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One Earth

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Review

Ten new insights in climate science 2024

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SUMMARY

The years 2023 and 2024 were characterized by unprecedented warming across the globe, underscoring the urgency of climate action. Robust science advice for decision makers on subjects as complex as climate change requires deep cross- and interdisciplinary understanding. However, navigating the ever-expanding and diverse peer-reviewed literature on climate change is enormously challenging for individual researchers. We elicited expert input through an online questionnaire (188 respondents from 45 countries) and prioritized 10 key advances in climate-change research with high policy relevance. The insights span a wide range of areas, from changes in methane and aerosol emissions to the factors shaping citizens' acceptance of climate policies. This synthesis and communications effort forms the basis for a science-policy report distributed to party delegations ahead of the 29th session of the Conference of the Parties (COP29) to inform their positions and arguments on critical issues, including heat-adaptation planning, comprehensive mitigation strategies, and strengthened governance in energy-transition minerals value chains.

INTRODUCTION

Early in 2025, the World Meteorological Organization (WMO) confirmed that 2024 was the warmest year on record, with an average global temperature of 1.55°C (±0.13°C) above pre-industrial levels, surpassing the record-breaking temperatures of 2023.[1] Consecutive record-breaking monthly temperatures continued well into 2024 for both surface air (June 2023 to June 2024) and sea surface (May 2023 to June 2024).[2] Underlying this trend, atmospheric concentrations of greenhouse gases

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(GHGs) continued their steady increase throughout 2023 and 2024.[2,3] The extraordinary level of warming has fueled a cascade of extreme weather events worldwide, including intensified heatwaves, wildfires, droughts, heavy rainfall, and floods.[4,5] Meanwhile, the projected global emissions by 2030 based on current policies would have to be reduced by 30% to be consistent with a 2°C warming limit (45% reductions for 1.5°C), with a 66% chance.[6]

Against this backdrop, the United Nations Framework Convention on Climate Change (UNFCCC) 29th session of the Conference of the Parties (COP29) took place in Baku, Azerbaijan. Important outcomes of COP29 included the adoption of the New Collective Quantified Goal (NCQG), an agreement on the framework for international carbon markets (Article 6 of the Paris Agreement) as well as progress of various aspects of adaptation governance and planning, including technical guidance on indicators and a support program for the implementation of National Adaptation Plans (NAPs) for the least developed countries.[7] Despite these advances, COP29 had major shortcomings, including the decision on an NCQG climate finance goal of $300 billion annually by 2035[8] (a figure much lower than the identified needs[9–12]), as well as lack of consensus on the implementation of fossil fuel transition commitments and minimal substantive progress on loss-and-damage negotiations.[9–11] The mobilization of sufficient financial resources is crucial to enable more ambitious mitigation and adaptation targets in the new round of Nationally Determined Contributions (NDCs). Worryingly, only 13 parties submitted their updated NDCs before the original deadline in February 2025.[13] An extended deadline for September 2025 was announced, given that this is the cutoff date for inclusion in the UNFCCC's annual NDC synthesis report, which will be presented at COP30 in Belém, Brazil, to offer the official assessment of global progress toward the Paris Agreement goals.[14] This pressing context underscores the need for the upcoming negotiations in the run up to and at COP30 to be firmly grounded in the latest research on climate change, including natural and social sciences, a principle that the United Nations (UN) system has made central to climate action.[15,16]

Robust science advice for decision makers on subjects as complex as climate change requires deep cross- and interdisciplinary understanding.[17,18] However, navigating the expansive body of peer-reviewed literature on climate change and identifying key insights from this vast landscape represents a significant challenge. This challenge stems from the sheer amount of new research being published every year,[19,20] as well as the expanding range of disciplinary perspectives, broadening of research topics, and diversification of research fields.[21–23] Since the late 1990s, the number of scientific publications referring to climate change has grown exponentially: by 2021, an average of 135 papers on climate change were published daily.[19] A rapid search on Web of Science Core Collection for the term "climate change" as a "topic" (i.e., title, keyword, abstract) shows that the number of articles published per year has more than doubled in the past 10 years: from an annual average of almost 16,000/year between 2014 and 2018 to over 33,000/year for 2019–2023.

Within the UNFCCC, the Subsidiary Body for Scientific and Technological Advice (SBSTA) provides an ongoing interface between science and policy, working closely with the Intergovernmental Panel on Climate Change (IPCC), organizing regular research dialogues, and requesting submissions on specific science topics.[24,25] The IPCC is the most authoritative voice on the state of scientific knowledge on climate change. It is responsible for periodically assessing the peer-reviewed literature and synthesizing it to provide a foundation for international climate negotiations under the UNFCCC and for national policies. The legitimacy of the IPCC assessment reports stems from the rigor and transparency of its process involving multiple rounds of expert and governmental review, building on the volunteer contributions of thousands of scientists worldwide, as well as its policy-neutral stance. Through this process, the IPCC fulfills a fundamental task of both generating and reflecting the scientific consensus.[26,27] The last assessment cycle of the IPCC (AR6) began in 2015 and concluded in 2023. Work toward the seventh assessment cycle (AR7) formally began this year (IPCC-60 in Istanbul, Türkiye, and IPCC-61 in Sofia, Bulgaria). Although timelines have not been set yet (as of September 2024), publication of these Working Group reports is expected between 2028 and 2029, with additional approved reports expected for 2027.[28,29] The fact that there are only 6–7 years between the publication of the synthesis report from one assessment cycle and the conclusion of the preceding cycle is a remarkable collective achievement, given the thematic breadth and procedural demands of these assessments. Yet, it is also true that, given the volume of research conducted and published every year and the gravity of the decisions at stake, more frequent updates of the advances in climate-change research are needed to better inform the work of negotiators and policymakers.

Update reports are published every year by UN agencies, intergovernmental organizations, and independent research institutes and networks, complementing the knowledge basis that the IPCC can only update every 6–7 years, making them a crucial component of the science-policy landscape. This constellation of reports and interdisciplinary academic papers also addresses topics not covered by IPCC reports, particularly regarding climate action. Key reports in this space include the WMO State of Global Climate[5] and the United Nations Environment Programme's (UNEP) "Gap Reports" (on emissions[6] and adaptation[30]) and the Stockholm Environmental Institute (SEI)-led report on production of fossil fuels.[31] The United in Science report[32] is a multi-organization effort led by WMO that offers a high-level synthesis of the state of the climate and climate action and compiles the key outcomes from several of the reports listed above. Several reports produced by multilateral organizations also play an important role in international climate negotiations, including Climate Finance Provided and Mobilised by Developed Countries (OECD),[33] World Energy Outlook (IEA),[34] World Energy Transitions Outlook (IRENA),[35] and State of Carbon Pricing (World Bank).[36] Other reports, led independently by researcher groups and academic institutions, have also gained prominence over the years, including the Global Carbon Budget,[37] Net Zero Stocktake,[38] and State of Carbon Dioxide Removal,[39] in addition to several groups of researchers who have endeavored to generate annual overviews of key climate indicators, published in academic journals.[40–42]

Given the abundance of institutional reports and the numerous academic reviews and syntheses published every year in peer-reviewed journals, what justifies the 10 New Insights in Climate Science initiative? Each report listed above is an important resource for negotiating delegations, but their contribution is to provide updates on key indicators of the state of the climate and of climate action. However, they are not assessments of the science on climate change, nor are they syntheses of scientific advances or the evidence on specific issues. The IPCC is the only source in the science-policy interface for climate change with the mandate and capacity to provide comprehensive assessment and synthesis of climate-change research. While essential as the cornerstone of the science-policy interface, the focus on scientific consensus has limitations, including a tendency to downplay uncertainties and extreme possibilities[43,44] and the filtering out of perspectives that might be valuable for decision makers.[26,45] Numerous syntheses and literature review papers on specific climate-related topics are published yearly in academic journals (another rapid search on Web of Science Core Collection shows over 600 such papers published in 2023). However, policymakers (and individual researchers) face significant challenges navigating this broad and diverse body of academic literature, especially as this literature can be less accessible for non-experts.[46–48] This is the gap in the science-policy landscape that the 10 New Insights aims to contribute to fill.

The 10 New Insights initiative aims to identify recent advances in climate-change research across the natural and social sciences, prioritize a set of 10, and synthesize them on a yearly basis: more frequently than can be done by large assessments, and more accessible than common academic synthesis or review papers. This is not an exhaustive assessment or systematic review but an annual prioritization of key research advances. It is based on a bottom-up process to collate suggestions from experts, highlighting recent developments and emerging science that may not be reflected entirely on prior IPCC reports. The purpose of this work is 2-fold: (1) to foster cross- and interdisciplinary understanding among climate-change researchers (this paper), and (2) to inform negotiating teams and policymakers about new insights in climate-change research and their implications for ongoing negotiations and policy debates (the science-policy report[49] launched ahead of COP29, which is grounded on a preliminary version of this paper). Ultimately, the science-policy report aims to elevate the voice of a diverse community of climate-change researchers in the lead-up and during the UN climate COPs.

Over the past 8 years the 10 New Insights team has refined a bottom-up process to elicit expert views across global research networks to identify, prioritize, and synthesize recent advances in climate-change research with high policy relevance (see Methods section). The report itself has gained recognition in climate diplomacy circles, and both the former and current Executive Secretary of the UNFCCC have publicly expressed their appreciation and support for this annual collective effort of science synthesis and science communication. In this paper, we present a synthesis of the 2024 10 New Insights. A New Insight is defined as a key, recent development or advance in a particular area of climate-change research. By "key advance" we mean new evidence or analyses that significantly update our understanding of the patterns or processes of climate change, its impacts on societies, and the possible means and barriers to address them. A "key development" refers to novel research topics, fields, and approaches gaining recognition or becoming decisively established among climate-change research communities, as well as other emerging important issues on the horizon of climate change. To be considered recent, these developments or advances must be anchored in peer-reviewed literature published in 2023 and 2024 (references from 2022 and before can be included, but not as the sole foundation for the featured insight). It is important to note that this is not a top-10 list; the selection aims to reflect the thematic breadth of climate-change research, and the ordering of the insights does not indicate their relative importance. This year's insights focus on the following:

(1) Methane: increasing levels, and likely sources of emissions
(2) Aerosols: short-term climate challenges of reduced air pollution
(3) Heat extremes: extensive impacts on habitability and livelihoods
(4) Maternal and reproductive health (MRH): overview of recent evidence
(5) Ocean changes: economic costs of an intensifying El Niño-Southern Oscillation (ENSO) and potential weakening of the Atlantic Meridional Overturning Circulation (AMOC)
(6) Amazon's resilience: the role of ecological and biocultural diversity
(7) Critical infrastructure: vulnerability of interconnected systems
(8) Climate-resilient development in cities through a social-ecological-technical systems (SETS) approach
(9) Energy-transition minerals (ETMs): closing governance gaps for responsible value chains
(10) Acceptance of (and resistance to) climate policies

The policy implications derived from this year's insights include elements for more comprehensive mitigation planning strategies that incorporate a more refined understanding of short-lived climate forcers and the interactions between individual pollutants (1 and 2), and the urgent need to prioritize heat-adaptation planning, particularly in vulnerable tropical areas,

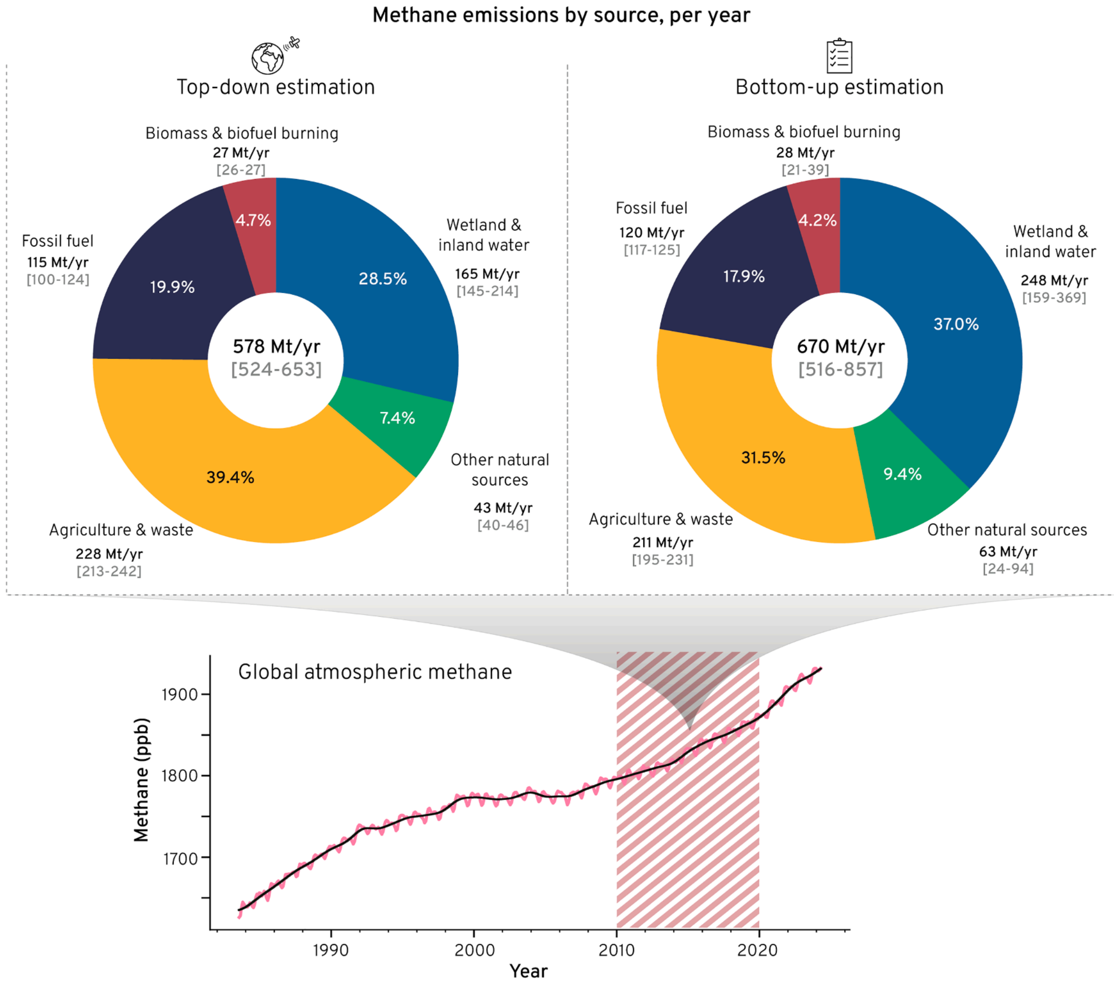

Figure 1. Annual methane emissions by source (average for the period 2010–2019)
Estimate based on top-down integrative methods (top left) and bottom-up integrative methods (top right). Uncertainty ranges are indicated in square brackets. Data adapted from Saunois et al.[54] Bottom: trends 1983–2024 in global atmospheric methane.[58] Shaded area indicates decade over which emissions sources are attributed.

and with specific provisions to protect high-risk groups (3 and 4). The insights underscore the urgency for significantly more ambitious and effective emissions reductions to mitigate the effects on the climate but also on the stability of other Earth system processes in the ocean and the biosphere (5 and 6). The importance of holistic, system approaches to enhance resilience in the face of changing climate are highlighted across several insights, most explicitly for the development of cities and planning around critical infrastructure (7 and 8). Finally, two domains with implications for just transitions are featured, one hinging on governance and international trade (8) and the other on political economy consideration for more effective climate policies (10).

THE 10 NEW INSIGHTS IN CLIMATE SCIENCE

Insight 1: The likely causes of rising methane levels

Methane levels have surged since 2006, driven primarily by human activities

Methane is a potent but short-lived greenhouse gas (GHG); increased emissions of methane account for 0.5°C global warming since the late 1800s. To limit warming within the Paris Agreement goals and prevent severe climate impacts, rapid and deep cuts in methane emissions are crucial.[50] As natural sources are hard to control, significant reductions in anthropogenic methane emissions, which may now contribute two-thirds of global emissions, are essential to meet global targets.[51]

Since 2006, observations have shown a resumed growth in atmospheric methane levels[52–54] with unprecedented high growth rates within the last 5 years[51,55] (Figure 1). Isotopic and remote-sensing evidence point to increasing biogenic emissions since 2006, likely from livestock, waste, and tropical wetlands as primary contributors.[52,56] Reductions in methane's atmospheric removal (via reaction with the hydroxyl radical, OH) may also contribute significantly, modified by changes in reactive gases that affect the atmospheric content of OH (OH is difficult to measure directly).[55,57] Furthermore, if natural methane sources continue to grow, deeper reductions in anthropogenic emissions will be necessary to compensate.

Understanding the main factors behind the long-term increase is crucial for developing an adequate mitigation strategy. Recent advances in remote sensing, the expanding ground network, and modeling progress have improved the characterization of methane sources and sinks. Expanded satellite capabilities improve estimation of anthropogenic emissions over large areas and now allow detection of large emissions from individual facilities.[59–61] Combined with atmospheric modeling, these capabilities improve quantitative understanding of emissions from more diffuse anthropogenic emissions from sources like rice paddies, landfills, and livestock.[56,62] Measurements of atmospheric trace constituents and isotopic analysis, combined with modeling, help constrain methane budgets and their balance between sources and sinks. Together, these capabilities provide the knowledge needed to design methane-emission mitigation strategies and evaluate their efficacy.

Here, we present recent evidence explaining the causes of atmospheric methane acceleration since 2006 and opportunities for enhanced mitigation.

Over the 2010–2019 decade, anthropogenic sources accounted for, on average, 63%–68% of total methane emissions,[54] depending on the approach for estimating emissions. However, uncertainties across sources and locations remain large, with varied methods yielding different results.[54] For example, estimates of fossil fuel methane emissions differ between activity-based bottom-up inventories, remote sensing, and isotopic analysis.[54,56,63] Another well-recognized source of uncertainty in inventories is that they do not sufficiently capture unintended emissions such as those associated with process excursions or equipment failures in the fossil fuel sector.[57,64] Despite these uncertainties and discrepancies, estimates for categories of anthropogenic sources and sinks are relatively well constrained (natural sources and sinks much less so) and generally converge.[51,65]

Evidence from global measurements of the 13C/12C methane isotope ratio, which differentiates fossil from biogenic sources, shows a steady increase beginning in the late 19th century, consistent with rising fossil energy emissions.[52] That trend reversed in the early 2000s, reflecting increases in the relative portion of biogenic sources.[52] This biogenic increase may stem from rises in anthropogenic sources such as livestock, and possibly waste emissions,[54,56] in addition to rising emissions from natural systems[65] (Figure 1). Recent attribution studies examining the causes of methane growth point to rises in anthropogenic methane emissions as the main driver, with highly variable natural sources modifying the trend in the short term.[57]

Emissions from natural systems, estimated from remote sensing, flux-site measurements and modeling, increased by about 4% from the 2000s to the 2010s, particularly from tropical wetlands.[54,66] From 2020 to 2022, a persistent La Niña pattern was implicated in the recent accelerated methane growth rate, driving enhanced fluxes from tropical wetlands, and a reduced growth rate in 2023 when La Niña switched to El Niño.[65] For Arctic regions that are less covered by remote sensing, a study using *in situ* observations suggests a 9% rise in emissions from the boreal-Arctic region since 2002, driven by warming and greening, with the highest emissions during heatwaves.[67] However, observing capacities (both surface and remote) are not yet sufficient for drawing conclusions on trends of circum-Arctic methane releases.[53] Climate feedback mechanisms, primarily from warming and precipitation changes, are expected to further amplify emissions from natural systems in a warming climate, with the largest contribution expected from wetlands.[68] Representing these feedbacks in models in order to make projections at a global scale is hugely challenging. The feedbacks that relate to the impact of climate change on natural methane emissions are often poorly constrained in representations of the climate system (models and model emulators), with the result that substantial uncertainty in the potential impact remains. This risks an underestimate of the future biogenic contributions to atmospheric methane rise in a warming world.[65,69,70]

Effective mitigation strategies must consider present-day sources and sinks of methane and the risk that methane-climate feedbacks will likely increase methane emissions, implying the need for additional reductions in anthropogenic emissions in the near term.[65]

Deep cuts to methane emissions from the fossil fuel industry and waste management sectors are most feasible, many of which are cost-effective or even cost-negative, through improved efficiencies and deployment of existing technologies.[71] Across both sectors, recently developed and rapidly improving satellite monitoring capabilities can enable detection of large emissions at a facility level to alert the need for action on the relatively small number of emitters that have an outsized impact on total emissions.[59–61,64]

The agricultural sector, the largest anthropogenic methane source, has lower technical potential for reduction, but is not without options.[71,72] Significant cuts are possible through a range of mitigations including livestock feed and manure management, removal of straw in rice paddies and non-continuous flooding, diet change away from dependence on livestock, and reduction of food waste.[72,73]

Emerging technologies for *in situ* methane removal or oxidation to CO_2 present a complementary opportunity to slow near-term warming but require significant development, scaling, and incentivization to be cost-effective. While CO_2 direct air capture and carbon storage technologies are small-scale but at least operational ($\sim$2 $MtCO_2$/year removed),[74] methane removal exploration has only recently begun.[75]

Despite uncertainties in the methane budget, sufficient information about the spatiotemporal distribution of sources is known to take action. Monitoring capacity is rapidly advancing and can improve emission inventories through reconciliation with activity-based national inventories and track the effectiveness of emission mitigation efforts through independent emissions observation. Methane-emissions reductions are tractable and have been demonstrated. However, methane emissions are still rising, which is incompatible with IPCC Assessment Report 6 mitigation scenarios that stay below 1.5° warming[54] which assume deep reductions in methane emissions. This represents a significant implementation gap in meeting global commitments. Given the current carbon budget, pursuing inadequate methane-emissions reductions puts achievement of the Paris Agreement temperature limit out of reach.[76] With only about 13% of methane emissions covered by mitigation policies,[77] more stringent and consistent action is needed to reverse the growth in atmospheric methane, slow near-term warming, and minimize the impact of stronger natural climate-methane emissions feedbacks. These actions are essential to maintaining the targets outlined in the Global Methane Pledge (GMP) and Paris Agreement.

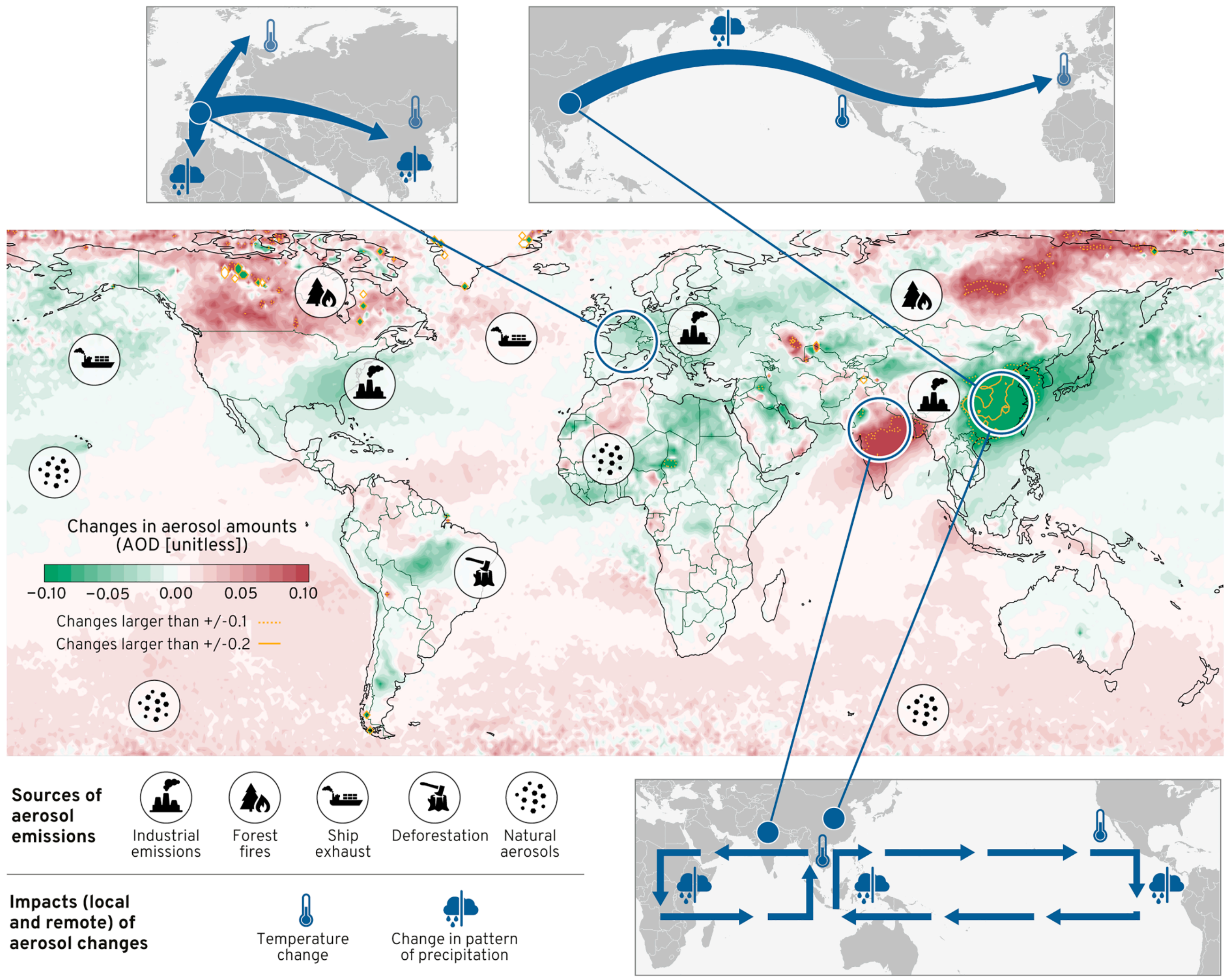

Figure 2. Recent changes in aerosols, related sources, and examples of remote effects
Recent changes in aerosol amounts (difference between 2014–2023 and 2004–2013 period averages), quantified as aerosol optical depth (AOD) observations from MODIS Terra and Aqua. Main sources of aerosol emissions, responsible for the observed AOD changes (icons on map), and examples of remote impacts (local not show here for simplicity) of changes in aerosol loadings over Europe, East Asia, and South Asia are depicted in the top and bottom windows (including Walker circulation, at the bottom). Modified from Persad et al.[80].

The GMP, signed by 158 country participants, has pushed the institutionalization of methane science and reporting forward. It aims for a collective reduction of methane emissions of at least 30% from 2020 levels by 2030. Key to achieving this pledge is for countries' mitigation action plans submitted to UNFCCC—NDCs—to be separated for each GHG gas. This would unlock the door to more transparent and accurate quantification of methane sources and greater policy stringency. Enforceable policies, such as legally binding regulations and differentiated markets, are needed to drive mitigation actions, with regional regulations emerging such as the US Environmental Protection Agency (EPA), which has a super-emitter program for the use of remote sensing to detect methane releases or leaks,[78] and the European Union (EU) Commission's regulation on methane emissions, which requires the fossil fuel industry in Europe to measure and report emissions.[79]

Insight 2: Implications of declining aerosol emissions

Reductions in air pollution have implications for global warming and regional patterns of precipitation

Aerosols, minute liquid or solid particles suspended in the air and major components of air pollution worldwide, have strong influences on the climate. Aerosol emissions and atmospheric loadings have been declining globally (though not in every region), especially in the past two decades (Figure 2), and recent insights show that this is influencing observed climate change via pathways distinct from GHGs.

Anthropogenic aerosol particles mainly stem from road traffic, domestic and commercial energy generation, agriculture, managed fires, and a range of other sources. Natural aerosol sources include volcanic eruptions, wildfires, deserts and oceans.[81] This airborne particulate matter is considered to be the world's largest environmental health threat: 58% of the total 8.1 million premature deaths attributed to air pollution in 2021 are attributed to ambient $PM_{2.5}$.[82] Beyond premature deaths, it is worth noting that air pollution, including ambient particulate matter, impacts health across the entire life course,[82] and almost the entire global population (99%) lives in areas where air quality does not meet WHO guidelines.[83,84] In addition to their impacts on human health, aerosols from both natural and anthropogenic sources have an important impact on global and regional climate.

Broadly, GHGs have warmed the climate over the industrial era, while the net effect of aerosol changes on global climate over the historical era is cooling,[85] thereby partly "masking" anthropogenic warming from GHGs, and also reducing precipitation change.[86] Due to the variety of emission types, physical interactions, and chemical reactivities, however, aerosols affect the climate through different pathways and with different efficacies than GHGs. For instance, unlike CO_2, aerosols are short-lived climate forcers (SLFCs), thereby influencing climate on different spatial and temporal scales, as compared to well-mixed GHGs with their influence on the global mean temperature and total precipitation.

Aerosol emissions, properties, and climate effects are heterogeneously distributed across regions and time evolving (Figure 2), which adds complexity to describing them in climate models. Recent studies provide details on the complex role ongoing changes in aerosol emissions are having in observed climate change, both near to and far from emission sources. These effects transcend the often-discussed influence on global mean temperature, and they differ in strength and geographic distribution from the effects of concurrent increases in GHGs.[80] Critically, the short-term local and global impacts of aerosol changes are strongly dependent on the location of the emission changes; depending on where the aerosol change occurs, the resulting global and local temperature and precipitation impacts and associated societal damages can span orders of magnitude.[87–89]

One key insight relates to the pattern of recent emission changes (Figure 2). GHG and aerosol emissions share similar sources, and mitigation policies for GHG are highly intertwined with those for air pollution. The efforts in recent decades to reduce aerosol emissions have, while also partly mitigating GHG emissions, successfully improved air quality in many regions of the world. Particularly, Europe, North America, and East Asia have already experienced a notable decline in anthropogenic aerosol loadings as a result of successful air quality policies in the past decades.[90,91] To the contrary, while aerosol emissions have begun declining globally, they continue to rise in South Asia and, to a lesser degree over parts of South America, and the trajectory of future African emissions is particularly uncertain.[85,90] Hence, the local effects of aerosol changes have been co-located with many of the world's most populated areas from South and East Asia to South America,[91,92] amplifying shifts in climate risks. However, heterogeneous aerosol emission changes also have and will continue to produce remote effects on atmospheric circulation, air temperature, and precipitation and thus are not only a concern for currently polluted regions.[80,93,94]

These changes can be robustly detected from satellite data, and the overall corresponding decline in negative effective radiative forcing by aerosols over the period of 2000–2019 is estimated to be 0.1 to 0.3 W m^{-2}.[90] This corresponds to 15%–50% of the increase in effective radiative forcing caused by CO_2[85] in the same time period. Concurrently, many studies have documented a recent step up in the rate of global warming,[95] and, recently, aerosol cleanup has been implicated as a contributing factor.[96] These recent findings support expectations that future aerosol reductions will significantly contribute to climate warming, and aerosol impacts are expected to outweigh those of GHGs under the carbon-neutrality scenario.[93,97]

The climate implications of the current trends in aerosol emissions are not fully quantified. Aerosol-cloud-precipitation interactions remain a persistent uncertainty,[98] and aerosol-cloud interactions (ACIs) dominate the radiative forcing from anthropogenic aerosol emissions and its uncertainty.[85,99,100] Persistent ACI uncertainty limits our understanding of both the total influence of aerosols on surface temperature and the transient climate sensitivity[101] and, therefore, must continue to be a focus of research efforts. Further areas requiring research investment include the many pathways that connect aerosol radiative and microphysical effects to precipitation,[87] how global warming influences emissions of natural aerosol types,[102] and aerosols' influences on extreme and compound events. One complicating factor is that, due to the climate system's thermal inertia and the non-linearity of ACIs, the additional warming arising from air-pollution mitigation can be delayed by two or three decades in heavily polluted locations.[103] Adding to this concern, recent studies suggest a potential underestimation of the anthropogenic aerosol loadings in the past decades.[104] Given the expected decline in aerosol loadings, these recent findings and persistent aerosol-related uncertainty further underline the need for immediate climate-change mitigation and adaptation measures.

Another key recent insight concerns the climate impact of emissions of soot, or black carbon aerosols. Dark aerosols such as soot absorb sunlight and act to warm the climate much like GHGs. Until recently, soot was considered a strong contributor to observed global warming, but recent studies have found that this effect is counteracted by atmospheric effects (so-called rapid adjustments) therefore underlining the importance of mitigating dangerous climate change through GHG reduction. The total effect of present-day black carbon emissions was assessed by the IPCC to be around 0.1°C only.[85] Later studies have, however, emphasized the potential role soot has in driving precipitation change and influencing climate phenomena, making it a highly relevant contributor to regional climate change.[86,87,105]

Recently, there has also been discussion of a potential role of reductions in sulfur content in ship fuels in the 2023 record-high surface temperatures.[106–110] The recent regulations from the International Maritime Organization (IMO), in effect from 2020, have drastically reduced sulfate aerosol loading resulting from shipping emissions, and this is expected to lead to some additional global warming. The magnitude of this effect has been estimated by a number of studies, but no consensus has yet been reached. Most estimates lie around 0.1°C, though some studies point out that the effect is also, as yet, indistinguishable from year-to-year variability.[110]

A consensus among recent studies is, however, that aerosol emission changes are key in differentiating the rate and nature of climate change experienced by different regions, which leads to a differentiation in loss and damage and adaptation pressure.[111] While this is evident from the discussed findings on aerosols' impacts on temperature, precipitation, and circulation, decision-making support generally suffers from a lack of knowledge, which needs to be addressed by differentiating the effects of aerosols, starting with the distinction between different aerosol types. For instance, regional climate models, as important suppliers of climate information, should be equipped to better reproduce the detected effects.[80,99,112]

The latest findings on anthropogenic aerosols make it clear that the necessary phase-out of fossil fuels to stay within the Paris Agreement warming limit range[68] will also bring about considerable co-benefits for human health via aerosol reductions, yet these aerosol reductions also increase the urgency of GHG mitigation.

Cleanup of anthropogenic aerosol emissions is having, and will continue to have, massive benefits for human and ecosystem health and on clean energy from solar and wind.[113] It is, however, also unavoidably strengthening the ongoing global warming, and adding complexity to the regional evolution of temperature, precipitation, and rates and magnitudes of extreme events.

Insight 3: Losing habitability due to extreme heat

A growing fraction of the planet is now under climate conditions outside the historical range of habitability

Extreme heat is one of the major factors making parts of the planet less habitable. It is one of the leading causes of weather-related mortality across the world[114,115] due to the many ways it imparts physiological strain on the human body.[116] Recent epidemiological studies have shown that extreme heat is not only associated with increases in all-cause mortality[117,118] but also with case-specific causes such as cardiovascular.[119,120] Notable heatwaves like those that affected the North American Pacific Northwest in 2021 and western Europe in 2022[121] resulted in a large number of excess deaths and heat-related illnesses, including heat stroke and severe headaches. Extreme heat events like these that were associated with excess mortality are occurring more frequently, a trend that will continue with climate change.[115]

Is there a limit to the heat conditions that the average human can withstand? Put another way, are there combinations of temperature and humidity at which the human body is no longer able to physiologically compensate for prolonged environmental heat stress leading to core temperature increases that put a person's internal organs at risk of function failure?[122] Over the past year, new studies have focused on the limits of human thermal habitability under future climate change based on both previous epidemiological as well as new empirical physiological literature. We synthesize these latest developments and how they fit within the context and definition of human habitability.

Although habitability can encompass other factors such as drought, wildfires, and infectious diseases, thermal habitability is emphasized more in recent literature (and is the focus here) as it is one of the key factors currently contributing to uninhabitability due to climate change.[123] Thermal habitability can be considered in terms of the overall concept of habitability.[124] However, here, we specifically refer to it as the suitability of an environment's temperature for human comfort, and survival, considering the range of temperatures that humans can tolerate and thrive in and taking into account factors such as temperature and humidity level, which affect how the human body maintains its core temperature and performs daily tasks.[125,126]

One way to evaluate habitability is via the "human climate niche," the climatic conditions (and specifically temperature conditions for this insight) where people have historically settled. Archaeological records and climate reconstructions reveal that, since neolithic times (~6,000 years ago) humans have concentrated in a surprisingly narrow subset of Earth's available climates, with mean annual temperatures ~13°C and mean annual precipitation ~1,000 mm.[127] In present-day societies, most people, and most agricultural and economic output, are still within this same human climate niche.[127] The human-induced climate changes (and specifically warming) we are currently facing are pushing areas outside habitable climatic conditions.[124,128] A recent study estimates that, at the current ~1°C warming level, >600 million people already live outside the human climate niche, while projections presented in this study show that every degree of future warming could further push >10% of the world's population outside the niche, assuming no massive migrations due to climate[123] (Figure 3). It is important to note that the human climate niche describes where most humans, not all humans, have lived and continue to live. Conditions outside the ranges of the human climate niche are not necessarily uninhabitable and have been made more habitable thanks to modern adaptation technologies like irrigation and air conditioning.

While the human climate niche describes the average conditions most conducive to human habitability, heat extremes experienced during heat waves are also an important consideration for habitability. In the future, most regions of the world will likely experience an increased frequency, duration, and magnitude of extreme heat.[129] Heat extremes impact human health in numerous ways. The most directly fatal impact is heat stroke—though this only constitutes a small percentage of heat-related deaths. Other heat-related illnesses include severe headaches, vital organ damage, decreased metabolic activity, preterm births, kidney and urinary tract complications, and mental disorders.[116] Although the occurrence of heatwaves and dry conditions can be dangerous to human health, it is particularly the occurrence of heatwaves alongside humid conditions that is dangerous for health. This is because such conditions hinder evaporative cooling and reduce the ability to regulate core temperature (Figure 3). Recent empirical studies indicate that young, otherwise healthy humans are unable to thermoregulate in conditions of minimal metabolic activity beyond a wet-bulb temperature of ~31°C in humid conditions, ~4°C less than previously theorized.[126] Especially vulnerable groups, whose thermoregulatory limits would likely be even lower, include the elderly and young children; people with chronic cardiovascular conditions, respiratory conditions, cerebrovascular conditions, pre-existing mental illness, and with cognitive and/or physical impairments. Without other infrastructural or technological adaptive measures (e.g., air conditioning), prolonged exposure of a few hours to these conditions would drastically increase the risk of morbidity and mortality in wide swaths of the population.

Extreme heat impacts extend beyond direct harms to human health. Heat also causes reduced work capacity,[130] especially

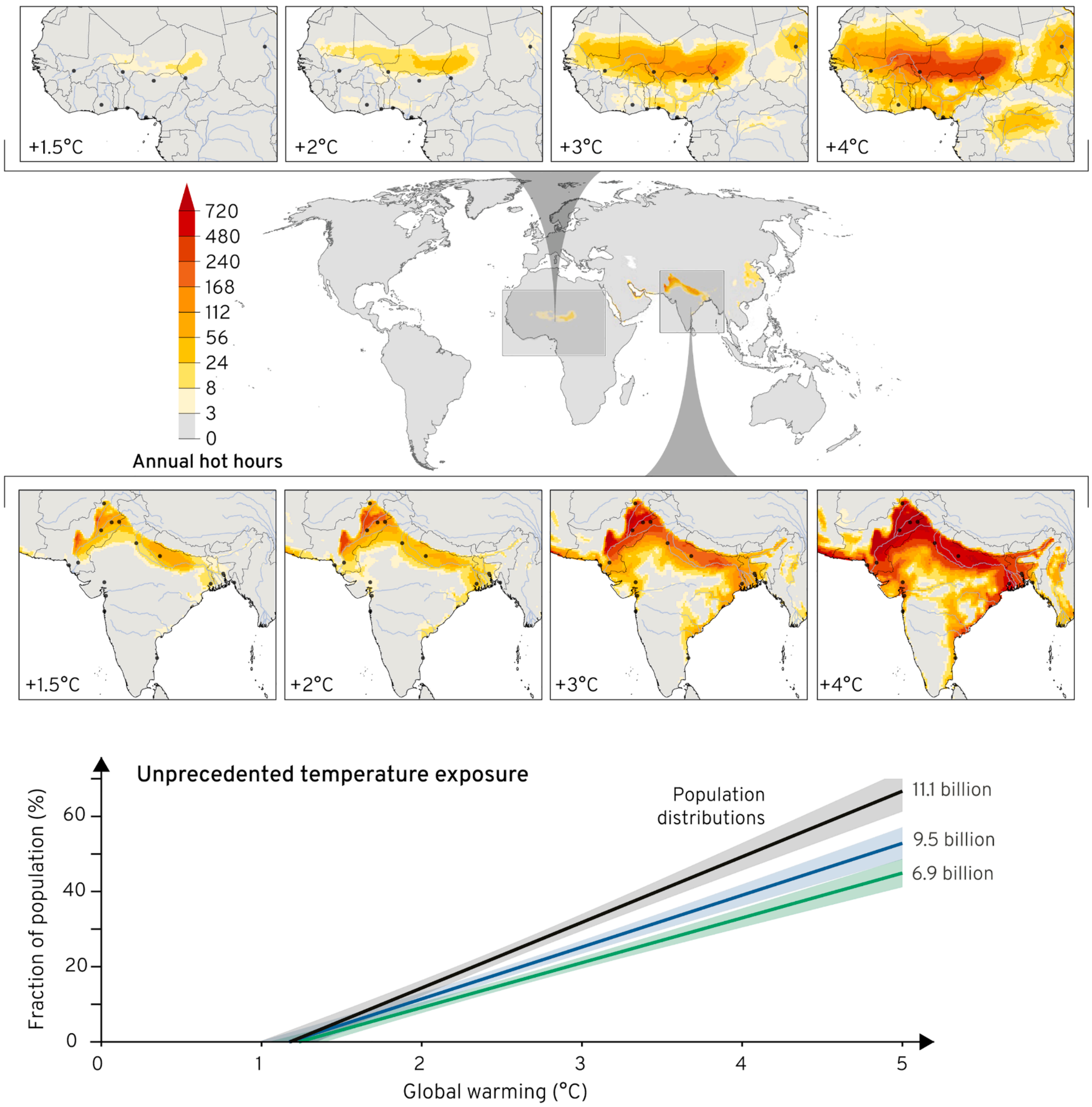

Figure 3. Increasing exposure to prolonged heat at different levels of global warming

Implications of global warming for the proportion of the population exposed to heat. Map of present heat-humidity risks to humans with inset projections of the heat-humidity changes for West Africa as well as a plotted projection of the percentage of humanity exposed to unprecedented temperatures, both under different warming scenarios. Annual hot-hours global map (under 1.5°C warming) and West Africa and South Asia projections (under 1.5°C, 2°C, 3°C, and 4°C warming).[126] Bottom left plot: projection of fraction of humanity exposed to unprecedented temperatures.[123] Population (%) exposed to unprecedented heat (mean annual temperature ≥29°C) for the different population distributions: 6.9 billion (green), 9.5 billion (blue), and 11.1 billion (gray).

for outdoor workers.[131] Communities with a greater proportion of outdoor and informal sector workers, such as farm workers, construction workers, waste pickers, and street vendors, are particularly affected. Non-direct impacts to health also occur, such as that climate warming may amplify the risk of algae blooms, increasing human exposure to cyanotoxins.[132] Increased global temperature increases the burden of vector-borne diseases, including malaria. With warmer temperatures, vectors, including mosquitos and ticks, which can survive in more regions and for longer timescales.[133]

Beyond the specifics of the limits of thermoregulation in humans, heat extremes affect different regions and population groups differently. The world is not warming evenly, with some regions becoming exposed to extreme heat more rapidly (Figure 3, inset of West Africa in particular). Powis et al.[134] show that many regions across the world already experience hot and humid conditions beyond the physiologically determined thermoregulatory thresholds. Ramsay et al.[135] find that humid-heat risk is underestimated in some of the most vulnerable regions due to the numbers of people living in informal settlements, limiting their adaptive capacity. As the world approaches 1.5°C warming, potentially lethal temperature and humidity levels are expected in India, Pakistan, and Bangladesh.[135,136] Global-scale analyses suggest that heat extremes will be concentrated in low-latitude regions, which disproportionately includes many Global South countries.[123]

Habitability is not only an individual, physiological concept but also one dictated by the suitability of the surrounding environment to live and thrive in, including the availability of food. Drought-heatwave and humid-heatwave events are increasingly occurring and are impacting agriculture and food security globally.[68,137] Extreme heatwave-drought events significantly impact staple crop yields, like maize.[138] During growing seasons that coincide with El Niño events, areas like southern Africa and Australia, more frequent and intense heat coincide with drier-than-normal conditions, substantial impacts on crop and livestock production[137,139]; this was observed in many parts of southern Africa during the 2023/2024 El Niño event.[140]

Understanding when, and by what margin, heat extremes are likely to occur is vital for adaptation planning. For example, the El Niño superimposed on global warming trends can exacerbate record-breaking heat, especially humid heatwaves.[139] A variety of climate modeling methods can be used to investigate the physical characteristics of possible unprecedented extremes in current and future climates, allowing plausible adaptation levels to be determined. Better understanding of the plausible extremes allows prioritization of adaptation measures, implementing measures such as expanding air conditioning, creating green urban spaces, and improving heat action plans in the regions where they will have most impact. It is important to push adaptation efforts to be based on future models because current levels of heat adaptation are typically aligned only with past (if recent) record temperatures.[141] Instead adaptation needs to be based on what models are anticipating in the future.[142]

As we described, multiple lines of new evidence are showing that large parts of the globe are at increasing risk of becoming uninhabitable due to warming. This is occurring due to higher average temperatures and/or discrete periods of extreme heat, both of which test the limits of what humans can physiologically tolerate. 2024 has seen a series of extreme heat events globally. For example, over 1,000 fatalities at the Hajj pilgrimage were linked to a heatwave, while, in India, early-season heat overwhelmed hospitals.[143] Other climatic extremes, such as intensified storms, droughts, and wildfires, can also render regions uninhabitable, though these fall outside the scope of this Insight.

While environmental indicators show a shift toward uninhabitable conditions, there is substantial heterogeneity in adaptive capacity across populations. Physiological adaptation appears to occur in populations continuously exposed to warmer conditions, reducing health impacts.[144] On the other hand, vulnerable populations, such as the elderly or those with underlying medical conditions, have different, lower, physiological thresholds for extreme heat.[145] This shows that it is not possible to empirically determine a single level of human tolerance for heat. The limited empirical studies on heat and humidity tolerance do not yet cover this full range. Vecellio et al.,[126] for example, looked at individuals from a population with generally low exposure to heat), and this inhibits the ability to adapt appropriately for the local context. It is also important to note that heat sickens and kills at values well below the habitability thresholds discussed here and regardless of ambient humidity.[146,147] All these factors may contribute to the disconnect between the epidemiological and the physiological results around heat and humidity.[148] Higher-income countries within vulnerable regions (e.g., United Arab Emirates and Singapore) can afford the required technological adaptations and lifestyle changes to withstand the worst effects of extreme heat. In contrast, poorer households, even within affluent regions, will endure higher heat exposure due to limited access to cooling.[149] Greatly expanding access to such adaptive measures will be critical in responding to the increasing inhabitability due to heat.

Insight 4: Impacts on MRH

Climate change is increasing risks for pregnant women, fetuses, and newborns, threatening progress in MRH

Changing climate patterns have been exacerbating health problems worldwide, increasing heat-related deaths, infectious diseases, respiratory illnesses, and more.[150] Recently, there has been rising concern over the growing impacts of climate change on MRH, an important element in tackling the existing gendered impacts of climate change.

While it has been shown that pregnant women can thermoregulate effectively in situations of acute, short-term heat stress (typically several hours or less from exercise in heat, for example),[151] it is less well known as to how effective thermoregulation is with prolonged excess heat exposure (days to weeks), especially in light of the multi-system adaptation taking place across pregnancy to accommodate the demands of a growing fetus.[152] Indeed, excess heat exposure and other extreme weather events have been directly and indirectly linked to hypertensive complications of pregnancy, increased pregnancy loss, preterm births, severe maternal morbidity, and more (Figure 4).[152,153] Impacts are worse in climate-vulnerable regions where pregnant populations are less able to adapt to increasing heat and other extreme weather events due to their prevailing socio-economic conditions and limited access to resources.[154] Climate-change impacts to MRH may also be intergenerational. Some studies associate pregnancy exposure to extreme weather events with long-term behavioral and cognitive impacts on offspring.[155]

However, there is still need for further research. For example, while it is clear that excess heat exposure results in adverse pregnancy outcomes, exact pathophysiological pathways have not yet been determined. Hypotheses include overwhelmed physiological thermoregulatory systems; decreased placental blood flow resulting in fetal growth restriction and/or placental abruption; premature labor resulting from direct heat-related uterine hypercontractility or enhanced oxytocin and prostaglandin release as well as increased uteroplacental inflammation and dehydration; and hypercoagulability.[156] The exact size and scale of impacts on MRH also remain unclear, particularly in the most climate-vulnerable regions, where there is a gap in research. In addition, policies and practices in place to prepare for these impacts remain insufficient[157]; for example, only 27 out of 119 NDCs make reference to maternal and newborn health and sexual reproductive health.[158]

Recent global movements such as the "Protecting maternal, newborn and child health from the impacts of climate change" call to action aim to raise urgency over this matter.[159] Without effectively addressing the direct and indirect impacts from climate change on MRH, we risk reversing progress made in the field over the recent decades.

To address some research gaps, multiple studies were published last year, such as on the impact of extreme weather events

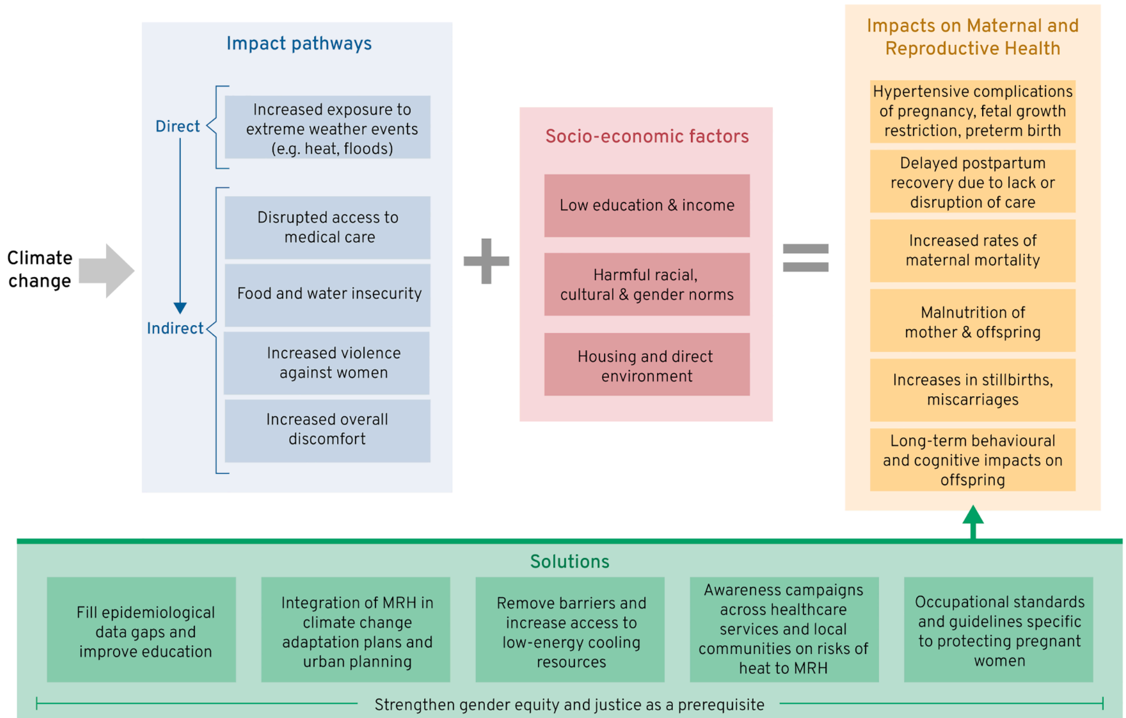

Figure 4. Direct and indirect pathways of climate-change impacts on MRH
Impacts are further amplified by socio-economic factors in a given setting. To strengthen preparedness and protect MRH in a changing climate, solutions must address existing challenges in climate adaptation plans, data, education, and gender and socio-economic norms and be driven by gender equity and reproductive justice.

on MRH in low- and middle-income nations. Rekha et al.[154] explore the impact of occupational heat stress on 800 pregnant women in India. Results show that nearly 50% of the women reported excess heat stress exposure (beyond wet-bulb globe temperatures of 27.5°C and 28°C for heavy and moderate workloads, respectively), with the risk of miscarriage was found to be doubled when compared to pregnant women not exposed to heat stress. These results have strong implications for tropical nations where millions of working women risk facing exposure to occupational heat stress.[154] In their study of over 400,000 pregnancies in southern California, Jiao et al.,[160] showed significant associations between long-term heat exposure and increases in severe maternal morbidity (unexpected conditions during birth). These health risks were identified to be higher across patients with lower levels of education and green-space exposure. Another recent large cohort study from Australia also found significant interactions between green spaces, heat exposure, and odds of preterm births.[161] Analyzing urban green infrastructure combined with social determinants of health adds to our understanding of prevention options. Bonell et al.[157] link heat to changes in epigenetics and gene imprinting; congenital abnormalities; and alterations in placental circulation, growth, and function as pathways of harm that can lead to increased stillbirth risk.

But it is not only heat stress that negatively affects MRH. A large-scale study across 33 low- and middle-income countries covering parts of Asia, Africa, and South and Central America found a significant correlation between gestational flood exposure and increased pregnancy loss risk, with this risk being more pronounced for women dependent on surface water, with lower income or education levels. The study also estimated that, between 2010 and 2020, over 107,500 excess pregnancy losses annually could be attributed to maternal exposure to gestational floods across the studied regions, with the highest losses in South Asia.[162]

Through indirect pathways, climate change can magnify these direct impacts (for instance, by affecting health systems and infrastructures; see Insight 7: Critical infrastructure under pressure) and exposing societal weaknesses.[153] For example, increased heat can reduce food and water availability. New mothers have to travel long distances in the heat to secure water, which delays their recovery. Food insecurity can result in inadequate nutrition during pregnancy, which may increase the risks of low birth weight and reduce breast milk production.[163] Research from Kenya and Burkina Faso show that extreme heat discourages important behaviors to MRH. Examples include a decline in breastfeeding frequency, mother-child bonding (e.g., "kangaroo mother care), traveling for antenatal and postnatal care, and use of mosquito nets, which is an additional factor increasing exposure to vector-borne diseases.[163–165] Impacts are further heightened in migrating pregnant women as access to reproductive care services and health care in general is disrupted and can remain absent. Climate-related displacement has been linked to inadequate prenatal care visits, lack of proper nutrition, insufficient rest, unsanitary conditions, loss of social support networks, disrupted breastfeeding, and insufficient neonatal support.[166] Increasing gender-based domestic violence is also another indirect impact

Box 1. Definitions

The ENSO is a climate pattern characterized by interannual variations in sea-surface temperatures and atmospheric pressure across the equatorial Pacific Ocean, leading to substantial global weather extremes. ENSO alternates between two phases: El Niño, associated with warmer ocean temperatures in the central and eastern equatorial Pacific and often resulting in wetter conditions in the Americas and drought in many parts of South Asia, Australia, the Maritime Continent, and southern Africa; and La Niña, marked by cooler ocean temperatures in the central and eastern equatorial Pacific and typically causing opposite weather patterns.

The AMOC is a large system of ocean currents, including the Gulf Stream, in the Atlantic Ocean. The AMOC transports and distributes relatively warm and salty surface water in the upper ocean from the subtropical South Atlantic across the Equator toward high latitudes in the North Atlantic where it becomes denser and sinks to return back south as deep cold water from the North Atlantic back south. The AMOC is a crucial element in the climate system regulating global climate by the storage and redistribution of heat, salt, and other properties around the globe. Disruptions or slowdowns in the AMOC can significantly impact regional weather and climate patterns, water cycle, sea levels, and marine ecosystems.

of climate change on MRH. A study by Zhu et al.[167] in three South Asian countries found that a 1°C increase in the annual mean temperature was associated with a 4.5% increase in intimate partner violence. Women also face increased risk of sexual violence during climate-related migration.[153,166]

Existing justice and gender discrimination further exacerbate these challenges to MRH. Scorgie et al.[164] in Kenya report that, in areas where heat is normalized and behavioral changes conflict with gender norms, pregnant women often continue their physical activities (for example, collecting firewood and water) during extreme heat events. Globally, it is also well known that women of color, low income, and low education levels are exposed to harsher environments, face more impacts of climate change, and have limited access to healthcare services.[168] As a result, they face disproportionate challenges to their MRH. These disparities highlight the importance of addressing the intersection of social and economic inequalities with climate vulnerabilities and recognize the need for a reproductive gender and justice lens.[163–165,168]

To strengthen efforts to protect MRH from climate change, more research from regions highly vulnerable to climate change is needed to fill in existing epidemiological data gaps and better understand the direct and indirect pathways that amplify risks to MRH. At the national level, policy makers should integrate MRH in the NDCs, increase low-emission cooling across health care facilities,[163] or use low-tech solutions to reduce heat (such as painting maternal and neonatal buildings in light colors and relocating from the top floors).[168] Other solutions include, but are not limited to, awareness campaigns to warn pregnant women to avoid peak heat hours (for example, in Andhra Pradesh), increased access to hydration points within a city, disseminating information around nearby air-conditioned public spaces, and providing financial assistance to low-income families to reduce costs of air conditioning (for example, in the states of New York and California)[168,169] while prioritizing low-energy cooling. Integrating education around climate change across medical higher-education programs and training can help increase medical community preparedness to climate-change impacts on health.[155,170] Community-level education campaigns on the risks of heat to MRH, including early signs of dehydration, should be carried out in collaboration with community members, such as local leaders, women support groups, traditional birth attendants, and other health care members.[157,163,171] This can contribute toward dispelling harmful gender norms that increase risks to MRH.[163] Regulations around occupational safety for pregnant women can help set in place best practices to reduce heat stress in workplaces. It is crucial that solutions implemented consider gender equity and justice to avoid further discrimination and to ensure equitable access to health resources to all pregnant women.

While the focus of the current update is on heat and flooding impacts to pregnancy, it is important to mention that other climate-change-driven impacts, such as air pollution and wildfire, continue to be a major concern due to significant associations with several adverse pregnancy outcomes, including preterm birth, low birth weight, hypertensive disorders of pregnancy, placental abruption, and other complications.[172] Policies and actions should account for all manner of climate-change-related harms.

Insight 5: Concerns over ENSO and AMOC

Concerns about ENSO and the AMOC in the context of unprecedented ocean warming

Changes in oceanic conditions can significantly impact global climate patterns through mechanisms such as teleconnections and the redistribution of heat and moisture, posing substantial risks to ecosystems and human societies. We focus on the ENSO and the AMOC due to their profound influence on global climate variability and their critical roles in modulating weather extremes, unlike other phenomena such as the Pacific Decadal Oscillation (PDO) or regional monsoon systems. ENSO is an ocean-atmospheric phenomenon primarily occurring in the central and eastern Pacific Ocean, influencing global weather patterns (Box 1). The AMOC is a system of ocean currents in the Atlantic Ocean, crucial for redistributing heat and regulating climate (Box 1).

We will consider ENSO from an economic perspective because new research shows that the global economic costs of El Niño are orders of magnitude larger than previously understood, implying considerable societal vulnerability. In contrast, we will examine AMOC from a physical perspective because new research suggests that the AMOC, a climate-essential system of global ocean currents regulating and redistributing heat, is exhibiting behavior that could mean its slowdown and/or collapse at lower global-warming thresholds than those predicted by earlier assessments. Together, these two insights suggest that human well-being is highly sensitive to ocean variations and that large-scale oceanic changes are more likely over the near term, with substantial potential societal costs.

ENSO

Unprecedented ocean warming since the beginning of 2023 broke various sea-surface temperature (SST) records not just in the tropical Pacific but also in the North Atlantic, Gulf of Mexico, the Caribbean, and large areas of the Southern Ocean. Even as the El Niño dissipated in the Pacific, the unusual warming of nearly 0.5°C above the reference average period (1991–2020) remained long after the event, as the first quarter of 2024 has persistently been warmer than the respective months in 2023 (Figure 5A). ENSO events are intricately related to long-term changes in SST: warming in the eastern equatorial Pacific can trigger and amplify an El Niño event, whereas warming in the western equatorial Pacific is conducive to strong La Niña events.[173] ENSO SST anomalies driving weather and climate extremes have direct social and economic impacts. New research on large-scale climate features such as the ENSO reveal increasing evidence that natural climate variations are more than two orders of magnitude costlier to the global economy than previously understood, independent of any impacts from global warming.[174,175] While it has long been understood that climate variability can generate socio-economic impacts, the true costs of El Niño events and how those costs evolve alongside warming were unknown. Two scientific issues require resolution to address the question of historical and future ENSO costs: (1) whether and for how long the economic impacts of El Niño events persist, and (2) how projected changes to ENSO will shape the wider costs from global warming. The first striking finding was that historical El Niño events have persistently reduced country-level economic performance of US$4.1 trillion and US$5.7 trillion in global income losses attributed to the 1982–1983 and 1997–1998 El Niño events, respectively[174] (Figure 5B). Similar startlingly large estimates of US$2.1 trillion and US$3.9 trillion global loss due to the 1997–1998 and 2015–2016 extreme El Niño events were found based on different estimations[175] (Figure 5B). Economic loss grows dramatically with increased ENSO variability from global warming. Projected potential economic losses due to increases of ENSO amplitude (under current mitigation pledges and high-emissions scenarios) have been estimated at US$84 trillion, or an additional median loss of US$33 trillion to the global economy over the remainder of the 21st century, at a 3% discount rate in the high-emission scenario. The opposite ENSO phase, La Niña, has statistically insignificant impact and the cumulative global gross domestic product (GDP) benefits gained were negligible. These studies[174,175] reveal how poorly adapted our economies are to natural climate variability, despite the fact that they do not represent novel climate states.

AMOC

Emerging research highlights that AMOC is weakening under climate change and is expected to decline further over the course of the 21st century.[179–181] Beyond the lack of effective climate adaptation over interannual timescales, there is also indication of warming-driven changes to other large components of the climate system operating over longer timescales. The sixth assessment report of the IPCC suggested, with medium confidence, that an AMOC collapse is not likely during the 21st century.[182] New insights question this IPCC statement and indicate that the AMOC is on tipping course, and the tipping point will possibly be reached within this century.[177,178] The 20-year-long observation record of AMOC is at the moment too short to detect any long-term trend.[183] The observational AMOC record may be complemented by reconstructions[184] and model output where these results show early warning signals of a potential AMOC collapse (Figure 5C). However, it should be noted that there are still remaining uncertainties in predicting tipping point due to modeling assumptions, the representativeness of time series data, and gaps in observational coverage. Substantial AMOC weakening by the end of this century[185,186] or a full AMOC shutdown[178] would have profound and complex effects on global climate, weather patterns, sea levels, marine ecosystems, and human societies, necessitating comprehensive monitoring and mitigation efforts to address these potential impacts.[187]

What changes to impactful climate features—and the associated climate risks—can we expect this century? Answering this question requires an assessment of the trustworthiness of models and the sufficiency of observations for responsibly interpreting the projections. For example, the majority of latest Coupled Model Intercomparison Project (CMIP6) models indicate that ENSO amplitude will likely increase even under strict mitigation targets,[188] while some large ensemble simulations suggest nonlinear and time-dependent changes.[189,190] Biases in climate models' inability to reproduce observed SST patterns lead to underestimating climate sensitivity and future warming,[191] indicating that actual climate sensitivity could be higher than previously thought. Multicentury climate simulations and single-model large ensembles forced with pre-industrial GHG conditions can answer the question, helping to represent the spectrum of internal variability consistent with and without anthropogenic forcing. It remains, however, that model interpretations will be tethered to the short observed record in addition to persistent model biases in simulating SST mean state and large inter-model and inter-ensemble spreads in projected changes in ENSO SST variability.[190,192,193] Going forward, a key focus for research is to close the gap between models and observations in both ENSO and AMOC, which would constrain uncertainty in their potential state changes over the near-term decades.[178] For example, while climate models consistently show AMOC decline during the 21st century from climate models,[179] they also reveal a wide range of weakening rates. This uncertainty needs to be addressed with improved models with longer observational records, including more accurate SST records, to help to sort the signal from the noise.

Recent research underscores the significant economic and societal impacts of climate phenomenon like ENSO, which is particularly notable given the recent evidence suggesting alterations of natural climate variability and potential rapid state changes by possible further global warming. El Niño and its teleconnections are well understood, societies have experienced them for centuries, and yet there is a large latent vulnerability to them. ENSO's economic costs are far greater than previously estimated and persist at least 6 years after an El Niño event, while AMOC may be closer to a critical slowdown or collapse than earlier predicted. The large macroeconomic impacts of El Niño suggest potential consequential costs associated with an

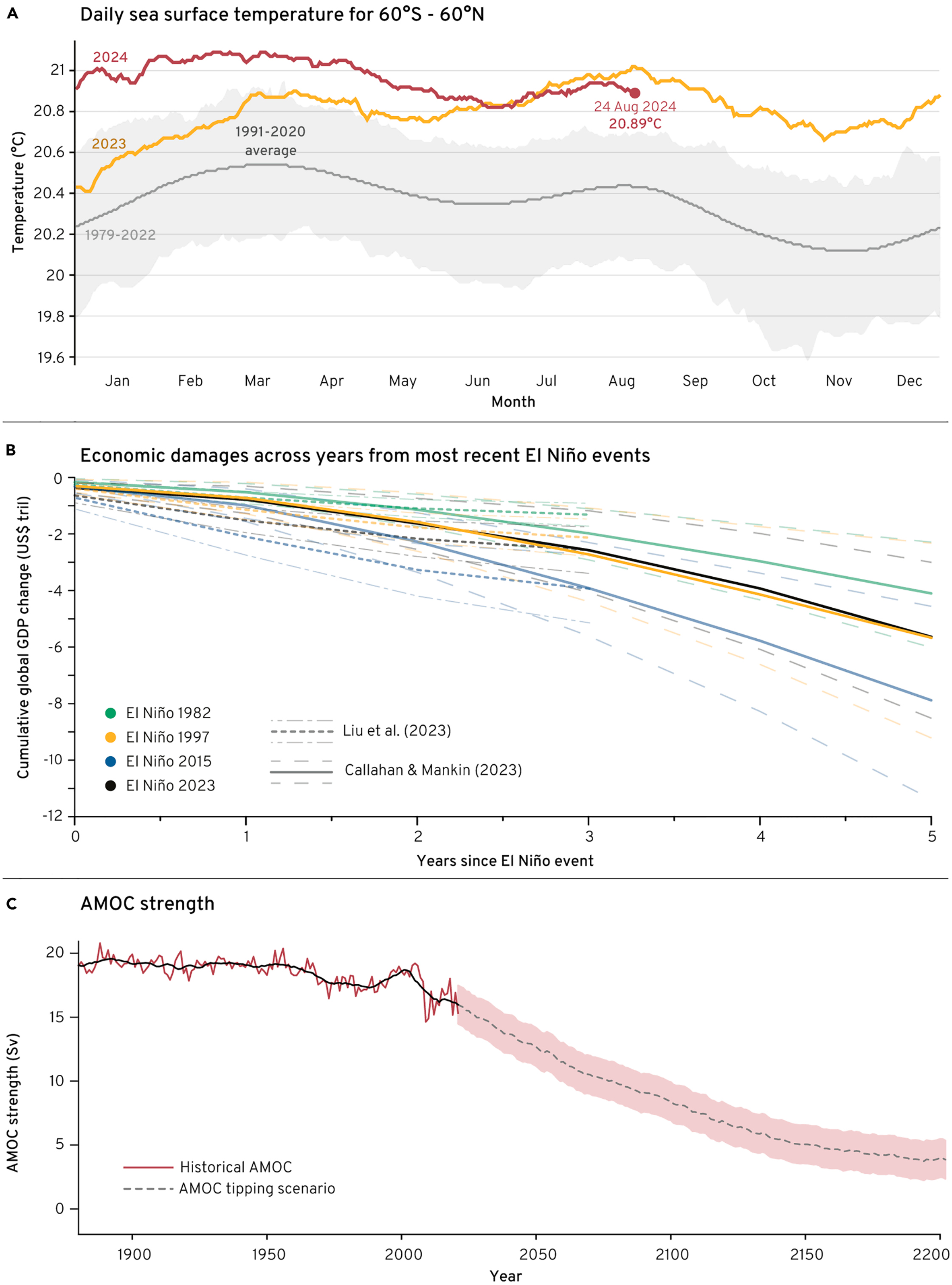

Figure 5. Unprecedented SST, El Niño costs, and potential weakening of AMOC

(A) The mean daily SST across the globe, collected from January 1979 to August 24, 2024 from ERA5.[176]

(B) Economic damages calculated as GDP change for the 3–5 years after noteworthy El Niño events with the center line indicating the mean of the projection and shading showing the 95% confidence intervals across regression bootstrap samples.[174,175] Global GDP change is only calculated for countries with statistically significant marginal effects.

(C) The historical AMOC strength based on a combination of annually averaged SST observations and reconstructions (red)[177] shown with 11-year running means (black solid) indicating potential AMOC tipping scenario from 2021 to 2200 (gray dashed) with shading of interannual variability and uncertainty.[178]

AMOC slowdown or other rapid climate changes. It is also important to address uncertainties in predicting climate processes and understand the impact of rising sea-surface temperatures. This will help refine estimates of future warming and guide effective strategies to protect society from environmental changes over time. The findings emphasize the importance of closing gaps between climate models and observations to better predict and mitigate future risks. Addressing these uncertainties is crucial for developing effective climate-adaptation strategies alongside rapid decarbonization to protect society from potential large-scale environmental changes and risks.

Insight 6: Protecting diversity for the Amazon's resilience

Biocultural and ecological diversity can bolster the Amazon's resilience against climate change

The Amazon is a heterogeneous and complex system composed of various types of interconnected aquatic and terrestrial ecosystems, shaped over tens of millions of years. It hosts ~10% of the Earth's terrestrial biodiversity and more than 400 ethnicities of Indigenous peoples and local communities.[194] By recycling a tremendous amount of water, it substantially affects the planetary energy balance through the cooling effect that evapotranspiration promotes.[194] Moreover, it currently stocks as much carbon as has been released as CO_2 from global land-use change since 1850.[37]

A multitude of human-related drivers have simultaneously altered the vegetation cover throughout the Amazon system.[195] Habitat fragmentation, the extraction of timber and other goods, forest fires, and climate-change-induced extreme droughts have increased degradation to about 40% of the remaining forest.[195] The conversion to farmland (e.g., cattle ranches), infrastructure construction, mining, and an increasing urbanization within the Amazon ecosystems have reshaped its landscapes after deforesting 18% of the total Amazon forest system.[196] These disturbances are not only reducing biodiversity but are synergistically transforming the Amazon ecosystems.

While, under increasing disturbances, the permanent changes in climate and vegetation may not be immediately apparent, societies are already experiencing the early signs of declining ecosystem services, such as reduced water quality and availability.[197] Some parts of the Amazon system have switched from carbon sink to carbon source, effectively reinforcing climate change.[196] Contrasting events such as the 2020–2022 floods and the subsequent 2023–2024 extreme drought have substantially affected social-ecological systems throughout the Amazon region.[198] Impacts were observed on both people (e.g., displacement, transportation shortages) and ecosystems (e.g., reduced productivity).[199] The repercussions extend far beyond the region, threatening water, energy, and food sovereignty locally and globally and jeopardizing the stability of the system itself. Despite some uncertainty, growing concern centers on the possibility of a systematic collapse of the Amazon forest system triggered by self-reinforcing feedback loops induced by climatic and human-driven disturbances. While local or regional tipping points are expected to occur first, a large-scale and systemic tipping of the Amazon forest system may soon follow.[200] These disturbances are unevenly distributed in space and time and are pushing the system toward different thresholds (temperature, rainfall, seasonality, dry season length, and deforestation) at different times.[200] Recent studies have shown that temperature thresholds can significantly influence photosynthesis efficiency, pushing the forests closer to their physiological limits.[201]

The presence of a richer functional diversity enhances resilience of the Amazon to climate change.[202] A richer functional diversity—the range of roles species play within an ecosystem—supports resilience by stabilizing ecosystem functions in the face of disturbances. For example, diverse plant communities with varying tolerances to heat and drought can maintain forest productivity under climatic stress, reducing the risk of forests tipping into degraded states.[202,203] This relation suggests that conserving biodiversity is essential for bolstering forest resilience.[202,204,205] Indigenous ecological knowledge and practices can help in this regard. Evidence shows that the creation of nutrient-rich soils and food forest by Indigenous communities has enhanced the diversity of soils and plant communities, improving the forest's resilience.[206] These practices illustrate the potential of Indigenous knowledge to maintain forest resilience and mitigate the risk of an Amazon forest systemic tipping point.[200]

Maintaining the diversity and resilience of the Amazon system extends beyond preserving its biophysical integrity but must also consider strengthening its biocultural diversity. This includes safeguarding traditional knowledge, governance systems, and ways of life that contribute to the Amazon's resilience (Figure 6).[207] The participation of Indigenous peoples and local communities in decision making and law enforcement,[208] as well as the transformation toward a new socio-bioeconomy—an economic model that values and sustains the region's biodiversity while supporting local livelihoods—is key to maintaining and rebuilding healthy standing forests.[209,210] Restoration of diversity from degraded forests,[207] incorporating local socio-ecological conditions, and co-developing reforestation plans locally can potentially grow rural economies, empower local communities and Indigenous people, and improve livelihood in the long term.[207] The transition toward a sustainable use of its socio-biodiversity can not only ensure the continued provision of ecosystem services but also offer significant opportunities to improve the living conditions of rural, forest, and urban populations, currently facing poverty and inequality.[210] The foundation for this sustainable use is broad and diverse, encompassing traditional activities of forest communities, biodiversity-rich family farming, and all stakeholders within rural landscapes.[210]

Social-ecological "hopespots" demonstrate successful cases of biocultural conservation, such as the Xingu hopespot[206,211] and protected areas in the Cerrado-Amazon ecotone.[206,211] Social-ecological hopespots are defined as areas that can enhance social-ecological resilience, where Indigenous and local communities are integrated with science and technology for the conservation of biodiversity and cultures. Community-based conservation initiatives for sustainable-use protected areas, where local communities are empowered to protect their own territories against illegal fishers, loggers, and poachers and have a large degree of autonomous decision making, have proved effective to not only maintain biocultural diversity and conservation but also enhance the livelihoods in rural Amazonia.[212] These areas are crucial for maintaining the multiple dimensions of biocultural diversity and their interactive functions.[213] By acting as buffers

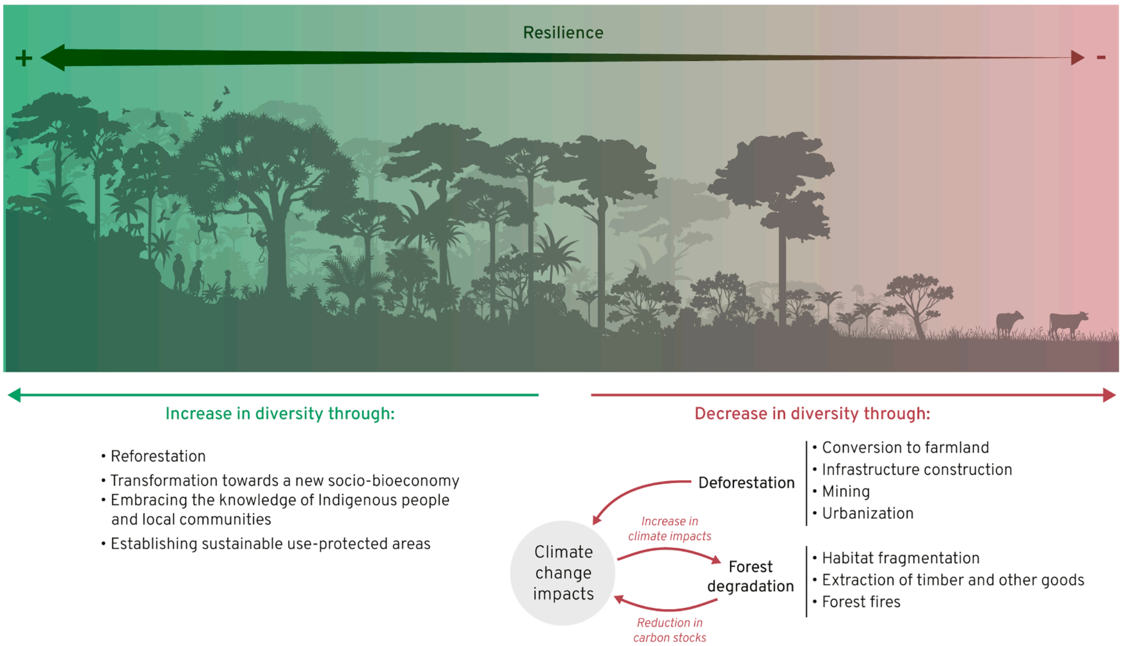

Figure 6. Amazon's biological and cultural diversity enhance its resilience to climate change
A high biodiversity landscape, both biological and biocultural, has higher resilience to climate-change impacts, compared to less diverse landscapes. Climate change and forest degradation are self-reinforcing feedbacks reducing the diversity of the Amazon system. Reforestation, a transformation toward a new socio-bioeconomy, embracing the knowledge of Indigenous people and local communities as well as protecting and establishing sustainable-use protected areas can increase diversity, effectively disrupting the self-reinforcing feedback loop.

against large-scale deforestation and degradation, Indigenous territories and protected areas play a critical role in preserving the Amazon's resilience and biodiversity.[206]

In addition to the largely local efforts discussed above, a concerted global effort to reduce GHG emissions is also necessary to curb the influence of climate change on different forms of Amazon forest degradation, such as via extreme droughts and fire.[195]

Insight 7: Critical infrastructure under pressure

Critical infrastructure is exposed to climate hazards, with risk of cascading disruption across interconnected networks

Energy, transportation networks, telecommunications, and environmental technologies and water infrastructure provide essential services—powering, connecting, and sustaining livelihoods in schools, homes, hospitals, and economic services—and are vital for the functioning of society. Should these critical infrastructures suffer damage, even briefly, the functionality of society could be notably disrupted. When impacted by climate-change hazards, the impacts can lead to billion-dollar-level damages to infrastructure-related assets alone, not to mention their broader socio-economic repercussions. These vulnerabilities are heightening[214] due to extreme weather events, increasing the risk of significant disruptions.[215]

Various types of climate-related hazards from creeping droughts and wildfires to heatwaves to supercharged storms and deadly floods and landslides impact lives and livelihoods through their interactions with critical infrastructure. Energy systems—an example of a critical infrastructure system—contain a network of facilities to produce, convert, transmit, distribute, and provide access to the multiple uses of energy in society. Most of its components, particularly power lines that link the supply and demand of electrical energy for grid-wide connectivity, interact with other services, including mobility and sanitation, and pose risks for wide-ranging impacts. Table 1 highlights interactions between hazards in energy systems that are found to be more severe and likely due to human-induced climate change.

Risks to critical infrastructure arise as single or multiple hazards or as compound or coincident weather events, with cascading impacts through interconnected systems.[222] Interdependencies between critical infrastructure systems like energy distribution and healthcare, or food supply and transport, can intensify these risks, causing a domino effect where one system failure disrupts others.[223] There can be three stages of effects, starting from a single isolated disruption of a facility/asset, in which direct local impacts disrupt physical infrastructure, such as a drought interrupting hydroelectric power or wildfire affecting transmission systems.[224] Managing such disruptions locally is vital as it reduces the wider-scale impact. In the next stage, spreading disruptions can take place through the specific system (within the sector), beyond a local issue, if poor local management, and/or vulnerable design and operation of infrastructure[224] conditions exist. Especially when extending to interconnected systems, multi-dimensional impacts on society require more time before full or partial recovery.[225] Thus, widespread infrastructure or major transportation network disruptions need to be reduced,[226] requiring local containment.

Cascading impacts on critical infrastructure around the world are already happening as various hazards are increasing in

Table 1. Climate-related hazards, interactions within energy systems, and recent findings

Hazards	Interactions within energy systems	Related recent findings
Drought	water stress and cooling-water shortages	less generation and exceedance of plant design temperature[216]
Flood	flood-water inundation of power plants	damage to infrastructure[217]
Heatwave	power outages from high cooling loads, curtailment due to operating conditions	average of 41 days of additional dangerous heat in 2024 and more than 130 days in the small island developing states[218]
Storm	transmission and distribution network infrastructure damage and power outages	power losses equal to billions of customer hours per cyclone[219]
Wildfire	sedimentation from wildfire-induced runoff in reservoirs for hydroelectricity generation	sediment concentrations multiple times above pre-fire levels[220]
Sea-level rise	exposure of critical coastal infrastructure	impacts on livelihoods[221]

frequency and severity, and the damages are significant. In Southeast and East Asia alone, the total expected annual damage of tropical cyclones and coastal floods on power infrastructure is projected to reach up to US$105 billion.[219] Hurricane Maria also damaged 80% of Puerto Rico's electrical power system and disrupted essential services for several months, including water distribution, which led to impacts on access to clean drinking water, waterborne diseases, and water treatment.[217] In addition, thermal power plants are prone to chronic physical hazards related to water temperatures and water stress impact. Reduced cooling-water accessibility of thermal power plants due to drought already accounts for power-generation losses. In wet-cooled plants, sustained water temperature rises could increase the exceedance probability of design temperatures by up to 27% and lead to an additional loss in power generation, including 2.1 TWh in 2030 across a sample of power plants.[216]

In the context of these challenges with disruptions to networks and services, there are emerging solutions to increase the resilience of critical infrastructure through mitigation, adaptation, and their synergies at various scales of implementation from local to system-level options. Integrated microgrid planning using local decentralized renewable energy systems[227,228] can increase access to clean energy and basic services, enabling improved mitigation and adaptation. Microgrids and cross-sector interoperability over distributed microgrids with large-scale renewable energy[229] can also increase equity and sustainable development when there is integrated microgrid planning and decision making. For example, power outages during major storms and hurricanes can pose greater risks in communities and households with social vulnerabilities, so site-specific microgrid planning, enabling equal development opportunities, integrated with sustainable urban development, is important for emergency preparedness. The need to ensure the availability of critical services for relief, health, and security across microgrids has also led to new approaches for urban-resilient microgrid districting, such as for solar photovoltaics and energy storage.[230]

Highly targeted interventions to preserve safety[231] and grid hardening[232] can also greatly increase network and supply-chain resilience. In the case of a Texas power grid, for example, identifying and protecting critical transmission lines, which represented only 1% of the total, significantly reduced hurricane-induced power outages by a factor of 5–20.[232] The range of solutions[232] to address climate-related hazards in the energy sector (discussed elsewhere[227–229,231]), including undergrounding the distribution network, increasing distributed energy sources, and regional energy grids, can also benefit multiple sectors and systems. Smart grids, supported by artificial intelligence (AI), machine learning (ML), and predictive analytics, are other emerging advances available as part of adaptations to a rapidly changing climate and to building resilience in the energy infrastructure.[233] These technologies can increase the efficiency of predictive maintenance systems, the accuracy of renewable-energy forecasting models, and the robustness of cybersecurity algorithms. In short, they can fundamentally upgrade the capacity to monitor grid operations and respond to climate-induced disruptions in a timely manner. AI/ML tools can also facilitate energy storage optimization and management, thereby optimizing energy distribution, reducing costs, and enhancing energy efficiency while ensuring reliable energy supply in a constantly evolving environment. Advanced analytical and predictive capabilities are also relevant for other sectors while providing efficient resource management.

Frameworks to address the complex nature of cascading impacts are also important.[234,235] For example, the urban heat-island effect[236,237] can exacerbate the impacts of extreme heat events and further strain energy grids.[238] Moreover, the underserved and marginalized communities often require more attention due to vulnerabilities.[239,240] Infrastructure service disruptions, including due to floods, cyclones, and landslides, often affect the most vulnerable disproportionately. Low-income communities already have higher hazard exposure and lower access to services, such as health centers, education facilities, and electricity substations.[241] Policies for protecting lives against the widespread impacts of climate change may include loan provisions to vulnerable households.[242] Co-optimizing urban functions, urban form, urban infrastructure, and networks could support urban areas.[243] Increasing attention is also being paid to nature-based solutions with the potential to reduce some of the climate impacts on critical infrastructure. For example, urban green infrastructure such as vegetation and increased soil cover can reduce local temperatures[244] and mitigate flood risk, exhibiting both social and ecological benefits.[245]

While there is a high level of privatization in many sectors, climate action requires engagement from both private and public sectors, within which perceptions of risks and capabilities for risk assessments can vary.[246] Other examples of targeted interventions in infrastructure span transportation networks, drinking water supply and irrigation, waste management systems, and their interconnections that require greater attention to climate-resilient and decarbonized planning and implementation.[247] As a

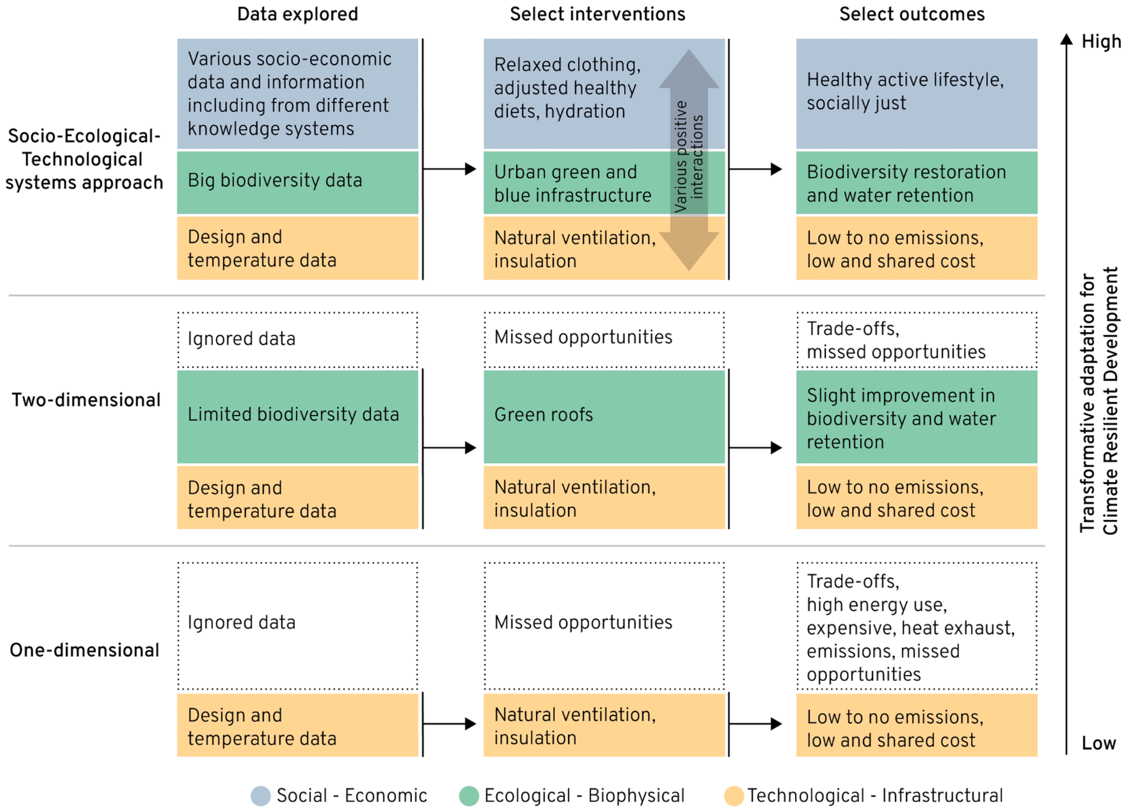

Figure 7. SETS approach to urban heat
Illustrated solutions to urban heat using a SETS approach[254] compared to conventional approaches, to guide planning and integrate policies with co-benefits.

result, these insights can be useful to address cascading disruptions across interconnected networks in critical infrastructure and consider potential solution areas to reduce these risks.

Insight 8: Climate-resilient development in cities

Systems approach to climate-resilient development in cities can help decision makers to identify co-benefits

Cities are home to the majority of the world's population[248] and account for major sources of GHG emissions,[128] biodiversity loss, and degraded ecosystem functions.[249] They often expand into high-risk areas, especially those with informal settlements, where recurring disasters such as floods are enforcing the poverty gap,[250] requiring significant disaster-risk-reduction efforts.[251] These issues are often treated as silos in conventional development models, leading to undesirable trade-offs and injustices.[252]

Research highlights a need to facilitate transitions for climate-resilient development with an open and dynamic SETS approach[253,254] (Figure 7). Climate-resilient development is a process to implement local-level climate action together with developmental and sustainability concerns.[255,256] The SETS framework helps to accommodate different strategies and minimize trade-offs (e.g., inequality and adaptation) that may emerge when isolated or bilateral social, ecological, or technological measures are taken.[253,257] It allows decision makers to integrate social, ecological, and technology measures for climate risk(s). It further allows for an evaluation of co-benefits and trade-offs, for example, among highly competing sectors, such as environmental protection, transportation and housing, as well as subsystems both within cities and cross-boundaries (e.g., with nature-based solutions[258]).

Emerging, rapidly growing, established, and shrinking cities across the globe are facing different challenges from climate-change impacts. Each requires tailored development strategies that reflect their unique development stages and SETS.[259,260] For example, development legacies and current planning decisions exacerbate socio-economic disadvantages.[68,261,262] Cities have recorded higher heat-related deaths and illnesses in minority neighborhoods that contain less greenery,[263–265] yet new green infrastructure can give rise to gentrification, further intensifying inequality in adaptation.[252] Additionally, migration in some rapidly growing cities has drawn poor households to informal settlements in flood-prone areas,[266] and recurrent floods lead to a poverty trap,[250] increasing vulnerability. In shrinking cities, socio-demographic change, such as a declining population, reduces residents' ability to withstand and adapt to shocks.[267] These issues collectively call for caution in addressing the multiple deprivations affecting both society and the environment in cities' resilient development. They urge broader action to mitigate and adapt using innovative institutional strategies to reduce anticipated loss and damage. However, few cities combine mitigation and adaptation in their action plans. Among those that do, most show only a moderate level of integration.[268] Based on data from the Carbon Disclosure Project collected from 776 cities located in 84 different countries, the most frequently identified mitigation actions in cities were building energy-efficiency measures (1,444 actions) and on-site renewable production (644), while the most common actions for adaptation were tree planting (283) and flood mapping.[269] Furthermore, one meta-analysis focused on mitigation found that many interventions were not as effective as planned for,[270] calling for a need to rethink approaches.

To illustrate the effectiveness of the SETS approach, extreme heat is selected as a climate-induced issue. SETS allows for addressing heat without compromising climate-change mitigation, public health, and social justice. While air conditioning is the most common technological solution for heat, it presents drawbacks. Air conditioning creates positive-feedback loops through heat exhaust[271] and is energy intensive, emissions producing, and often unaffordable for many residents.[272] To overcome the limitations of isolated technological interventions like air conditioning, SETS allows for the integration of ecological and social measures. Ecological approaches, such as green and blue infrastructure, can help mitigate the heat-island effect. Social measures, including awareness campaigns and behavioral changes (e.g., promoting natural ventilation, incentivizing passive buildings, and adapting cultural norms like relaxed office dress codes), are equally important.[273] However, individually, ecological or social interventions also have limitations. Behavioral changes alone may have insufficient adaptation potential and could potentially lead to health risks if not properly implemented. Similarly, bilateral approaches that only consider two dimensions of the SETS framework may fall short. For example, while green roofs (ecological) on air-conditioned buildings (technological) can reduce cooling demand, they may not be financially viable for all (socially). Therefore, a comprehensive SETS approach is necessary to address heat effectively. By simultaneously considering and integrating social, ecological, and technological dimensions, planners and policymakers can develop more holistic, sustainable, and equitable solutions to heat challenges. This integrated approach minimizes trade-offs and maximizes co-benefits, ultimately leading to more resilient and livable cities.[257]

The integration of smart solutions and technologies with various conventional social, ecological, and technological systems can help for the adoption of the SETS approach. Decision makers can rely on advancements in information and communication technologies and big-data analytics to develop optimal solutions using SETS. Some cities have experimented with such approaches, such as in Guangzhou, where a systems approach to collaborative decision making showed promising results for nature and human health.[274]

Overall, innovative mechanisms that encompass all components of SETS are better suited to deal with trade-offs and conflicts. In the absence of SETS approaches, adopting non-comprehensive and obsolete frameworks can lead to an oversight of critical emerging issues in the planning process, impeding cities' ability to achieve multiple benefits from climate-action implementation and reducing long-term trade-offs and conflicts.[268] In doing so, cities can move toward climate-resilient development based on transformative decisions.[275] Rapidly growing cities in low- and middle-income countries may need more support to develop such approaches because of a lack of socio-economic capabilities,[276] especially cities classified as high risk or when dealing with informality.

Insight 9: ETM governance

Closing governance gaps in the ETM global value chain is important for a just and equitable energy transition

The transition to clean energy is driving demand for minerals and metals for manufacturing advanced technology-based equipment and machinery. These materials, essential for low-carbon development as well as for meeting economic and national-security objectives, are termed ETMs.[277] Although the criticality of a specific mineral to a particular country may depend on the vulnerability of that country to supply-chain risks and price shocks, the materials essential for the energy transition remain universally important. ETMs include, but are not limited to, cobalt, copper, graphite, lithium, nickel, and some rare-earth elements used for various applications, including battery storage, wind-turbine magnets, and solar-panel technologies.

Mineral demand forecasts show a significant gap between future needs and current reserves. By 2050, lithium demand may surpass 25% of global reserves, reaching 12 times the current production. Cobalt demand could range from 6,000 tonnes to 3.6 million tonnes annually, depending on scenario assumptions, compared to reserves of 8.3 million tonnes.[278] Similarly, global consumption of rare earth elements is expected to increase 5-fold by 2030 compared to 2005 levels, and that demand may exceed global reserves by 2050.[279]

An additional burden is the substantial rise in waste generation posed by the extraction, processing, and disposal of ETMs. Under a business-as-usual scenario, projections indicate that, by 2050, 953 gigatonnes (Gt) of dry waste will be produced just from the extraction of copper, nickel, manganese, and lithium, contributing to 2,000 Gt of global mining waste.[280] Therefore, examining the impacts of the ETM value chain is crucial as it highlights how extraction in resource-rich nations, processing elsewhere, and consumption in different regions contribute to a global distribution of benefits and burdens. With the surge in ETM demand driven by decarbonization initiatives,[281] understanding the value chain is essential for assessing how increased mining activities may strain planetary boundaries and exacerbate existing challenges related to waste management, water scarcity, biodiversity, land use, governance, and social vulnerability.[282]

The value chain refers to the various stages of a product's life cycle, from inception and design, delivery to end-users, and ultimately end-of-life management.[283] In the mining and minerals sector, attention is often centered on extraction, processing, and refining,[284] which are closely tied to economic and technological factors to ensure cost-effective ETM supplies (Figure 8). Given the urgent call to transition to a low-carbon energy system, it is equally important to prioritize factors such as environmental protection, circular economy principles, social justice, and equitable distribution of benefits.[285] The concept of "just energy transition," which encompasses various perspectives, including labor rights, justice, socio-technical aspects, governance, and political dimensions, captures this. Emerging frameworks like planetary just transitions broaden the discussion beyond Western-centric and national approaches, incorporating decolonial perspectives.[286] These approaches are key to addressing the

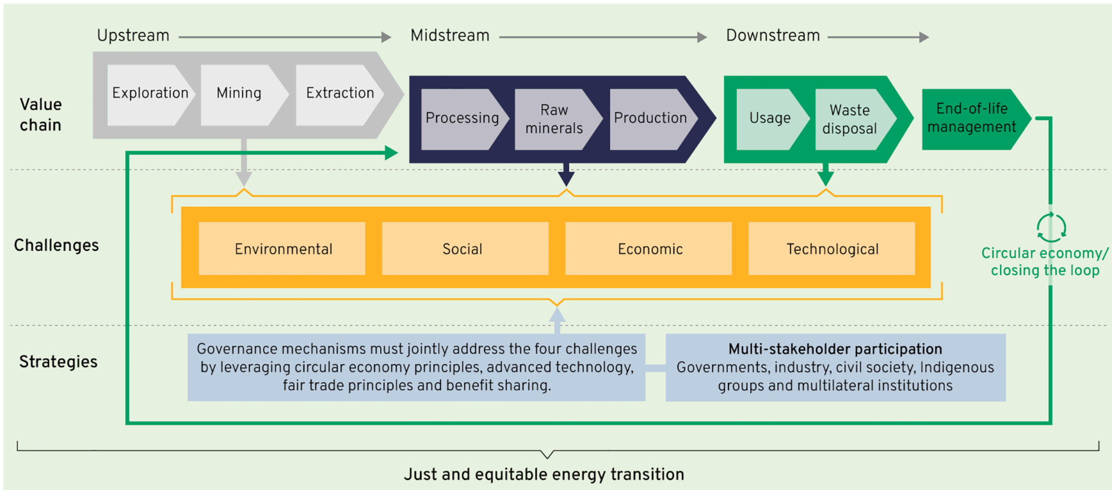

Figure 8. Addressing challenges of ETM value chain to achieve a just and equitable energy transition
The ETM value chain and the challenges different stages present across environmental, social, economic, and technological domains.

multiscalar challenges in value chains and linking them to just-transition[287] discussions. Creating a governance system that balances these elements is essential for ensuring a just transition to a sustainable energy future.

Key concerns surrounding ETM value chains are multifaceted, encompassing trade dynamics in raw materials, processing and refining, end-use application, and end-of-life management. The projected global increase in ETM demand, along with potential supply disruptions and price fluctuations, are shaping new geopolitical dynamics in international relations,[277] such as the emergence of geopolitical trade blocs,[288] and triggering strategic responses from governments, such as offering tax credits, imposing mineral import bans, and forming alliances to preserve supply security. The surge in demand for ETMs is also expected to prompt the expansion of mining operations worldwide, including deep-sea mining.[289] Despite expanding mining operations, a mineral-intensive energy transition could lead to supply risk for some minerals,[290] potentially causing shortages or disruptions. While ensuring resource security and strengthening resource inventories are well within national interests, aligning these with the global goal of a just and equitable energy transition is critical.[291] This is particularly important given the immediate and long-term impacts of the ETM value chain on biodiversity loss, land degradation, water scarcity, pollution, resource depletion, and cultural ecosystems, which require a coordinated approach to mitigate environmental harm and promote sustainable development. For example, mining could impact 50 million km2 of global land, overlapping with 8% of protected areas, 7% of biodiverse regions, and 16% of wilderness areas.[292] Technical challenges related to suboptimal processing and recycling methods could also exacerbate environmental impacts. Addressing these challenges requires not only improved recycling and processing methods but also prioritizing reductions in energy and material consumption, designing technologies with lower material demands, and enhancing the durability and lifespan of components. To this end, policy and regulatory frameworks, beyond market mechanisms, are essential.[286]

These impacts are especially pronounced in Indigenous lands and resource-rich Global South countries, such as Chile, Peru, and Mexico, which together account for 40% of global copper production, and Chile and Argentina, which contribute 35% of the world's lithium production.[293] This can exacerbate socioeconomic disparities and further strain agri-food systems, public health, and local livelihoods. A recent study surveying 5,097 ETM projects found that 54% are located on or near Indigenous peoples' lands, with 29% of these projects on or near lands under Indigenous management or influence for conservation purposes.[294] Additionally, 33% of these projects are located on or near peasant lands, with 69% of ETM projects surveyed being on or near Indigenous people's or peasant land.[294] These host communities, often located in the Global South, may bear a disproportionate burden while enabling others to access resources to advance the energy transition elsewhere.

Another key challenge in the ETM value chain is that, even when many of these minerals are located in the Global South, ownership of operations is largely concentrated in the Global North. For instance, while cobalt mines are predominantly located in the Democratic Republic of Congo (DRC), only less than 5% of production is controlled by DRC-owned companies.[277] This dynamic extends to the production of high-value products (e.g., electric-vehicle batteries) and the final consumption of end-use products, exacerbating geopolitical tensions over securing ETM access and at times leading to the fast-tracking of projects without proper due diligence.[277] A related challenge is promoting equitable benefit sharing to address issues such as limited economic diversification, inadequate technological capacity, and dependence on low-value extractive sectors while ensuring that mineral-rich Global South countries fully benefit from the energy transition.

The rising demand for these minerals is prompting unilateral actions from countries. Mineral stockpiling, especially by Global North countries, while intended to mitigate supply risks, could worsen market constraints, drive up prices, and contribute to an inequitable energy transition.[277] Several Global South

Box 2. Guiding principles on critical ETMs

The UN Secretary-General's Panel on Critical Minerals for the Energy Transition has put forward seven voluntary guiding principles,[302] drawing upon established norms, commitments, and legal obligations outlined in UN documents:

(1) Principle 1: human rights must be at the core of all mineral value chains.
(2) Principle 2: the integrity of the planet, its environment, and biodiversity must be safeguarded.
(3) Principle 3: justice and equity must underpin mineral value chains.
(4) Principle 4: development must be fostered through benefit sharing, value addition, and economic diversification.
(5) Principle 5: investments, finance, and trade must be responsible and fair.
(6) Principle 6: transparency, accountability, and anti-corruption measures are necessary to ensure good governance.
(7) Principle 7: multilateral and international cooperation must underpin global action and promote peace and security.

countries with significant mineral reserves (such as Indonesia, Namibia, and Zimbabwe) are imposing export restrictions and requiring domestic processing to capture more value. In response, Global North actors have turned to multilateral institutions like the World Trade Organization (WTO) to protect their interests by promoting market openness without pushing for reforms that would enable fairer trade and increase value addition in these countries.

Given the differences in regulatory frameworks and market infrastructure between the Global North and Global South, developed nations stand to benefit more from the energy transition, while impacts in the Global South are uncertain. Under current conditions, ensuring a responsible mineral value chain is a central step to minimize unequal benefits from the energy transition. A responsible mineral value chain involves a continuous, people-centered approach that upholds high labor standards; prioritizes well-being; actively engages local communities through all stages; minimizes environmental impacts and resource use; ensures transparency; and addresses environmental, social, and governance (ESG) risks throughout extraction, processing, and distribution.[295,296] Mainstreaming responsible mineral value chains emerges as an important policy step for just energy transition and emission reduction goals.[297] These steps must be complemented by managing demand-side and reduction policies such as promoting technology transfer agreements between the Global North and South, advancing circular economy technologies and practices for ETMs, supporting innovations that minimize mineral use, and fostering research and development (R&D) to develop alternative materials and substitutions enable producer countries to advance their just-transition process and address development challenges.

Despite several initiatives aimed at improving transparency, community participation, and due diligence across the supply chain at multiple levels (e.g., International Council on Mining and Metals, Extractive Industries Transparency Initiative, Initiative for Responsible Mining Assurance, EU Corporate Sustainability Due Diligence Directive, UN Guiding Principles on Business and Human Rights, UN Declaration on the Rights of Indigenous Peoples, UN Declaration on the Rights of Peasants and Other People Working in Rural Areas), comprehensive and coordinated governance mechanisms that effectively balance geopolitical interests, address the security-sustainability nexus,[298] harmonize trade rules and planetary boundaries,[299] and ensure civil society's involvement remain limited.[296] In the context of heightened competition and a geopolitical race to control mineral resources,[279,288] alongside increasing community opposition to mining operations,[277,300] there is an urgent need for governance frameworks that uphold social equity and environmental stewardship, leverage technological innovation across the value chain,[301] and provide long-term, context- and mineral-specific solutions rather than blanket approaches.[281] To improve coordination and advance equity and justice on the road to decarbonization and clean energy, the UN Secretary-General's Panel on Critical Energy Transition Minerals has put forth a set of guiding principles (Box 2).[302]

Governance mechanisms across the ETM value chain must be people centered, proactively addressing environmental, social, economic, and technological risks throughout the value chain—from extraction in the DRC, processing in China or Indonesia, and electrical vehicle use in the US. Such mechanisms should prioritize international collaboration and a circular economy,[279] by integrating transformative circularity measures that involve steps such as significantly reducing demand, incorporating durable designs and component reuse, and implementing efficient recycling processes, countering the tendency of national interest policies, such as domestic mining encouragement and friend-shoring, which often lead to unjust and inequitable energy transitions.[303] The responsible mineral value chain underscores the need for ethical sourcing, transparency, and traceability from extraction to end-use to ensure that the energy transition benefits are maximized globally.

Insight 10: Resistance and acceptance of climate policy

Public's acceptance of (or resistance to) climate policies crucially depends on perceptions of fairness

A successful climate transition, including instruments targeting private consumption of fossil fuels and local-level climate adaptation, cannot be achieved through top-down implementation. Policies must mirror the values and sentiments of the populace, both from a normative (democratic) perspective and from a pragmatic one, to allow the adoption of climate policy instruments. In some cases, lack of public support can trigger violent political opposition, social mobilization, and civil unrest. Examples include the Yellow Vests in France, 2024 European farmer's protests, and "quiet" resistance by disadvantaged populations worldwide.[304] Failure to understand resistance, including its agents, motives, repertoires, and consequences, may hamper urgent climate action. Moreover, the political costs associated with introducing or advocating climate policy initiatives without public support can be considerable for politicians. Certain political parties have also been fueling and shaping public opinion for

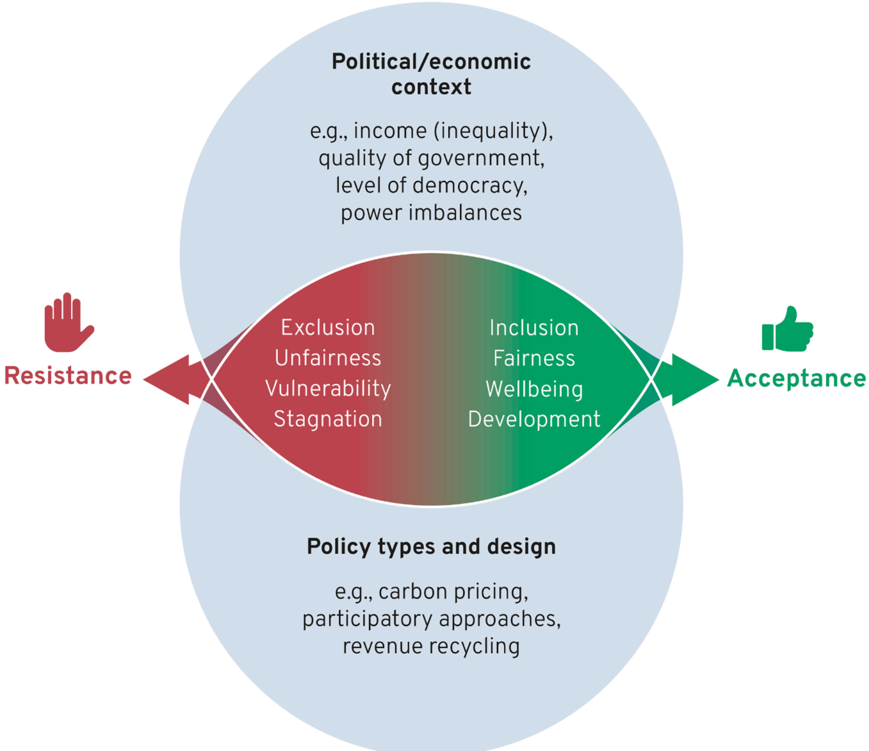

Figure 9. Interaction factors leading to climate policy resistance or acceptance
The interaction between political-economic contexts and policy designs can either lead to exclusion, injustice, and vulnerability—resulting in popular resistance—or to inclusion, fairness, and development—resulting in popular acceptance.

a backlash against climate politics to align with perceived sentiments in the general public.[305,306]

Diverse evidence on climate acceptance and resistance has allowed for the advancement of knowledge and new theory building. Resistance to climate policies is influenced by various societal conditions, including individual beliefs, social norms, cultural identities, and economic conditions.[304] Considerations of cultural factors should also include country-specific political-economic factors, which are crucial elements for the success of climate policies.[307] Across this evidence, the issue of (un)fairness emerges as a central determinant of acceptance and resistance (Figure 9). A recent meta-analysis of climate instruments found that perceptions about the fairness implications of policies were the strongest determinants among 15 individual-level factors.[308] Resistance can stem from a perceived unfair distribution of economic costs, job insecurity, cultural identity, and social justice concerns resulting from climate policy,[309] but also be based on perceived unfair procedures: that decisions are taken "from above" and that citizens or affected groups are excluded and do not have a fair possibility to voice their concerns or have a say in the policy process.[310] Resistance can also come from discourses of climate delays that argue about the negative social impacts of climate policies.[311]

Hence, both distributional aspects of specific policy instruments and the procedural elements of policy adoption are important for acceptability and resistance formation. In the energy sector, for example, establishing transition areas as collaborative spaces that promote stakeholder involvement, transparency, and public trust, while addressing social, political, and economic challenges, particularly in coal-dependent communities, and fostering adaptability and gender equality, is essential for achieving socially supported, inclusive, and sustainable energy transitions.[312] Public support for low-carbon energy transitions requires addressing broader social factors, such as combating corruption and ensuring fair practices through appropriate laws. For instance, introducing carbon taxes or removing subsidies on fossil fuels appears to generate a similar level of public resistance.[313] However, earmarking revenues or public savings increases acceptability by offsetting impacts perceived as unfair with targeted investments in well-being, reducing inequality and alleviating poverty—so-called revenue recycling. Some research suggests that people prefer revenues from carbon pricing to be spent on environmental measures,[314] while other recent studies conducted in the Global South support cash transfers to poor or vulnerable groups[315] and investments in social programmes.[316]

People's perceptions of fairness vary, including concerns about higher fuel prices, freedom, and living standards, affecting not only vulnerable groups.[317] Additionally, fairness beliefs encompass the recognition of wrongdoing by countries and industries that continue to harm the environment: justice cannot be achieved unless they take responsibility. Regarding procedural and distributional aspects, resistance can shed light on marginalized groups' overlooked needs and aspirations. In a recent review of resistance to climate adaptation plans or interventions, people's motives for resistance uncovered stories about local needs and aspirations often overlooked in UN political and scientific climate debates.[309] Examples include relocation programs from risk zones that do not consider people's social networks or livelihoods. The climate transition will impose short-term costs on particular groups, making them more vulnerable and requiring a balance between specific workers (e.g., farmers and truck drivers) and the common good.

Understanding how to pursue fairness in climate policies requires adopting new analytical lenses. Research has repeatedly shown that what works in one region may not be applicable in another; however, there are emerging traits. While people may oppose a new climate law or policy, their resistance is often culturally learned, historically entangled, and linked to issues beyond climate policies, such as lack of trust in the state.[304] Citizens who lack political power can adopt quiet resistance, such as false compliance or foot dragging, to undermine policies that they consider illegitimate or unresponsive to local needs.[309] Across countries, concerns about distribution and income inequality affect public support for policies that require the population to bear the economic costs, such as carbon taxes.[315] However, standard macro- and microeconomic analysis methods need to be complemented with the mesoeconomic analyses of sectors[309,318] and social groups.[319] The ability to design policies that consider the interests of influential social and industrial groups is key to reconciling the success of climate policies with their fairness. For example, the successful lobbying activity by the auto and motorcyclist lobbies in Indonesia played a decisive role in protests to stop fuel-subsidy withdrawal at various stages in the last two decades. Fishermen and farmers repeatedly took similar actions in Ghana to obtain an exemption from the subsidy withdrawal on kerosene, while labor unions advocated for exemptions on public-transport fare increases.[307]

Maintaining a balance between specific and general interests within countries has proved increasingly difficult in recent years. Previous national reforms, such as liberalization and privatization, as well as the degree of integration into the global economy, in some countries have increased inequality and exposed several social groups to deteriorated life conditions. These have led to weak social-security nets, job instability, increasing living costs, deterioration of public-service quality, and political underrepresentation.[307]

The underrepresentation of women in decision making and the prevalence of gender-blind energy policies, coupled with cultural norms that limit women's participation, lead to women's roles and opposition in energy transitions being overlooked. This highlights the need for more inclusive, gender-sensitive approaches and more research on women's resistance to low-carbon energy transitions.[312] Compared to mitigation, the discussion on resistance is much more nascent regarding adaptation, which has been seen mainly as an apolitical approach, hiding the winners and losers of adaptation processes.[304,319,320] There are also perception gaps: studies have highlighted widespread public support for climate action, with nearly 70% of respondents from a large-scale global study willing to allocate 1% of their income and almost 90% desiring increased government efforts, but they often underestimate their fellow citizens' willingness to contribute.[321] Failure to understand the broad spectrum between acceptance and resistance, and conflating opposition to negative consequences of climate policy with climate "denial," neglects that diverse groups of people are ready to embrace radical change if it is perceived as fair.[322]

Overcoming resistance requires inclusive, democratic processes and bottom-up approaches that involve local communities and authorities in decision making.[309,312] Climate policies must be tailored to societal conditions, addressing social norms, cultural identities, and economic factors. Their success depends on the policymakers' ability to maintain a balance among social and industrial interests while at the same time considering specific socio-economic fragilities that often derive from previous economic and political reforms.[307] However, not all resistance should be overcome, as it can represent an alternative form of political participation.[309] One viable perspective is to recognize and utilize resistance as a means to highlight and debate potentially overlooked needs in society, particularly those of marginalized and vulnerable groups. Consequently, efforts to understand, debate, and address resistance can significantly contribute to more effective and tailored climate policymaking. Without considering everyday citizens' needs, resistance will continue to hinder transformative climate laws and policies. There are today a number of innovative solutions to this, with, for example, (climate) citizen assemblies, and there is an ongoing academic and political debate on whether that increases legitimacy and improves democracy (see, for example, Wells et al.[323]).

DISCUSSION

The pressing nature of the decisions facing policymakers in the context of climate change calls for regular and accessible syntheses of climate-change research. However, the rapid expansion and diversification of climate-related peer-reviewed literature makes this increasingly challenging. While the IPCC assessments are the cornerstone of the science-policy interface, their 6- to 7-year period between the assessment cycles and the consensus-based approach necessarily limits the possibility of reflecting emerging research. Annual reports from UN agencies and international organizations provide important updates on climate indicators but are intended to reflect recent scientific advances. Academic reviews, while plentiful and varied, tend to be inaccessible for non-experts. The 10 New Insights in Climate Science series aims to address this gap by leveraging a bottom-up approach to elicit expert views across global research networks on recent research developments. A diverse group of leading researchers then prioritizes a set of 10 advances or insights, which are then synthesized by topic experts. In this section, we discuss the most salient policy implications of this year's insights, focused on the ongoing international negotiations. We conclude with a reflection on the 10 New Insights in Climate Change initiative in the broader science-policy context.

Policy implications

Comprehensive mitigation

Recent trends in emissions and atmospheric concentration of methane and aerosols have important implications for the goals of the Paris Agreement. First, the surge in atmospheric methane levels, tracking warming scenarios of 3°C or more,[54] underscores the urgent need for more stringent and enforceable methane reduction policies (Insight 1). This steady rise further shrinks the remaining carbon budget consistent with the Paris Agreement.[76] An implication toward the extended September deadline for new NDCs, ahead of COP30, is the priority of formalizing explicit, quantifiable methane-reduction targets, supported by mechanisms to assist countries in developing and implementing adequate strategies. While readily available mitigation measures exist for the fossil fuel and waste-management sectors, solutions for the agricultural sector require further development.[71,72]

Second, the declining aerosol loading in certain regions[80] presents complex challenges for near-term climate-change mitigation and adaptation (Insight 2). Although the reduction of anthropogenic aerosol emissions has been hugely beneficial for public health, it has also de-masked the true level of warming caused by accumulated anthropogenic GHG emissions.[90,96] This indicates the need for a more comprehensive approach to climate action planning that considers multiple pollutants and their interactions.[80] The UNFCCC, SBSTA, and delegations at COP30 could consider establishing a specialized task force to provide recommendations for integrating aerosol considerations into future NDCs, ensuring that climate risk assessments and adaptation strategies account for the regionally -differentiated impacts on temperature, precipitation, and extreme weather events. Addressing these issues is important for enabling countries to develop comprehensive mitigation strategies and adaptation plans that address the complex interplay between different climate forcers and their varied impacts across regions. These considerations are likely to be reflected in the Methodology Report on Short-lived Climate Forcers expected in 2027 as part of the IPCC AR7. In the meantime, it is important to advance the development of institutional infrastructure and ensure the adequate financial and technical support.

Adaptation to heat extremes

In the context of a series of record-heat months through 2023 and 2024, we highlight that hundreds of millions of people are already living in areas outside the historical conditions of temperature and humidity better suited for human physiology,[123] making heat-adaptation planning a top priority, especially for lower-income tropical countries (Insight 3). Specific provisions for vulnerable groups, such as pregnant women and newborns facing heightened risks from heat extremes,[116,154] should be incorporated into adaptation strategies (Insight 4). Unless comprehensive adaptation plans are implemented, there is a serious risk of reversing the progress made in MRH over the recent decades. Beyond direct impacts on human health, we also highlight economy-wide costs of heat extremes associated with ENSO, estimated in trillions of US dollars.[174,175] Considering the potential intensification of ENSO due to climate change,[188,324] this research underscores the inadequacy of current adaptation measures (Insight 5). This further emphasizes the importance of concrete financial commitments for adaptation in the Global South, beyond the formal NCQG agreed at COP29. The Framework for Global Climate Resilience (FGCR) should incorporate specific targets and indicators related to extreme-heat preparedness and emphasize the importance of heat action plans (HAPs) and early-warning systems (EWSs). The Early Warnings for All Initiative (co-led by the UN Office for Disaster Risk Reduction [UNDRR] and WMO) needs broad support to fulfill its goal of full global coverage by 2027.

Extreme heat and other climate-related hazards also underscore the urgency of addressing the vulnerability of critical infrastructure to prevent cascading failures that could cause social and economic disruption (Insight 7). The Global Methodology for Infrastructure Resilience Review, launched at COP28 by the UNDRR) offers a holistic approach for countries to assess their current state and identifying areas for improvement. Enhancing resilience of interconnected critical infrastructure systems is closely related to climate-resilient development in the context of urbanization. Cities are central nodes for climate action, as major drivers of emissions to be mitigated and as hosts of an increasing share of the population in need of adaptation. The heat-island effect further exacerbates the risks of heat stress and places additional strain on energy grids.[227,238] Few cities currently have integrated approaches to mitigation and adaptation, but systemic approaches can offer guidance for synergistic measures (Insight 8). Adopting a SETS approach[254,257] for urban climate resilience is aligned with and can help support the COP29 Presidency's Multisectoral Action Pathways (MAP) Declaration for Resilient and Healthy Cities.

Earth system stability

Following important commitments and declarations at COP26 (Glasgow, UK) and COP28 (Dubai, UAE), forests have consistently gained prominence in the climate agenda. Ahead of COP30 (Belém), Brazil has proposed the development of a Tropical Forest Forever Fund (TFFF), aiming to mobilize US$250 billion annually for tropical forest conservation. Moreover, the host of UN Biodiversity COP16 (Cali, Colombia) emphasized a synergistic agenda for climate and biodiversity, further giving momentum to international efforts to protect and restore forests. Brazil aims to have a fully operational facility for the TFFF on time for COP30. Recent research highlights the crucial role of functional and response diversity, as well as biocultural diversity, to enhance the resilience of Amazon forests to climate change[204,206] (Insight 6). Additionally, studies suggest a growing risk of Amazon forests nearing critical thresholds and facing potential large-scale collapse.[195,200,201] Similar concerns are raised by recent publications about the weakening, and even potential collapse, of the AMOC[177,178] (Insight 5). While much uncertainty remains regarding the likelihood and relevant timescale of these phenomena, these two cases underscore the need for rapid and deep reductions to GHG emissions to safeguard critical Earth system processes. Clear strides toward closing the gap between the *formal* NCQG on climate finance of $300 billion annually by 2035 and the *aspirational* goal to mobilize more than $1 trillion will be necessary for enabling more transformative action leading up to COP30.

Just transition

The first Global Stocktake, concluded at COP28, includes an important agreed-upon global goal to triple renewable energy capacity. The transition away from fossil fuels in the energy sector comes hand in hand with a rise in demand for ETMs,[278] further bringing to the fore challenges of geopolitical tensions and supply-chain risks, as well as socio-environmental impacts in the Global South (Insight 9).[288,290,294] The UN Secretary-General's Panel on Critical Energy Transition Minerals,[302] launched in April 2024, underscores these concerns and priorities for closing governance gaps in the ETM value chain, including through harmonizing regulations and developing binding agreements that prevent regulatory arbitrage. Benefit sharing across the entire value chain is an international dimension of the just transition that deserves explicit attention in the Just Transition Work Programme (JTWP) framework. Fairness is also crucial at the national and subnational levels, as the perceived fairness or unfairness of climate policies, and of the socio-economic context in which they are implemented, significantly impacts public acceptance of climate policies[308] (Insight 10). Disregarding citizens' needs or failing to understand their motives can deepen resistance, ultimately obstructing effective climate action.

This year's 10 New Insights in Climate Science report[49] elaborates on the points above. It was distributed to all party delegations ahead of COP29 with the aim of informing negotiators' positions and arguments. We hope that the implications of the science advances that the report highlights can also inform the delegations' work toward COP30 in Belém, Brazil.

Contributions to the science-policy interface: Looking forward

The 10 New Insights in Climate Science initiative aims to be an effective conduit for "knowledge brokerage,"[17] contributing to richer exchanges of information and ideas between climate researchers and policymakers. The science-policy report, based on this review paper, fulfills this intermediary function[46,48]: prepared by researchers but tailored specifically for policymakers and negotiators, it provides concise and accessible summaries and is disseminated through a targeted strategy, primarily to UNFCCC party delegations. From the researchers' perspective, traditional barriers to such intermediary work include a lack of dedicated institutional resources and limited professional recognition.[325] The 10 New Insights initiative provides a channel to overcome some of these barriers, providing the role of coordination and overall project management driving the development of this peer-reviewed paper and the science-policy report, as well as functions of communication and policy engagement.

Our vision for the 10 New Insights is to continue building institutional capacities and networks toward a bi-directional mechanism of knowledge brokerage at the science-policy interface. This approach transcends the linear view of science-policy interactions, where knowledge flows solely from researchers to policymakers. Instead, we envision a mechanism that enables researchers to improve their understanding of the policymakers' and negotiators' priorities, time frames, and key information needs.[17,326] In practice, this could be implemented through roundtable dialogues at global, regional, and national levels.[327–329] As the initiative grows to include these spaces of collaboration and knowledge co-production,[17,326] we anticipate additional challenges in maintaining scientific integrity. Specific measures will be needed to prevent oversimplification and biased use of evidence.[330,331] We will also aim to enhance transparency about our methodological approach to synthesis, providing descriptions of remaining uncertainties and scientific disputes.[17]

This vision is the result of continuous self-reflection on the role of the 10 New Insights initiative within the broader climate-change science policy, shaped by stakeholder dialogues over the last 2 years. Ultimately, we aspire to contribute to this landscape not just through annual reports but by fostering trusted networks of scientists and policymakers across the world.

METHODS

Input collection and selection process

Every cycle of the 10 New Insights in Climate Science incorporates lessons from the previous year, resulting in a progressively more robust process for the selection and development of insights. The process (see Note S1) described below builds directly on the one described by Bustamante et al.[68] Around mid-January, an open call for expert input is distributed as an online questionnaire (see Note S2), primarily across the partners' (Future Earth, The Earth League and World Climate Research Programme) global-reaching institutional networks. The main question that respondents answer is "What key recent advance in climate-change research do you think should be highlighted for policymakers?" Respondents are also asked to provide references of recent peer-reviewed publications (i.e., 2023 or 2024) that support their suggested key research advance.

The call for expert input was open between January 15 and February 10, 2024 (4 weeks), and received responses from 188 individuals(see Note S3), totaling 216 suggestions. The suggestions or "entries" collected were screened based on predefined inclusion/exclusion criteria; at least two team members screened each entry (see Note S4). When necessary, project coordinators conducted one additional round of screening to come to a final decision. This year, 84 entries met the inclusion criteria. After merging the closely related entries, the list was reduced to 43 themes and coded using a thematic framework based on all previous 10 New Insights reports. This list was complemented with a literature scan (see Note S5) of impactful papers in climate-change research published in the same period (2023 and the first months of 2024), which yielded 19 additional themes.

The final list of 63 themes (see Note S6) was then evaluated in a three-stage process by our editorial board, consisting of 17 well-established international climate-change researchers from various disciplines, who constitute our editorial board. First, the 63 themes were categorized into four broad categories: (1) the Earth system, (2) impacts, (3) action needed, and (4) barriers. The editorial board members then individually prioritized 4–20 themes (1–4 per category) that they considered most relevant overall. Second, building on the outcomes of the individual prioritization of themes, the editorial board members gathered virtually for a workshop to deliberate and collectively prioritize the themes, leading to a preliminary set of candidate insights.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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