of policies and implementation options. Finally, there is a need for research on realistic potentials, limitations, permanence, co-benefits and trade-offs with other policy objectives, as well as public acceptance, in order to inform global CDR policy design and governance.

8.1 Nurturing the potential of land-based mitigation and adaptation

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Given its significant anthropogenic GHG emissions and potential for carbon sequestration, the AFOLU sector is pivotal for achieving climate change mitigation targets. Contributions come from conservation and restoration of natural ecosystems, improvements in agriculture and forestry practices, as well biomass provision for mitigation in other sectors. While trade-offs may exist between the objectives to store carbon in ecosystems and to produce biomass as an alternative to fossil resources, these objectives are not always mutually exclusive, emphasasing the need for balanced decision-making that considers multiple goals. In addition to mitigation benefits, making agriculture and land-use climate-resilient is also crucial for protecting ecosystems and livelihoods, and for safeguarding food security.

Research should delve into the complex interlinkages between diverse sectors involved in landbased mitigation, including exploration of synergies and trade-offs between land carbon storage and biomass production across various forestry and agriculture systems across a spectrum of different net zero scenarios, while also considering adaptation, biodiversity, and other outcomes. There is a need to better understand how the interplay between bio-based and other low-carbon alternatives, policy, governance, land-use practices, private investments and public spending collectively shape mitigation and adaptation efforts in the AFOLU sector. This requires advancements in both sectoral and cross-sectoral modeling at national, regional, and global scales to better integrate climate change dynamics with land-use and other sectors, while also enhancing consistency between model outcomes and national statistics of GHG emissions and sinks. Advances in agent-based modeling are also crucial for studying the implications of different transition pathways and policy measures on farms, regional agricultural structures, and production activities. The significant anticipated contribution of the AFOLU sector to the EU's pursuit of net zero emissions, with consequences for other regions, makes the EU a valuable case study.

Policy relevance

Effective mitigation strategies in the AFOLU sector require a coordinated policy design across climate, agriculture, and other land-use relevant domains, in full consistency with other than climate policy objectives such as food, energy security, and biodiversity related, whilst properly accounting for the limitations and trade-offs associated with the contributions from the land-use sector.

Flag(s)

International cooperation

SSH

Gender

Biodiversity/ Ecosystem

Related fiche(s)

3.4, 6.1, 9.4.

8.2 Fostering sustainable use of biomass for climate change mitigation

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

While fostering food and nutrition security, sustainable management of natural resources, and reducing reliance on fossil fuels, a sustainable bioeconomy also provides multiple avenues for mitigating GHG emissions in the context of the transition to net zero. Mitigation opportunities are twofold: a) carbon storage in ecosystems (vegetation and soils) through a wide range of diverse land management measures and with multiple co-benefits (e.g. adaptation, biodiversity, soil quality), though this is subject to reversals and disturbances (climate events, insect infestations); b) use of biomass across different sectors as bio-based products, storing carbon and displacing fossil-based alternatives, also susceptible to leakage as well as, in regard of storage, to reversals. Although the two approaches are not mutually exclusive, they face trade-offs that need to be accounted for in the policy design.

Governance and policymaking addressing the bioeconomy is generally challenging since the optimal development of a bioeconomy varies geographically due to multiple, heterogeneous conditions. Consequently, the expansion of sustainable biomass utilisation across sectors must reflect a diversity of priorities and conditions, which must be viewed in an integrated manner.

Research should develop a new generation of global mitigation pathways that consistently cover biomass demand and supply of different sectors. Such pathways should encompass the whole biomass value chain (production, processing, and consumption aspects), account for indirect land use changes and leakage effects, notably those related to deforestation and ecosystem degradation, and address political economy issues associated with large-scale land and biomass use. This will require improvements in IAMs as well as sectoral models to better capture the complex dynamics associated with the bioeconomy, including better consideration of the competition and synergies between different biomass and land uses in the exploration of mitigation pathways while also accounting for the necessity to safeguard biodiversity, food security and ecosystem-based services.

Policy relevance

This research will produce science foundations to inform sustainable biomass supply and use strategies in the EU and beyond, maximising contributions to climate change mitigation and adaptation, but also focusing on the broader sustainability dimension, and accounting for climate impacts.

Flag(s)

International cooperation

SSH

Biodiversity/ Ecosystem

Related fiche(s)

3.4, 4.1, 9.4.

8.3 Achieving global climate, biodiversity, and health objectives by optimising the management of food systems

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Climate change, along with associated adaptation and mitigation efforts affect the state of biodiversity as well as the social and environmental determinants of food systems and health, which, in turn, affect societies' capacity for effective climate action. Food systems are associated with 23–42% of global GHG emissions while also causing severe biodiversity impacts, including from agriculture's spatial shifts as an adaptive response to climate change. The food-climate-biodiversity-health nexus is hence growing in attention and requires a coordinated policy response.

Accurately measuring the scale and impact of the interactions between climate change, biodiversity loss and human health remains challenging whereas integrated assessments fall short of accurately (or at all) representing those complex interfaces and associated land-use consequences. Further research is crucial to enhance our understanding of the interplay between the climate, biodiversity, and health dimension of food systems. This includes the direct and indirect effects and cross-sectoral linkages and evaluating mitigation and adaptation strategies in local and regional contexts within an evolving state of climate and biodiversity.

Improvements in integrated assessment and sectoral modeling, sub-system and single technology assessment are essential to improve knowledge of emission trends and drivers, adaptation and mitigation costs and potentials, regional specificities, sector-specific barriers and enabling conditions related to mitigation and adaptation options in the realm of food systems. Complementary approaches, drawing on disciplines such agronomy, engineering, natural sciences as well as social sciences can also offer comprehensive insights into food systems and should be explored to bridge system-level and bottom-up perspectives, addressing issues related to human behaviour, lifestyles, gender, culture, and socio-technical transitions in both producer consumer sides of food systems.

Policy relevance

Definition of consistent and realistic transformation pathways within the integrated framework of the climate-biodiversity-health-food nexus is essential for optimising governance of food systems and land-use to achieve climate- and biodiversity-friendly, as well as healthy, futures.

Flag(s)

SSH

Gender

Biodiversity/ Ecosystem

Related fiche(s)

3.2, 9.4.

8.4 Assessing long-term viability of agroforestry as a solution to climate change and food security

Earth system science | Impacts, risks and adaptation | Mitigation

Agroforestry is widely cited as a promising solution for addressing low yields, climate change, biodiversity loss, land degradation, water scarcity, food insecurity and rural poverty altogether. Yet, the evidence on the resilience potential of agroforestry systems, which is a precondition for delivering all these benefits, remains scattered, and the understanding of climate change impacts on agroforestry remains limited. There is a large body of literature stating the effect of tree-crop interaction on local evapotranspiration and microclimate, with corresponding benefits on farming systems, but research behind this evidence is typically conducted at small/local scale and would require larger scale assessments to strengthen the evidence base. Furthermore, the long-term nature of tree physiology, and thus actual benefits provided by agroforestry systems require a better representation of the complex interaction between long-term vegetation-climate interaction and short-term socio-economic challenges to better characterise the feasibility and effectiveness of this measure for a wide range of environments.

Many case studies that focus on agroforestry struggle to integrate the planetary dimension of the impacts such as feedback effects resulting from land-climate interaction. Furthermore, the magnitude of the effect of agroforestry on the water cycle and climate feedback is generally overlooked in large scale modeling assessments. Research is needed to improve the representation of agroforestry systems in global climate impacts and agroecosystem models capable of simulating large scale vegetation-climate interactions, together with the implementation of these advances into IAMs as well as land-sector models. Improvements are also needed in representing layered vegetation structures in many land-surface modules of climate models. Specific agroforestry systems and their role in food security and nutrition need to be studied with more granularity. In addition, there can be synergies and trade-offs with other climate solutions - for example, large-scale forestry may affect the viability and yield of wind and solar in some regions, yet they can also co-exist as integrated systems.

Policy relevance

Robust evidence on the benefits, disadvantages and trade-offs associated with agroforestry systems will help address the food security and climate change nexus, fostering more effective land-use management strategies, especially if the modeling work is accompanied by policy and governance research. This research will also shed light on whether benefits from agroforestry are greater than those of alternative land-uses, supporting the realisation of multiple SDGs.

Flag(s)

Biodiversity/ Ecosystem

Related fiche(s)

2.1, 5.3, 9.2, 9.4.

8.5 Designing carbon dioxide removal policies and governance

☐ Earth system science ☐ Impacts, risks and adaptation ■ Mitigation

The latest IPCC report emphasises that achieving the goals of the Paris Agreement will require CDR at scale for counterbalancing hard-to-abate residual emissions to get to net zero CO_2. Net negative CO_2 emissions will also be needed to compensate for remaining non-CO_2 emissions to reach net zero GHG emissions. CDR methods include conventional (afforestation, soil carbon sequestration) and novel bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), ocean alkalinisation, enhanced weathering, biochar). These approaches differ in technological maturity, deployment levels, cost, scaling potential, durability, and reversibility of CO_2 storage, as well in terms of side-effects and trade-offs with adaptation and other development objectives. Overall, more knowledge is needed on future CDR availability, not least due to the challenges and risks associated with many of the methods.

A considerable gap exists between how much CDR is required in the modelled net zero pathways and what the countries are planning in the medium (2030) and long-term (2050), in particular regarding less conventional options. For example, achieving net zero CO_2 emissions in the EU by 2050 would require several hundred million tonnes of CO_2 per year of CDR, well above current levels.

Better knowledge, particularly from the social sciences, is needed to support the design of effective CDR policies and governance frameworks. Research should enhance the understanding of the state of art and pace of innovations in CDR, different CO_2 storage times, levers for acceleration, management of side-effects, options for maximising synergies and co-benefits with other policy objectives such as food security and biodiversity protection and the implications for policy design, institutions, and governance. Other evidence gaps relate to the political economy of CDR including distributional aspects and consequences for regional development as well as the role of CDR in international climate policy with particular emphasis on feasible deployment levels and options for a just national, regional, and international effort sharing .

Policy relevance

This research will inform global efforts on how to develop robust CDR governance frameworks, including careful management of uncertainties and risks, whilst avoiding overreliance. It will also support institutional design to successfully incentivise the scale-up process needed to grow a new industry. Scientific assessment of different monitoring, reporting, and verification schemes to inform the EU's carbon removal certification framework is also high on the research agenda.

Flag(s)

International cooperation

SSH

Biodiversity/ Ecosystem

Related fiche(s)

3.5, 9.4.

CLUSTER 9:
EQUITY AND JUST TRANSITIONS

Climate change is already negatively affecting inequality and poverty, both within and between countries. It hurts the poorest and most vulnerable the most, undermining the efforts to achieve justice and equity across the world. Climate-induced resource stresses - including on water, agricultural crops, or other biotic resources - increasingly drive conflict, threatening the peace and inclusivity of societies, and undermining social justice. Climate change-related impacts and disasters are also key drivers of human displacement and migration and can worsen gender inequalities. The transition to a net zero emissions society will also have significant distributional consequences across countries, sectors, businesses, and households.

Against this background, the latest IPCC report emphasises the importance of prioritising equity, social justice, inclusivity and just transition when addressing climate change. This fosters transformative change, drives support for high-ambition climate policies by building consensus and social trust across the society, helps to resolve trade-offs with other SDGs and leads to better outcomes in general. The IPCC also underscores the importance to strengthen the consideration of justice and equity in the formulation and execution of adaptation strategies, particularly when addressing extreme events, to achieve greater outcomes by supporting highly vulnerable regions.

The Paris Agreement recognises the principle of common but differentiated responsibilities and respective capabilities among nations, aiming to ensure that wealthier nations support developing countries in their efforts to mitigate and adapt to climate change, and encouraging countries to consider equity and fairness when implementing climate policies. The importance of ensuring a just transition is being increasingly acknowledged by governments worldwide and mainstreamed into climate plans and strategies. The European Green Deal, with its overarching objective of "leaving no one behind", is a good example. It aims at shielding regions, communities, and industries from adverse social and economic impacts, and highlights the need to ensure a fair distribution of both benefits and burdens of the EU's transformation towards climate neutrality.

Therefore, the assessment of climate change impacts, risks and future development pathways needs to be grounded in the context of the distributional aspects and equity. However, the complex linkages between climate action and justice are still not well understood nor fully addressed in policy responses and require more research. For example, there is a need to develop mitigation scenarios with greater attention to equity and justice that better reflect regional and sub-regional development priorities, as well as the conditions and constraints of the poor and vulnerable communities and societal groups. The consideration of equity, justice and climate resilient development also needs to be strengthened in disaster risk reduction and adaptation strategies, which frequently do not properly consider the needs of the poorest and most vulnerable groups or lack the gender dimension. Progress is also a need in the exploration of inequity and injustice as constraints to individual and collective climate action.

> **"Prioritising equity, social justice, inclusivity and just transition fosters transformative change and drives support for high-ambition climate policies by building consensus and social trust."**

Given that justice principles are relevant to mitigation, adaptation, and other sustainability transitions, and to all sectors, research should support a more integrated treatment. The AFOLU sector is one example where the immense and potentially competitive demand for land and biomass assumed by low-emission scenarios makes equity and justice even more vital for designing feasible and fair policies. Research is needed to better understand the distributional implications of climate strategies in diverse agricultural, forestry, and land use contexts.

9.1 Attributing climate impacts in a climate justice context

■ Earth system science ■ Impacts, risks and adaptation □ Mitigation

The issue of climate justice and procedural and distributional impacts is becoming critical as impacts increase both in Europe and across the world. Extreme event attribution has advanced the understanding of how human influence has affected the likelihood of occurrence and intensity of climate and weather extreme events, increasingly leading to widespread impacts on ecosystems, economies, and societies, disproportionately affecting vulnerable communities. While the science of attribution has advanced, numerous gaps remain which require major scientific advances. These gaps include the impacts and hazards being investigated, in particular compound and cascading events, the interplay between slow and fast onset events, the regional focus on events being investigated, and the relationships between insights from attribution studies relevant for today's climate and the potential high impact events or combinations of events expected to emerge in the near-term (for example in a 1.5°C warmer world, relevant for this decade). Advances are also needed to link information about changes in extreme event characteristics in the context of wider sustainability challenges, for example including the water-land-climate nexus, taking into consideration the related vulnerability and exposure.

While climate change disproportionately affects vulnerable communities and societal groups (e.g., children, disabled persons, elderly, women, marginalised groups), consideration for climate justice in the context of the equitable distribution of burdens and benefits allows for an optimised way of addressing the climate crisis. Policies and actions that integrate climate justice require science-based attribution of climate events, and the advancement of research relevant for climate legal frameworks, specifically relating to the emergence of responses to climate change in complex societal, political, and legal systems. The analysis should consider comprehensively the attribution of damages, costs and benefits and legal responsibilities in complex systems.

Policy relevance

Improving the science of attribution will advance our understanding of the anthropogenic signal in climate phenomena and impacts. This will not only impact policy, and potentially early warning systems, but also serve as a basis for establishing legal responsibility in a fair and proportionate manner.

Flag(s)

International cooperation

SSH

Gender

Related fiche(s)

4.4, 4.6, 5.1.

9.2 Improving the consideration of equity and justice in adaptation strategies to build resilience

☐ Earth system science ■ Impacts, risks and adaptation ☐ Mitigation

There is an emerging recognition that successful adaptation needs to properly integrate equity and justice considerations to be effective and contribute to building lasting resilience. However, present adaptation strategies at national and local levels often focus primarily on climatic hazards (floods, extreme precipitation, heat stress, droughts, etc.) and first order impacts with standards and methods to account for equity and justice dimension often missing. Much less attention is paid to vulnerability reduction although it is central for adaptation measures given that adaptive capacities differ according to the level of vulnerability. Consequently, just, and equitable reconstruction and adaptation requires better consideration and reduction of risks particularly for the most vulnerable groups and sectors.

Equity and justice need to be further operationalised to be relevant for practical adaptation programmes, for example, by defining concrete indicators, quality standards and criteria. Research is needed to analyse selected adaptation strategies and programmes and their impacts on climate justice and equity across different societal groups (children, disabled persons, elderly, women, marginalised groups etc.) and sectors. The analysis should capture not only first, but also second order impacts of adaptation strategies, as well as their cascading effects. For example, relocation has severe social impacts whereas large protection measures such as storm barriers may decrease economic activities. These examples raise important questions about justice and equity in terms of both access to adaptation measures and their differential consequences that research could shed some light on. In addition, adaptation enablers and barriers often present a gender dimension, which should also be investigated.

Policy relevance

This research will enable planners and decision makers to better consider equity and justice in adaptation, risk reduction and reconstruction strategies in the broader context of climate resilient development, enhancing their acceptability.

Flag(s)

International cooperation

Gender

SSH

Related fiche(s)

4.3, 4.4, 4.6, 5.4, 8.4, 10.2.

9.3 Improving integrated assessment models to represent different dimensions of justice and equity

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

The current generation of global mitigation pathways lacks a systematic consideration of justice or equity. Even though these pathways incorporate assumptions about distributional aspects and result in declining levels of absolute poverty across all scenarios they have faced criticism for a continuing "equity deficit". This deficit concerns, for example, slow convergence of gross domestic product per capita, perceived inattention to common but differentiated responsibilities and respective capabilities, and a lack of transparency.

A new generation of scenarios is needed, capable of more effectively representing justice and equity considerations. This involves moving beyond pure economic convergence assumptions and embracing all different dimensions of justice, spanning from procedural to distributive justice and also addressing aspects of political economy. The new scenarios should be carefully co-designed with key stakeholders and regional experts as part of a transparent and inclusive community process including a review of key input assumptions and main elements of the narratives.

The representation of justice and equity in these scenarios should extend beyond the conventional Integrated Assessment Models' (IAM) focus on interregional equity and burden sharing assumptions for emissions reductions. It should include a bottom-up representation of well-being (social and physical) and how mitigation and adaptation efforts affect the living standards in diverse circumstances. It is also crucial to better integrate institutional effectiveness and governance in the models to improve the representation of differentiated capacity and policy feasibility. This requires a more robust integration of social sciences and empirical research into the IAM models.

Policy relevance

A wider range of socio-economic pathways with attention to equity and justice that better reflect the conditions and constraints of the Global South will help promote broader international acceptance of scenario findings with potential to unlock momentum in global climate negotiations.

Flag(s)

International cooperation

SSH

Related fiche(s)

3.2, 3.4, 4.5.

9.4 Designing just transition policies for agriculture, forests and other land use

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Agriculture and patterns of land use will need to change significantly in any scenario taking the world to net zero GHG emissions, with implications for global inequalities across and within individual countries. Just transition principles have been applied to energy transitions, but less attention has been given to the AFOLU sector, despite the immense demand for land and biomass implied by low-emission scenarios, leading to social and economic challenges. In those scenarios bioenergy remains a major energy source, and additional land is required for CDR technologies and renewables such as solar and wind. Simultaneously, demand for biomass is expected to increase for food, including higher shares of animal-based foods, and material use. Such developments might lead to the conversion of agricultural land to other uses, with implications on patterns of land tenure, risking to further exacerbate justice issues through changes in the size of holdings, ownership models, and landowner-tenant relationships.

On the one hand, farmers may diversify their land use and benefit from new income sources, and the introduction of new cultivation systems (agroforestry systems, perennial plants) into agricultural landscapes can enhance landscape diversity, habitat quality, retention of nutrients, erosion control, climate regulation, pollination, pest and disease control, and flood regulation. Other influencing factors with relevance for justice also encompass regulation and financial incentives for actions that deliver climate outcomes, including the sharing of mitigation burden and benefits (e.g., ownership of credits, liabilities for emissions).

Research needs to assess the implications of the transition to net zero for actors in the AFOLU sectors, by interpreting mitigation and adaptation scenarios, and by assessing a variety of stakeholder perspectives (e.g., elderly or gender) on the implied changes and identifying synergies between climate actions and other policy objectives such as food security, biodiversity conservation and human development. The International Labor Organisation's principles - social dialogue, social protection, rights at work and employment - should be an integral part of the research.

Policy relevance

This research will support more effective and equitable climate policy design by promoting and operationalising just transition principles for land use. It will guide the creation of effective financial incentives and strategies that address both adaptation and mitigation, while ensuring the equitable sharing of greenhouse gas mitigation costs and benefits.

Flag(s)

SSH

Gender

Biodiversity/ Ecosystem

Related fiche(s)

5.3, Cluster 8.

CLUSTER 10:

ACCELERATING CLIMATE ACTION: LEVERS AND ENABLERS

The window of opportunity to secure a liveable and sustainable future for all is closing rapidly, the latest IPCC report warns. Yet, despite the existing commitments and availability of multiple feasible, proven, and effective options that can significantly reduce emissions in all sectors, global emissions continue to rise. The pace and scale of climate action is deeply inconsistent with the goals of the Paris Agreement, making these ambitious objectives increasingly challenging to meet.

This underscores the need for greater prioritisation of near-term climate action, with rapid, deep reductions in GHG emissions in this critical decade, as this will largely determine whether warming can be limited to 1.5°C or 2°C this century. The closing of implementation and ambition gaps in climate policy requires research that draws more attention to the levers and enablers of near-term action, and their incorporation into the development and exploration of possible future scenarios. This includes optimising policy interventions to ensure they are fit for purpose to address multiple global crises, environmentally effective, economically efficient, socially acceptable and rooted in the best available scientific evidence.

For assessing the performance of policy instruments, rigorous methods are needed to learn which strategies work and under what conditions. Feasibility and implementation potential are particularly important criteria, especially in the context of key social drivers, dynamics, and tipping points to achieve deep decarbonisation actions, together with a comprehensive assessment of enabling conditions and barriers. Recent shocks such as COVID-19 pandemic, wars, energy, and cost of life crises, can also provide lessons as to the ability to implement drastic policy interventions regionally or globally (e.g., travel bans, lockdowns, shifts in energy trade patterns, mobilising trillions for investments in safety nets and bailouts, etc.).

Amongst the essential enablers of climate action, finance has potential to serve as a major catalyst for societal transformation. Adequate funding is crucial for the development and deployment of effective, flexible, and affordable net zero solutions and adaptation measures. Investors, both public and private, have the power to mobilise and channel resources towards climate-related initiatives, influencing and enabling the society-wide adoption of more sustainable practices. Nonetheless, substantial knowledge gaps persist in our comprehension of the interplay between climate change and the financial sector, constituting a critical barrier and a potential lever to scaling mitigation and adaptation investments to the levels compatible with the Paris Agreement.

> **“There is a need for greater prioritisation of near-term climate action, with rapid, deep reductions in GHG emissions in this critical decade, as this will largely determine whether warming can be limited to 1.5°C or 2°C this century.”**

Communication is another key agent for climate action. In absence of a common understanding of the key scientific messages, there is a significant barrier for society and policymakers to make science-based decisions and have an informed dialogue on the causes, consequences, and responses for climate change. The propagation of disinformation, for example via social media and traditional media, also causes confusion and hampers efforts to communicate science effectively. In this context, research on more impactful communication of climate science emerges as an important area of scientific inquiry.

Finally, acceleration of climate action will occur when it is made meaningful to people's daily lives and incorporated into their thinking, behaviour and daily choices. This requires awakening motivation in people and a deep desire for personal and social transformation, accompanied by a sense of urgency, which fuel demand for changes from policy makers and the private sector. Central to this is fostering the perception that climate justice not only exists but is actively pursued. This requires avoiding the creation of climate elites that turn climate action into a luxury and addressing intergenerational justice by strengthening the connection with younger generations and incorporating their demands. Research on just climate transitions is thus a pivotal priority, as detailed in the preceding cluster.

10.1 Communicating and translating climate science to policymakers and general public

Earth system science | Impacts, risks and adaptation | Mitigation

The relevance of climate change science for people's daily lives is growing, yet, for many, it remains difficult to understand, in part due to challenges in communicating complex scientific concepts. Despite the IPCC's efforts to clearly convey the assessment outcomes, the messaging often remains technically complicated. The propagation of disinformation, identified as a top short-term risk in the 2024 Global Risk Report of the World Economic Forum, further hampers the communication of science-based evidence to decision-makers and the public.

Within the IPCC context, the science of communication suggests replacing passive strategies with more engaging and dialogic approaches. Research is required to operationalise these recommendations and, more broadly, to understand how communication can enhance awareness and climate literacy to enable effective climate action. This involves delving into cognitive processes of understanding and absorbing complex information, the influence of socio-cultural factors, development status and values on perception and learning.

Improving knowledge on how communication can stimulate various actions, how to measure outcomes, and understanding the interplay of behavioural change and wider societal choices within broader political, governance, economy, and policy context, is also crucial. Research should also identify the most impactful tools, messages, and co-design processes for communicating about climate change, with links to journalism and the media.

Recognising the power of storytelling to instill agency, research should explore narratives that integrate climate change information into people's lives, focusing on solutions-orientated messaging that people can identify with. Beyond the array of available climate-related visualisations, there is a need to bridge the gap on making data relevant to people's everyday existence. Social science research is essential to determine the most effective messages and tools, while cognitive psychology can contribute to understanding how individuals receive messages and how these messages transform or influence their experiences.

Policy relevance

Absence of a common understanding of the key scientific messages about climate change is a significant barrier for society and policymakers to make science-aligned decisions. More effective communication is vital for aligning the society behind ambitious and far-reaching responses, inspiring the policymakers to make courageous decisions.

Flag(s)

Gender

SSH

10.2 Understanding social dynamics, including tipping points, as drivers of climate action

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

The current pace of mitigation and adaptation is falling short of the transformational change needed now and in this decade to address climate change and its consequences. The barriers to climate action need to be identified through monitoring and evaluation of past measures/policies, together with the societal thresholds that can unlock rapid action. In the latest IPCC report, social movements are considered as a catalyst for social tipping points, which either positively unlock rapid social action or lead to system destabilisation. Empirical evidence shows that social tipping points can be triggered before tolerance thresholds are reached, yet much better understanding of these processes is needed.

We need to learn more about the relationships between adaptive capacity, social capital and social tipping points, both positive (e.g., transformational structural changes for fast decarbonisation and resilience) and negative (e.g., system destabilisation, social unrest, migration), the political economy, structural power issues, perceptions, and also climate justice and distributional aspects (including both costs and benefits of the transition). Migration decisions, for example, can be based on perceptions of environmental changes by local populations rather than on actual changes themselves. There is a need to better understand social perceptions and psychological aspects of climate change, as well as the role of education in closing information gaps and bringing motivation and societal readiness.

Future societal decisions are impossible to predict due to the deep uncertainty associated with social structures, the many interacting processes, abrupt changes in other fields, unintended consequences of certain policy decisions, and other factors. While the latest IPCC report has comprehensively assessed the feasibility of mitigation or adaptation options, societal dynamics (including social inertia, path dependency, disruptive change, user practices, actor constellations, and regulatory environment) determine the plausibility of these measures being implemented and deserve more in-depth exploration.

Policy relevance

Investigating the activation of social dynamics towards net zero will help to design effective policies for low carbon climate resilient transformation. It will also expedite the pace of climate action by providing insights on how to trigger social mobilisation and pro-environmental behaviour.

Flag(s)

Gender

SSH

Related fiche(s)

3.6, 4.3, 9.2.

10.3 Accelerating near-term climate action to meet long-term goals

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

The EU and other jurisdictions have established near-term emission targets that represent important milestones on the path towards net zero CO_2 emissions by 2050. Meeting these targets would put the world on a path towards meeting the Paris Agreement goals whereas failure risks closing/narrowing down options and may place long-term goals beyond reach. Successful implementation of climate policy requires research that draws more attention to the factors influencing near-term climate actions and their incorporation into modeling tools.

Modeling activities that underpin transition pathways tends to focus on longer-term time horizons and proceeds through multi-year time steps (5 or 10 years). The feasibility of emissions pathways is another issue of key importance for defining effective and realistic response strategies, including for the short-term. There has been some good progress over the past few years with research addressing geophysical, technological, economic, socio-cultural, and institutional feasibility dimensions. The existing emissions scenarios have been benchmarked against these considerations, but what is now needed from the scenario framework is more focus on near-term perspectives and extended plausibility analysis. By plausibility analysis we mean the extent to which societal dynamics will plausibly activate enabling conditions or barriers, and hence the credibility of mitigation measures actually being implemented. Plausibility builds on history, context, and agency, each conceptualised based on theories of change, drawn, for example, from social movement theories or organisational theories.

Issues such as labour markets (mismatches) and supply chains, finance, policy information, institutional capacity, social acceptance, distributional and equity considerations, the influence of and interplay with non-climate policies, political economy, and power structures (including incumbents) also need to be addressed. This research could benefit from expert and local knowledge to feed into near-term scenario development.

Policy relevance

This work will result in a better understanding of the feasibility and plausibility, as well as challenges and barriers to the acceleration of climate action in the near-term, and of the capacity to enhance implementation. It will give policymakers tools to assess the effectiveness of various policy interventions to unlock ambitious near-term climate action.

Flag(s)

SSH

Gender

10.4 Assessing the performance of climate policy instruments using rigorous evidence synthesis methods

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

In times of multiple global crises and increasingly tight public finances, it is ever more important to ensure that policy interventions are environmentally effective, economically efficient, and socially acceptable and are rooted in the best available scientific evidence.

A growing number of scientific studies evaluate mitigation and adaptation interventions in terms of how successful they have been in reducing GHG emissions and/or enhancing climate resilience, but also relevant outcomes such as economic costs, distributional implications, social acceptance, impact on labour markets, innovation dynamics, economic competitiveness, health, and well-being etc. What is missing are rigorous evidence syntheses of this exponentially growing body of evidence to assess the performance of policy instruments and policy instrument packages. Such a synthesis exercise would enable accelerated learning in science and policy on which strategies actually work, under what conditions, while identifying critical synergies and trade-offs with other policies or policy objectives.

The assessment should be focussed on evidence from ex-post evaluations and cover a broad range of policy instruments (e.g., market-based, regulatory, and voluntary instruments, information and education programmes) across relevant outcomes and address compound effects on other policy objectives. Climate-relevant policies with a different primary objective such as improvement of air quality, protection of the ozone layer or biodiversity/ecosystems should also be covered. With rapid advancements in AI, new potentials for accelerating or partially automating evidence synthesis methodologies should be further explored as well as related research frontiers such as "living evidence".

Policy relevance

By enabling a comprehensive assessment of climate policy performance via a consistent systematic review ecosystem, this work will generate rigorous, context-specific, and actionable knowledge for decision-makers, thus contributing to the effectiveness of climate action. The identification of gaps in evidence including the lack of high-quality monitoring and research will contribute to a more efficient knowledge generation process around climate policies.

Flag(s)

Digitalisation/AI

Gender

SSH

Related fiche(s)

3.4, 4.1, 5.4, 6.1, 7.2.

10.5 Shifting to climate-resilient development

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Limiting global warming in line with the Paris Agreement requires comprehensive change that is achieved not only by addressing the direct causes of emissions and immediate barriers to adaptation, but also via understanding and addressing the foundational drivers of development patterns, with consideration of distributional aspects and transformative levers.

Critical research questions remain open, firstly, to understand how development pathways have evolved in the past. The literature on past systems change, notably at large scale, remains limited. Understanding how past changes have been driven, and to what extent, is also critical to inform policymaking today, including where climate was less of a focus. Secondly, we need to investigate how current development pathways (across scales and contexts) affect our capacity to mitigate and adapt. This is to identify where current development pathways constitute a barrier to mitigation and/or adaptation and assess what could be achieved by changing them. Finally, research should analyse how development pathways can shift towards sustainability and resilience, and how that would affect progress towards development goals, in addition to our ability to mitigate and adapt. It asks which alternative pathways exist for a given barrier, what are the implications, and what is necessary (in terms of institutions, policies, finance, innovation, cross-sector, international cooperation) to effectively implement such a change.

Addressing these questions requires drawing on many fields of knowledge beyond the boundaries of climate research, such as development studies or sector-specific literature. Economics, social sciences and humanities are central to this analysis, but within a pluri-disciplinary framework that captures scientific and technical realities and acknowledging that there are competing visions of how change can be achieved across disciplines. Energy- economy-environment modeling is one of the relevant tools to address the second and third questions. A challenge is that unlike the climate community, the development community has produced few forward-looking studies.

Policy relevance

Answering these questions will provide a better understanding of how development pathways drive emissions, mitigation and adaptive capacities. In turn, these are essential to shift development pathways towards sustainability and resilience across a broad range of development goals, including but not limited to climate.

Flag(s)

International cooperation

SSH

Gender

10.6 Investigating how global shocks (fail to) enable climate action

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

Experience from recent global shocks (e.g., responses to the COVID-19 pandemic; the Russia's war of aggression against Ukraine, the energy and cost of living crisis) has shown that despite regional or global ability to implement drastic interventions (such as travel bans, lockdowns, dramatic shifts in energy trade patterns, mobilising trillions for investments in safety nets and bailouts, etc.), these shocks have not been used effectively to achieve the objectives of the Paris Agreement, sometimes even adding fossil fuel capacity and deepening lock-ins. Similar patterns often emerge in the context of smaller or more localised shocks, including partly climate-induced ones, such as in the case of weather-related disasters.

Research should investigate how we have dealt with these shocks to (avoid failing to) implement the transformational change needed to avoid catastrophic climate change and how to make better use of the opportunity windows provided by such shocks for more radical strategies/measures. Deeper knowledge and planning are needed to inform policymakers on how to most effectively and durably respond to shocks to harness their momentum for the benefits of climate action.

A methodological development of typology of possible shocks, from known unknowns to unknown unknowns, could lead to an adaptive decision-making and operating framework. There is a role for ex-post evaluation to learn from responses; equally we want to learn on how models, such as integrated assessment models (IAMs), can be used to explore shocks, as well as updating scenarios to take into account recent occurrences. There are also new concepts that have emerged. For example, in health, COVID-19 triggered the "living evidence/living systematic reviews" paradigm, where scientific knowledge gets continuously updated to enable an immediate response based on the best available information.

Policy relevance

The aim of the research is to prepare decision makers for shocks, both in the sense of managing the direct consequences, and to enable transformative climate action in those defining phases requiring major societal and governmental responses. This will provide relevant climate policy responses beforehand to leverage the momentum of a shock, rather than focusing on the short-term needs, reactively.

Flag(s)

SSH

Related fiche(s)

3.6, 4.5.

10.7 Mobilising climate finance through improved understanding of financial sector behaviour

☐ Earth system science ■ Impacts, risks and adaptation ■ Mitigation

The latest IPCC report underscores the necessity for significantly increased financial flows to the Global South to meet mitigation and adaptation needs. However, challenges like high capital costs, high levels of indebtedness and economic vulnerability hinder the ability of developing countries to mobilise the required funds. Substantial climate-related regulatory interventions targeting the financial industry in the Global North, including the EU Sustainable Finance Taxonomy, present an opportunity to shape investment choices and enhance climate finance outcomes for the Global South. The IPCC also identifies knowledge gaps in the assessment of climate related financial risk as a major barrier to achieving ambitious climate finance flows in the near term. Underestimation of transition risks by public and private financial actors often leads to inefficient capital allocation that is inconsistent with the mitigation objectives.

Research should address knowledge gaps regarding how regulatory interventions targeting the financial sector can contribute to a more efficient allocation of capital for climate action. It should address various dimensions of impact, including additionality and liquidity in local capital markets, particularly vital in the Global South. It is crucial to also investigate whether and how new data points such as on taxonomy compliance and Green Asset Ratios, can be effectively leveraged. Regarding financial risks, there is a need for a broader analysis of transition risks and opportunities that considers a classification of all economic activities that could be affected, well beyond the current focus on stranded assets in the fossil fuel industry. Research is also needed on bridging climate change economics and asset pricing to assist the financial industry in better understanding the weaknesses in their transition risk assessments and valuations.

Policy relevance

Understanding the implications of current regulatory interventions in the financial sector will help developing more efficient policy packages, better capable of leveraging increased levels of financial flows into climate action in both the Global North and the Global South and including North-South transfers. More realistic corporate finance valuation, better capturing climate-related risks, will facilitate a redirection of financial flows towards Paris-aligned investments.

Flag(s)

International cooperation

CLUSTER 11:
CLIMATE INTERVENTION

As impacts of climate change unfold, and the efforts to curb carbon emissions prove inadequate, interest in geoengineering is on the rise. The IPCC used to define geoengineering as a broad set of methods and technologies that aim to deliberately alter the climate system - atmosphere, land or ocean - in order to alleviate the impacts of climate change. The two key characteristics of geoengineering are its global or regional influence on the climate system and the potential for significant unintended effects that transcend national boundaries. Geoengineering comprises a diverse array of options, but the literature commonly divides them into two main categories: solar radiation modification (SRM) and carbon dioxide removal (CDR).

SRM methods seek to reduce the amount of solar energy absorbed in the climate system by reflecting the incoming sunlight back into space through techniques such as artificial injection of stratospheric aerosols, marine cloud brightening or space-based mirrors. Yet, SRM is fundamentally distinct from mitigation action since it does not address the root cause of the problem - continued GHG emissions - nor does it tackle other critical issues such as ocean acidification associated with high atmospheric CO_2 concentrations. This makes SRM the most contentious and potentially the most risk-laden geoengineering technique. On the other hand, CDR intends to increase net carbon sinks from the atmosphere at a scale sufficiently large to alter climate and includes a variety of methods, both natural and technological, ranging from afforestation, direct air capture, to ocean fertilisation and enhanced weathering. Both SRM and CDR can have multifaceted impacts on the climate system, influencing regional albedo, altering atmospheric chemistry, disrupting circulation patterns, affecting nutrient cycles, and introducing other, less predictable changes. These complexities justify the necessity for a precautionary approach.

The controversy surrounding SRM arises from its potentially very significant yet still poorly understood impacts and unintended consequences, introducing novel risks to both the environment and society. Furthermore, uncertainties extend to the institutional, economic and technical feasibility of SRM measures, their social acceptance, and the hazards related to (abrupt) termination of interventions or a reduced commitment to proven mitigation methods. The risks associated with the cross-border effects of some of these technologies, national political and economic interests, the possibility of weaponisation, and private sector initiatives driven by purely commercial interests, are all possible sources of global tensions or conflicts, further exacerbated by the absence of international rules, institutions and proper governance structures.

> **“There is high uncertainty around the response of the climate system to SRM, its side effects on economies, ecosystems, crop yields, and human health, on top of the challenges related to international equity, security, governance and ethics”**

The latest IPCC report, while acknowledging that SRM may reduce some climate impacts if surface temperatures are decreased, qualifies it as part of “more speculative” technologies for tackling climate change. The assessment underscores high uncertainty around the response of the climate system and the side effects on economies, ecosystems, crop yields, and human health, on top of the challenges related to international equity, security, governance and ethics. The IPCC also expresses concern over, amongst other things, residual and overcompensating climate change and the likelihood of abrupt water cycle changes if SRM techniques were to be deployed at scale.

A more comprehensive understanding of the risks, uncertainties and limitations associated with geoengineering techniques is essential to facilitate an open and transparent debate that could lead to a global consensus on their use, including development of common rules, and, if deemed appropriate, implementation of moratoria.

11.1 Assessing interdisciplinary research on solar radiation modification

Earth system science | Impacts, risks and adaptation | Mitigation

Solar Radiation Management (SRM) remains controversial but is gaining increased attention from both the public and policymakers. There is a scope for more coordinated and transparent interdisciplinary research on proposed SRM strategies with public institutions in the lead to comprehensively and critically assess viability, impacts and risks. Knowledge gaps identified in the IPCC reports should be addressed, such as the limited understanding of the climate system's response to SRM, especially at the regional scale, the risks and risk reduction potential to people, biodiversity, and ecosystems, both marine and terrestrial. The following aspects should be tackled[9]:

- Context and goals, including modeling scenarios, strategies for decision-making under uncertainty, and the capacity needed for all countries to engage meaningfully.
- Impacts and technical dimensions, including the properties of injected aerosol particles and their interactions with radiation, clouds and atmospheric chemistry, possible climate outcomes and subsequent impacts on socio-ecological systems, advancing monitoring and attribution capabilities, as well as techno-economic feasibility of various SRM methods.
- Social dimension, including research on domestic and international conflict and cooperation, options for effective governance, and integration of justice, ethics, and equity considerations.

A truly transdisciplinary approach, integrating aspects from Science, Technology, Engineering, and Mathematics, to SSH (with elements from governance, conflict and cooperation, societal acceptance, environmental law, equity, and ethics) is necessary, leveraging collaboration between the respective research communities. It should be non-experimental and far from actual SRM deployment (laboratory research would be acceptable).

Policy relevance

This research will provide policymakers with a toolbox necessary to perform risk-risk analysis on SRM, i.e., weighing the risks of under-mitigated climate change against the risks of SRM implementation. It will support advancing the efforts on establishing more robust arrangements and frameworks for SRM governance, including research related aspects, in accordance with the precautionary principle.

Flag(s)

International cooperation

SSH

Biodiversity/ Ecosystem

9. Building on: National Academies of Sciences, Engineering, and Medicine. 2021. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC: The National Academies Press.

ACRONYMS AND ABBREVIATIONS

AFOLU	Agriculture, Forestry and Other Land Use
AI	Artificial Intelligence
AMOC	Atlantic Meridional Overturning Circulation
AR6	6th Assessment Report of the IPCC
BECCS	Bioenergy with Carbon Capture and Storage
CBD	Convention on Biological Diversity
CDR	Carbon Dioxide Removal
CO_2	Carbon Dioxide
DACCS	Direct Air Carbon Capture and Storage
EU	European Union
GHG	Greenhouse Gas(es)
IAM	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry
MAT	Marine Air Temperatures
NBS	Nature-Based Solutions
R&I	Research and Innovation
SDG	Sustainable Development Goals
SRM	Solar Radiation Modification
SST	Sea-Surface Temperatures
UNFCCC	United Nations Framework Convention on Climate Change
WGI/ II/ III	Working Groups of the IPCC
WMO	World Meteorological Organisation
ZEC	Zero Emissions Commitment

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As climate change impacts intensify globally in both frequency and magnitude, and with scientific consensus on what is yet to come if the world fails to act, the imperative to step up our collective response has never been more pressing.

By providing the knowledge necessary to formulate effective mitigation and adaptation strategies, climate science serves as a critical enabler of climate action and a vital input to evidence-based policymaking. Bridging the knowledge gaps in climate change research is crucial for guiding the transition towards a low-carbon climate resilient future, for fostering consensus and alliances, for empowering global cooperation and for mobilising stakeholders across the society.

This report draws attention to where additional research is required to effectively and adequately address climate change, aiming to inform future calls under the EU Horizon Europe R&I Programme and beyond.

Studies and reports

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