Ten New Insights in Climate Science 2024

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Author list and affiliations

Roberto Schaeffer[1], E. Lisa F. Schipper[2], Daniel Ospina[3,87,*] Paula Mirazo[4,**] Ane Alencar[5], Mehrnaz Anvari[6,7], Paulo Artaxo[8], Mehmet Efe Biresselioglu[9], Tanja Blome[10], Melanie Boeckmann[11], Ebba Brink[12], Wendy Broadgate[3], Mercedes Bustamante[13], Wenju Cai[14, 15], Josep G. Canadell[16], Roberto Cardinale[17], Maria Paz Chidichimo[18,19], Peter Ditlevsen[20], Ursula Eicker[21], Sarah Feron[22], Mahelet G. Fikru[23], Sabine Fuss[24,25], Amadou T. Gaye[26], Örjan Gustafsson[27], Niklas Harring[28], Cheng He[29], Sophie Hebden[3,30], Adrian Heilemann[7], Marina Hirota[31], Nandakumar Janardhanan[32], Sirkku Juhola[33], Tae Yong Jung[34], Jiang Kejun[35], Şiir Kilkiş[36], Nilushi Kumarasinghe[37, 38], David Lapola[39], June-Yi Lee[40,41], Carolina Levis[42,43], Adelaide Lusambili[44], Joannes D. Maasakkers[45], Claire MacIntosh[46], Jemilah Mahmood[47], Justin S. Mankin[48,49], Pía Marchegiani[50,51], Maria Martin[7], Aditi Mukherji[52], Tischa A. Muñoz-Erickson[53], Zeenat Niazi[54, 55], Joseph Nyangon[56], Santosh Pandipati[57], Amarasinghage T.D. Perera[58], Geeta Persad[59], Åsa Persson[60,61], Aaron Redman[4,62], Ilona Riipinen[27], Johan Rockström[7,63], Sarah Roffe[64,65,66], Joyashree Roy[67], Boris Sakschewski[7], Bjørn H. Samset[68], Peter Schlosser[4], Ayyoob Sharifi[69], Wan-Yu Shih[70], Giles B. Sioen[71,72], Youba Sokona[73], Detlef Stammer[74], Sunhee Suk[72,75], Djiby Thiam[76], Vikki Thompson[77], Erin Tullos[78], René M. van Westen[79], Ana Maria Vargas Falla[12], Daniel J. Vecellio[80], John Worden[81], Henry C. Wu[10], Chi Xu[82, 83], Yang Yang[84], Mariam Zachariah[85], Zhen Zhang[86], and Gina Ziervogel[77]

[1] Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
[2] University of Bonn, Bonn, Germany
[3] Future Earth Secretariat, Stockholm, Sweden
[4] Julie Ann Wrigley Global Futures Laboratory, Arizona State University, Tempe, AZ, USA
[5] Amazon Environmental Research Institute (IPAM), Brasilia, Brazil
[6] Fraunhofer Institute for Algorithms and Scientific Computing SCAI, St. Augustin, Germany
[7] Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
[8] University of Sao Paulo, Sao Paulo, Brazil
[9] Sustainable Energy Division, İzmir University of Economics, İzmir, Turkey
[10] Climate Service Center Germany (GERICS), Helmholtz-Zentrum hereon, Hamburg, Germany
[11] University of Bremen, Bremen, Germany
[12] Lund University Centre for Sustainability Science (LUCSUS), Lund, Sweden
[13] University of Brasilia, Brasilia, Brazil
[14] Physical Oceanography Laboratory/Frontiers Science Center for Deep Ocean Multispheres and Earth System/Sanya Oceanographic Institution, Ocean University of China, Qingdao, China
[15] State Key Laboratory of Marine Environmental Science & College of Ocean and Earth Sciences, Xiamen University, Xiamen, China
[16] CSIRO Environment, Canberra, Australia
[17] Bartlett School of Sustainable Construction, University College London, London, UK
[18] National Scientific and Technical Research Council (CONICET), Buenos Aires, Argentina

[19]School of Habitat and Sustainability, National University of San Martin, Buenos Aires, Argentina
[20]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[21]Concordia University, Montreal, Canada
[22]University of Groningen, Groningen, Netherlands
[23]Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science and Technology, Rolla, MO, USA
[24]Mercator Research Institute on Global Commons and Climate Change (MCC), Berlin, Germany
[25]Humboldt-University of Berlin, Berlin, Germany
[26]Cheikh Anta Diop University, Dakar, Senegal
[27]Stockholm University, Stockholm, Sweden
[28]Department of Political Science, University of Gothenburg, Gothenburg, Sweden
[29]Institute of Epidemiology, Helmholtz Zentrum München—German Research Center for Environmental Health (GmbH), Neuherberg, Germany
[30]ESA ECSAT, Harwell Science & Innovation Campus, Oxfordshire, UK
[31]Group IpES, Federal University of Santa Catarina, Florianopolis, Brazil
[32]Institute for Global Environmental Strategies (IGES), Hayama, Japan
[33]Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland
[34]Yonsei University Graduate School of International Studies, Seoul, Republic of Korea
[35]Chinese Academy of Macroeconomic Research, Beijing, China
[36]Scientific and Technological Research Council of Turkey (TÜBİTAK), Ankara, Turkey
[37]Future Earth Secretariat Canada Hub, Montreal, Canada
[38]Sustainability in the Digital Age, Montreal, Canada
[39]State University of Campinas - UNICAMP, Campinas, Brazil
[40]Research Center for Climate Sciences, Pusan National University, Busan, Republic of Korea
[41]Center for Climate Physics, Institute for Basic Science, Busan, Republic of Korea
[42]Graduate Program in Ecology, Federal University of Santa Catarina, Florianópolis, Brazil
[43]Brazil LAB, Princeton University, Princeton, NJ, USA
[44]Africa International University, Nairobi, Kenya
[45]SRON Netherlands Institute for Space Research, Leiden, Netherlands
[46]European Space Agency (ESA) - European Centre for Space Applications and Telecommunications (ECSAT), Oxford, UK
[47]Sunway Centre for Planetary Health, Kuala Lumpur, Malaysia
[48]Department of Geography, Dartmouth College, Hanover, NH, USA
[49]Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA
[50]Facultad Latinoamericana de Ciencias Sociales (FLACSO), Buenos Aires, Argentina
[51]Environment and Natural Resources Foundation (FARN), Buenos Aires, Argentina
[52]CGIAR, Kolkata, India
[53]USDA Forest Service, International Institute of Tropical Forestry, San Juan, Puerto Rico, USA
[54]TERI School of Advanced Studies, New Delhi, India
[55]Society for Development Alternatives, New Delhi, India
[56]US Department of Energy, Washington, D.C., USA
[57]Lōvu Health, USA
[58]Princeton University, Princeton, NJ, USA
[59]The University of Texas at Austin, Austin, TX, USA

[60]Stockholm Environment Institute, Stockholm, Sweden
[61]Department of Thematic Studies, Linköping University, Linköping, Sweden
[62]Monitoring and Evaluating Climate Communication and Education Project (MECCE), Canada
[63]University of Potsdam, Potsdam, Germany
[64]Agrometeorology Division, Agricultural Research Council – Natural Resources and Engineering, Pretoria, South Africa
[65]Department of Geography, University of the Free State, Bloemfontein, South Africa
[66]Global Change Institute, University of the Witwatersrand, Johannesburg, South Africa
[67]Asian Institute of Technology, Pathum Thani, Thailand
[68]CICERO Center for International Climate Research, Oslo, Norway
[69]Hiroshima University, Higashi-Hiroshima, Japan
[70]National Taiwan University, Taipei, Taiwan
[71]Sustainable Society Design Center, Graduate School of Frontier Science, University of Tokyo, Kashiwa-no-ha, Japan
[72]Future Earth Secretariat, Tsukuba, Japan
[73]African Climate Policy Centre, Bamako, Mali
[74]University of Hamburg, Hamburg, Germany
[75]Nagasaki University, Nagasaki, Japan
[76]University of Cape Town, Cape Town, South Africa
[77]Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands
[78]University of Texas at Austin, Austin, TX, USA
[79]Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, Netherlands
[80]Virginia Climate Center, George Mason University, Fairfax, VA, USA
[81]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[82]School of Life Sciences, Nanjing University, Nanjing, China
[83]Breeding Base for State Key Lab. of Land Degradation and Ecological Restoration in northwestern China/Key Lab. of Restoration and Reconstruction of Degraded Ecosystems in northwestern China of Ministry of Education, Ningxia University, Yinchuan, Ningxia 750021, China
[84]School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, China
[85] Imperial College London, London, UK
[86]Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China
[87]Lead contact: daniel.ospina@futureearth.org

*Correspondence: daniel.ospina@futureearth.org
**Correspondence: paula.mirazo@asu.edu

Ten New Insights in Climate Science 2024

Summary

Climate change research is broad, diverse and constantly growing. Cross- and interdisciplinary understanding is essential for generating robust science advice for policy. However, it is challenging to prioritise and navigate the ever-expanding peer-reviewed literature. To address this, we gathered input from experts across various research fields through an online questionnaire and prioritised a set of 10 key research advances with high policy relevance. This year, we focus on: (1) Declining aerosol emissions, (2) soaring methane emissions, (3) concerning ocean dynamics, (4) diversity and resilience of Amazon forests, (5) expanding risk of “uninhabitability”, (6) climate impacts to maternal and reproductive health, (7) climate-resilient development for cities, (8) vulnerability of critical infrastructure, (9) governance of the energy transition minerals value chain, and (10) public acceptance of climate policies. This science synthesis and science communication effort is also the basis for a policy report which aims to elevate climate science every year ahead of the UN Climate Summit.

Introduction

Tens of thousands of papers were published in 2023 on the broad topic of climate change. This literature is not only voluminous but also very diverse, spanning multiple disciplines and interdisciplines across the natural and social sciences; covering phenomena ranging from the geophysical to ecological, and from the technological to economic, political and cultural, and of course, the connections between them. Political and societal actions to confront climate change ought to be informed by the advances of research in all of these intersecting dimensions. More specifically, robust science advice to policymakers on climate change requires a high degree of cross- and interdisciplinary understanding. However, it is challenging for individual researchers to stay informed about developments in fields beyond their own. This review is a contribution to improve cross- and interdisciplinary understanding in climate change research. We present ten succinct pieces on priority topics, ten ‘Insights’, each prepared by a team of experts and written for a broader academic audience.

The Intergovernmental Panel on Climate Change (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 synthesising it for the benefit of society at large. The seventh assessment cycle of the IPCC began this year, with bureau meetings and an open call for nominations of experts for the scoping meeting to draft the outline of the Seventh Assessment Report (AR7). The AR7 Working Group reports are expected to be published between 2027 and 2029, at the earliest. Given the thematic breadth and procedural demands of these assessments, this timeline is a remarkable collective achievement. Yet, there is a concern that during the years in between IPCC cycles, climate change research features less prominently in public debate. Moreover, while science advances every year, new findings and their policy implications often remain ‘hidden’ in the academic literature, obscure and inaccessible to negotiators in multilateral fora and to policymakers, who are not always resourced to sift through the ever-increasing flow of peer-reviewed publications. The Insights presented in this review are also used as the foundation for a policy report which aims to contribute to closing these gaps. The report serves as a tool for policymakers and party delegations at the United Nations Framework Convention on Climate Change (UNFCCC) process to stay up-to-date and grounded in the latest peer-reviewed research, highlighting the links between these recent scientific advances and the ongoing negotiations and policy debates. The report also aims to elevate the voice of a diverse community of climate scientists ahead of and during the UNFCCC Conference of the Parties (COP).

Over the past eight years the ‘10 New Insights’ team has refined a process to collect expert input from across global research networks, and prioritise a small set of key advances in climate change research with high policy relevance (see Methods section). 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 addressing it. 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).

Before introducing the 2024 Insights, it is worth reflecting on the extraordinary observations of the climate in 2023. Surface temperature in land and ocean surpassed previous records by a significant margin (C3S, 2024; WMO, 2024). The year was characterised by multiple and prolonged heatwaves, with many parts of the world facing at least 20 additional heatwave days, compared to the previous three-decade average (Perkins-Kirkpatrick et al., 2024). Several other records were broken, including highest ocean heat content, lowest Antarctic sea-ice extent, and highest global average sea level rise (C3S, 2024; WMO, 2024). Amidst these concerning observations of the climate system, atmospheric concentration of the main greenhouse gases (GHG) continue their steady increase in 2023. In this regard, 2023 was *not* extraordinary: While the 2023 GHG emission increases were not as sharp as those observed in the immediate post-pandemic recovery years, yet the steep trend of the past decade continues(NOAA-GML, 2024). According to the most recent analysis of the Climate Action Tracker (2023), there is a significant “target gap” of 19–22 $GtCO_2e$ between the emission levels projected for 2030 by the nationally determined contributions (NDCs, as of December 2023) and the benchmark emissions for a 1.5°C compatible pathway. The “implementation gap”, i.e. between current policies and action relative to the 1.5° compatible benchmark, is even larger: 24-27 $GtCO_2e$. Both of these gaps suggest end-of-century median warming estimates that are well *above* 2°C of warming above pre-industrial levels. The first Global Stocktake (GST), completed at COP28, provides a frame for the next round of NDCs to be aligned with limiting global warming to 1.5 °C (UNFCCC, 2023). New NDCs should be submitted by all parties by February 2025, the latest.

This year, the first two Insights focus on atmospheric emissions that play a crucial role in global warming and, therefore, must be well understood and monitored. Specifically, we highlight recent advances in understanding the climate effects of reductions in anthropogenic aerosol loadings in recent decades (Insight 1), and the recent rise in methane emissions and its likely sources (Insight 2).

Next, we address growing concerns about major components of the Earth system: the Amazon forests (Insight 3) and large-scale ocean-climate processes (Insight 4). Then, four Insights address direct impacts on human societies: The expanding geographical extent of hot-humid conditions threatening lives and livelihoods (Insight 5), the growing awareness of climate change impacts on maternal and reproductive health (Insight 6), the challenges and options for cities to advance climate-resilient development (Insight 7), and the closely related issue of critical infrastructure vulnerability (Insight 8). We then zoom into ‘energy transition minerals’, specifically the existing governance gaps and challenges across value chains. Finally, we feature the latest understanding of factors underpinning social acceptance of, and resistance to, climate policy for mitigation and adaptation (Insight 10).

Insight 1. Decline of aerosol emissions over recent decades is complicating climate change

Atmospheric aerosols, minute particles suspended in the air, and major components of air pollution worldwide, are harmful to the environment, ecosystems, and human health. Air pollution, caused by road traffic, domestic and commercial energy generation, natural and managed fires, and a range of other sources, is considered to be the world's largest environmental health threat, accounting for around seven million deaths around the world every year(UNEP, 2021). Moreover, aerosols from both natural and anthropogenic sources have an important impact on global and regional climate. Broadly, greenhouse gases (GHGs) have warmed the climate over the industrial era, and increased global precipitation, while aerosols have had a cooling and drying effect. However, unlike GHGs, aerosols are short-lived climate forcers and, due to the variety of emission types, physical and chemical properties, interactions and reactivities, they affect climate through different pathways and with different efficacies than GHG. To further add complexity, aerosol emissions, properties, and climate effects are heterogeneously distributed across regions and time-evolving [Figure 1]. Thus, they are one of the largest sources of uncertainty in the climate system (IPCC, 2021, chap. 6; Mahowald et al., 2024). The net effect of aerosols on global climate over the historical era is cooling (IPCC, 2021, chap. 7), thereby partly "masking" anthropogenic warming from GHG.

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 successfully improved air quality in many regions of the world. Concurrently, many studies have documented a recent step-up in the rate of global warming (Samset et al., 12 2023), and, recently, aerosol cleanup has been implicated as a contributing factor (Hodnebrog et al., 12 2024). Associated with air quality and climate policies, strong trends in aerosol emissions will continue, influencing climate in the near future (Wang et al., 12 2023). 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 (Insight 2 in Bustamante et al., 2023) will also bring about considerable co-benefits for human health via aerosol reductions, yet these aerosol reductions also increase the urgency of GHG mitigation.

The influences of recent aerosol emissions changes on the climate transcend impacts on global-mean temperature and have produced regionally distinctive effects on the hydrologic cycle and on diverse climate hazards. These effects differ in strength and geographic distribution from the effects of concurrent increases in GHG (Persad et al., 2023). Critically, the short-term local and global impacts of aerosol changes are strongly dependent on the location of the emissions 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 (Persad, 3 2023; Williams et al., 2023). Due to the nature of aerosols' industrial emission sources, 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 (Gao et al., 12 2023; Nair et al., 2023) [Figure 1], amplifying shifts in climate risks. However, heterogenous 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 (Fahrenbach et al., 2024; Persad et al., 2023; Wang et al., 12 2023). Notably, while aerosol emissions have begun declining globally, they continue to rise in South Asia and South America, and the trajectory of future African emissions is particularly uncertain (IPCC, 2021, chap. 7; Quaas et al., 9 2022). Aerosol emissions changes are key in differentiating the rate and nature of climate change experienced by different regions, contributing to differentiation in loss and damage and adaptation pressure, but are generally underrepresented in decision-making tools like regional climate models (Fiedler et al., 8 2023; Persad et al., 2023).

Many parts 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 (Gao et al., 12 2023; Quaas et al., 9 2022). 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} (Quaas et al., 9 2022). This corresponds to 15-50% of the increase in effective radiative forcing caused by CO_2 (IPCC, 2021, chap. 7) in the same time period. These recent findings support expectations that future aerosol reductions are expected to significantly contribute to climate warming, and aerosol impacts are expected to outweigh those of GHG under the carbon neutrality scenario (Wang et al., 12 2023; Yang et al., 5 2023).

Due to the climate system's thermal inertia and the non-linearity of aerosol-cloud interactions (ACI), the additional warming arising from air pollution mitigation can be delayed by two or three decades in heavily polluted locations (Jia and Quaas, 9 2023). Adding to this concern, recent studies suggest a potential underestimation of the anthropogenic aerosol loadings and their climate effects in the past decades (Julsrud et al., 11 2022). Given the expected decline in aerosol loadings, these recent findings further underlines the need for immediate climate change mitigation and adaptation measures.

Despite the significant recent progress in understanding processes and impacts, aerosol influences remain a major uncertainty in our understanding of current climate changes, and their impacts on nature and society. A notable knowledge gap is the aerosol-cloud-precipitation nexus. ACI dominate the radiative forcing from anthropogenic aerosol emissions, and its uncertainty (Blichner et al., 12 2024; Fiedler et al., 8 2023; IPCC, 2021, chap. 7) Hence, it limits our understanding of both the total influence of aerosols on surface temperature, and the transient climate sensitivity (Chen et al., 5 2024). Further uncertainties include the many pathways that connect aerosol radiative and microphysical effects to precipitation (Williams et al., 2023), which influences projections of air quality and health impacts, how global warming influences emissions of natural aerosol types, and aerosols' influences on extreme and compound events.

Cleanup of anthropogenic aerosol emissions is having, and will continue to have, massive benefits for human and ecosystem health. It is, however, also unavoidably strengthening the ongoing climate changes. Here, the ongoing rapid changes in aerosol-climate interactions are both a hazard and an opportunity. Close observation and thoughtful utilisation of the current changes may allow for improved constraints on aerosol-climate influences, including temperature, precipitation and extreme events, and hence help narrow a key remaining uncertainty on near-term and far-future climate projections.

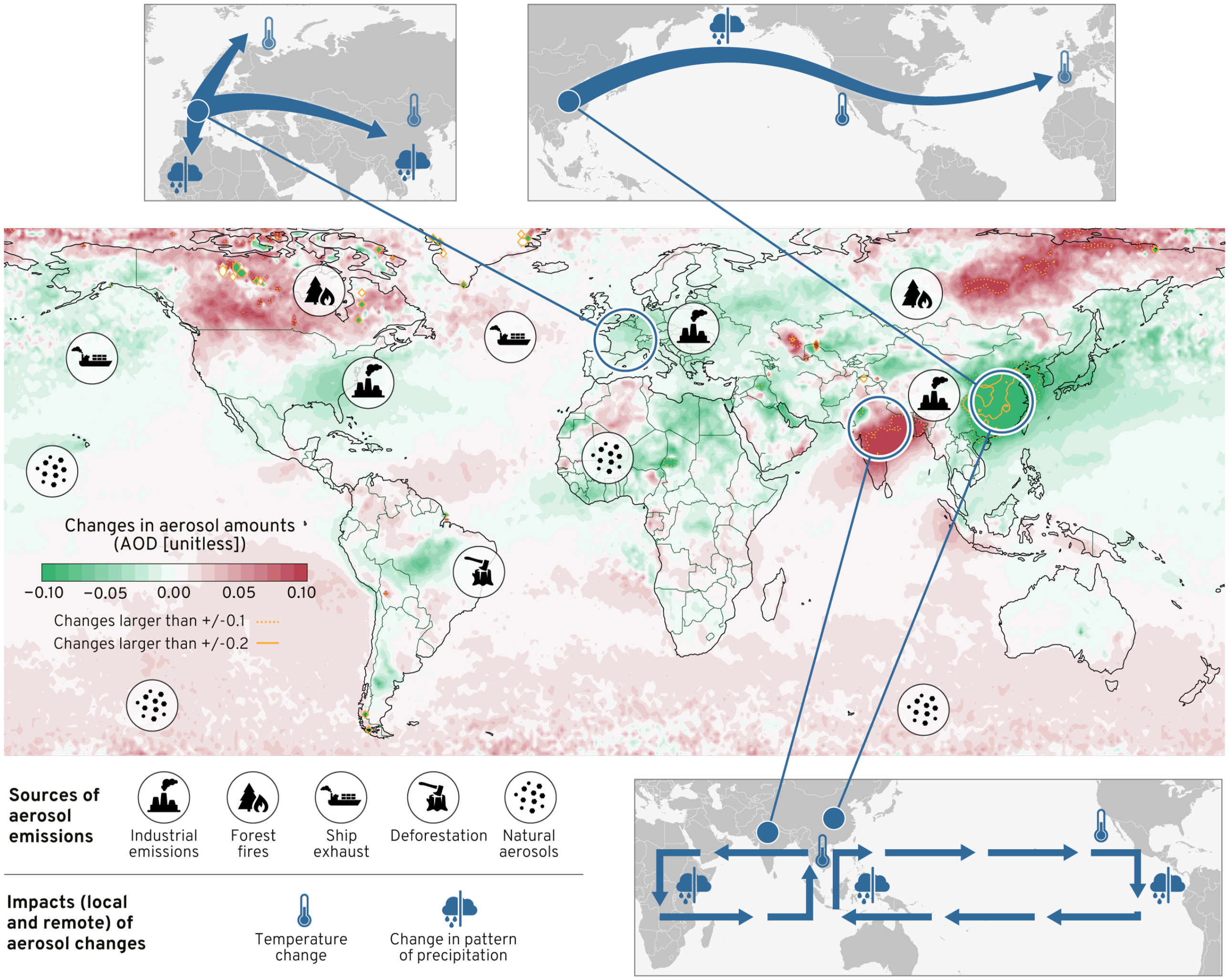

Figure 1. Recent changes in aerosols, related sources, and examples of remote effects.
Recent changes (difference between 2014-2023 and 2004-2013 period averages) in aerosol amounts, quantified as Aerosol Optical Depth (AOD) observations from MODIS Terra and Aqua. Main causes/sources of aerosol emissions, responsible for the observed changes (icons on map), and impacts (local and remote) of changes in aerosol loadings over Europe, East Asia, and South Asia are depicted in the top and bottom windows (including Walker Circulation (bottom). Modified from Persad et al.[39]

Insight 2: Soaring Methane levels and likely causes

Methane, a potent but short-lived greenhouse gas, accounts for nearly a third of the warming over the last 250 years. To limit warming below the Paris Agreement targets and prevent severe climate impacts, rapid and deep cuts in methane emissions are crucial (IPCC, 2022a SFP). As natural sources are generally uncontrollable, significant reductions in methane emissions from energy, waste, and agriculture are essential to meet global targets.

Since 2006, observations have shown an acceleration in atmospheric methane levels (Lan and Dlugokencky, 2024; Nisbet et al., 2023; Saunois et al., 2024 [submitted]) with 2020-2022 recording unprecedented high growth rates ((Feng et al., 2023) [Figure 2]. Isotopic and remote sensing evidence point to increasing biogenic emissions since 2006, likely from tropical wetlands and livestock emissions as primary contributors (Nisbet et al., 2023; Worden et al., 2023). 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 (Feng et al., 2023; Peng et al., 2022). Furthermore, if natural methane sources continue to grow, deeper reductions in anthropogenic emissions will be necessary to compensate.

Understanding the main factors behind this long term increase is crucial for developing an adequate mitigation strategy. Recent advances in remote sensing, the expanding ground network, and modelling 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 (Nesser et al., 2024; Schuit et al., 2023; Thorpe et al., 2023). Combined with atmospheric modelling, these capabilities improve quantitative understanding of emissions from more diffuse anthropogenic emissions from sources like rice paddies, landfills, and livestock (Wang et al., 2024; Worden et al., 2023). Measurements of atmospheric trace constituents and isotopic analysis, combined with modelling, 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 (Saunois et al., 2024 [submitted]), depending on the approach for estimating emissions. However uncertainties across sources and locations remain large, with varied methods yielding different results. For example, estimates of fossil fuel methane emissions differ between activity-based bottom-up inventories, remote sensing, and isotopic analysis (Basu et al., 2022; Saunois et al., 2024 [submitted]; Worden et al., 2023). Despite discrepancies, estimates for categories of sources and sinks generally converge.

Evidence from global measurements of the 13C/12C methane isotope ratio, which differentiate fossil from biogenic sources, shows a steady increase beginning in the late 19th century, consistent with rising fossil energy emissions. That trend reversed in the early 2000s, reflecting increases in the relative portion of biogenic sources (Nisbet et al., 2023). This biogenic increase may stem from rises in anthropogenic sources such as livestock, and possibly waste emissions (Saunois et al., 2024 [submitted]; Worden et al., 2023), in addition to natural systems [Figure 2].

Emissions from natural systems, estimated from remote sensing, flux site measurements and modelling, have increased by 4% from the 2000s to the 2010s, particularly from tropical wetlands (Saunois et al., 2024 [submitted]; Zhang et al., 2023). Whilst Arctic regions are less covered by remote sensing, in-situ observations suggest a 9% rise in emissions from the boreal-Arctic region since 2002, driven by warming and greening, with the highest emissions during heatwaves (Yuan et al., 2024). However, additional studies are needed to confirm this result (Lan and Dlugokencky, 2024). Climate feedback mechanisms, primarily from warming and precipitation changes, are expected to further amplify emissions from natural systems (Insight 4 in Bustamante et al., 2023). Most Earth System and Integrated Assessment Models do not include these feedbacks, likely underestimating future biogenic contributions to atmospheric methane rise in a warming world (Ma et al., 2023).

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

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 (Malley et al., 2023). Across both sectors, the recently-developed facility-level satellite monitoring capabilities can enable detection of large emissions (Nesser et al., 2024; Schuit et al., 2023; Thorpe et al., 2023), where a relatively small number of large emitters have an outsized impact on total emissions.

The agricultural sector, the largest anthropogenic methane source, has lower technical potential for reduction, but is not without options (Malley et al., 2023; Mukherji et al., 2023). Significant cuts are possible through a range of mitigations including use of water- and fertiliser-efficient crop varieties and lower emitting livestock breeds, diet change away from dependence on livestock, and reduction of food waste (Mukherji et al., 2023).

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 (~2 MtCO2/yr removed) (Hickey and Allen, 2024), methane removal exploration has only recently begun (Gorham et al., 2024).

Despite uncertainties in the methane budget, sufficient information about the spatio-temporal 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 climate policy through independent emissions observation. Methane emissions reductions are tractable and have been demonstrated. However, with only about 13% of methane emissions covered by mitigation policies (Olczak et al., 2023), more stringent and consistent action is needed to reverse the growth in atmospheric methane, slow near-term warming, and minimise the impact of natural climate-methane emissions feedbacks. These actions are essential to maintaining the targets outlined in the Global Methane Pledge and Paris Agreement.

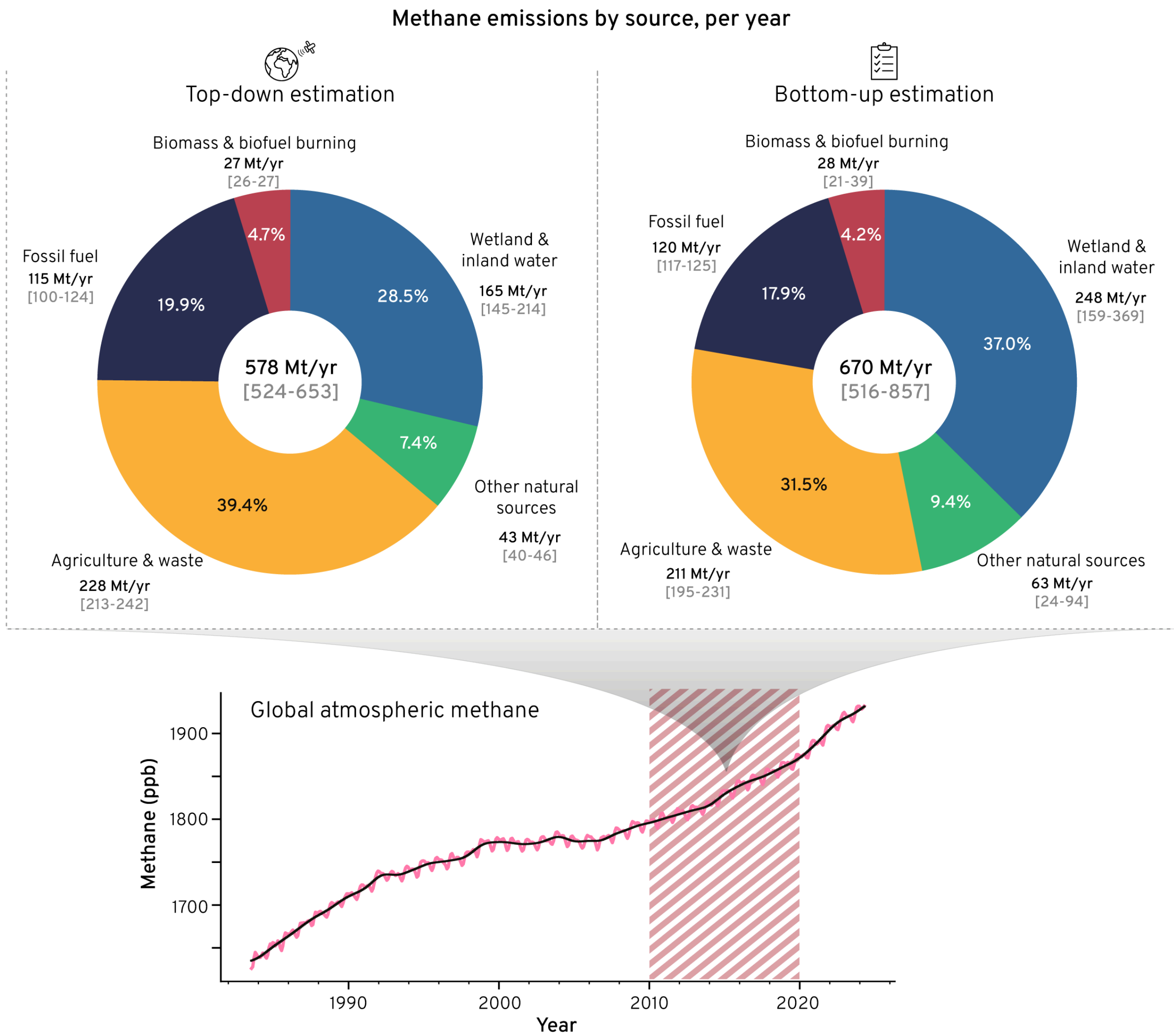

Figure 2. Annual methane emissions by source (average for the period 2010-2019)
Estimated based on top-down integrative methods (top-left) and bottom-up integrative methods (top-right). Uncertainty ranges are indicated in square brackets. Data adapted from Saunois et al.[10]. Bottom: Trends 1983-2024 in global atmospheric methane[34]. Shaded area indicates decade over which emissions sources are attributed.

Insight 3. Rising concern over changes in ocean dynamics

Unprecedented ocean warming since the beginning of 2023 broke various sea surface temperature (SST) records not just in the tropical Pacific due to the developing El Niño, but also in the North Atlantic, Gulf of Mexico, the Caribbean, and large areas of the Southern Ocean. Even as the El Niño dissipated, the unusual warming of nearly 0.5°C above the reference average period from 1991-2020, remains alarming, as the first quarter of 2024 has persistently been warmer than the respective months in 2023 (Figure 4, upper). El Niño-Southern Oscillation (ENSO) events are intricately related to changes in SST: anomalies in SST in the Pacific can trigger and amplify ENSO events. Changes in SST driving weather and climate extremes have direct social and economic impacts.

New research on large-scale climate features such as the El Niño-Southern Oscillation (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 (Callahan and Mankin, 2023; Liu et al., 2023). While it has long been understood that climate variability can generate socioeconomic impacts, the true costs of El Niños and how those costs evolve alongside warming were unknown. Two scientific issues required resolution to address this 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 Niños have persistently reduced country-level economic performance of US$4.1 trillion and US$5.7 trillion in global income losses attributed to the 1982–83 and 1997–98 El Niño events, respectively (Callahan and Mankin, 2023) (Figure 4a). Similar startling large estimates of US$2.1 trillion and US$3.9 trillion global loss due to the 1997-98 and 2015-16 extreme El Niño events were found based on different estimations (Liu et al., 2023) (Figure 4b). Economic loss grows dramatically with increased ENSO variability from 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 (Callahan and Mankin, 2023; Liu et al., 2023), or an additional median loss of US$33 trillion to the global economy over the remainder of the 21st century (Liu et al., 2023), at a 3% discount rate in the high-emission scenario. These studies reveal how poorly adapted our economies are to natural climate variability, despite the fact that they do not represent novel climate states.

Beyond the evidence of maladaptation to ENSO over interannual timescales, there is also worrying indication of warming-driven changes to other large components of the climate system operating over longer timescales. Recent studies have suggested a loss of stability or weakening of the Atlantic meridional overturning circulation (AMOC), alongside an enhanced risk of a shut-down, even this century (Ditlevsen and Ditlevsen, 2023; Jackson et al., 2022; Kilbourne et al., 2022; van Westen et al., 2024). These findings represent a stark contrast to the recent sixth assessment report of the IPCC, which—based on projection uncertainties with observations—suggested with *medium confidence* that an AMOC collapse will not occur during the 21st century (IPCC, 2021, chap. 4 and 8). Although two decades of direct AMOC observations provided no detectable long-term trend (Johns et al., 2023), model simulations and proxy reconstructions indicated early warning signals of notable variability and slowing circulation (Caesar et al., 2021; Ditlevsen and Ditlevsen, 2023; Lohmann et al., 2024; van Westen et al., 2024). An AMOC shutdown 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 (Rahmstorf, 2024).

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 latest CMIP6 models indicate that ENSO amplitude will likely increase even under strict mitigation targets (Cai et al., 2022). Yet this picture of future is incongruent with the prevailing La Niña-like conditions and wider real-world pattern of tropical Pacific SSTs so crucial to climate sensitivity (Armour et al., 2024); absent a longer and more accurate SST record, it is difficult to sort signal from noise. Multicentury climate simulations and single-model large ensembles forced with pre-industrial GHG conditions can help in this regard, 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. 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 (van Westen et al., 2024). For example, while there is a consistent picture of an AMOC decline during the 21st century from climate models (Ditlevsen and Ditlevsen, 2023; van Westen et al., 2024), improved models would clarify sources of uncertainty in the rate of transient-scale AMOC decline.

Irrespective of how global warming will influence these large-scale climate features, the recent scientific advances highlighted here are indicative of how vulnerable societies are to potential changes in their behaviour. Further adding urgency to the implementation of both mitigation and adaptation policies, for them to be effective. The large macroeconomic impacts of El Niño, for example, allude to the potential costs from AMOC slowdown or other potential rapid climate state changes. El Niño and its teleconnections are well-understood, societies have experienced them for centuries, and yet there is a large latent vulnerability to them. Addressing the uncertainties for predicting changes in these large-scale climate processes and understanding the consequences of the current increases in SSTs and its implications for the magnitude of warming and climate risks is crucial for raising the urgency of mitigation and developing effective adaptation strategies to protect society from significant environmental changes over multiple timescales.

The research advances highlighted here show how vulnerable human societies are to natural climate variations. Which is particularly concerning given how global warming is altering such variability on rapid transient timescales, with the potential to tip the Earth system into novel climates. Upward revisions of the risks presented over the near-term suggest wide societal challenges to global warming and variability over the remaining century. It also raises the urgency of climate adaptation focused on resilience to present-day variability (e.g., ENSO), alongside rapid decarbonization to reduce the risk of even larger costs of global warming resulting from novel climate states.

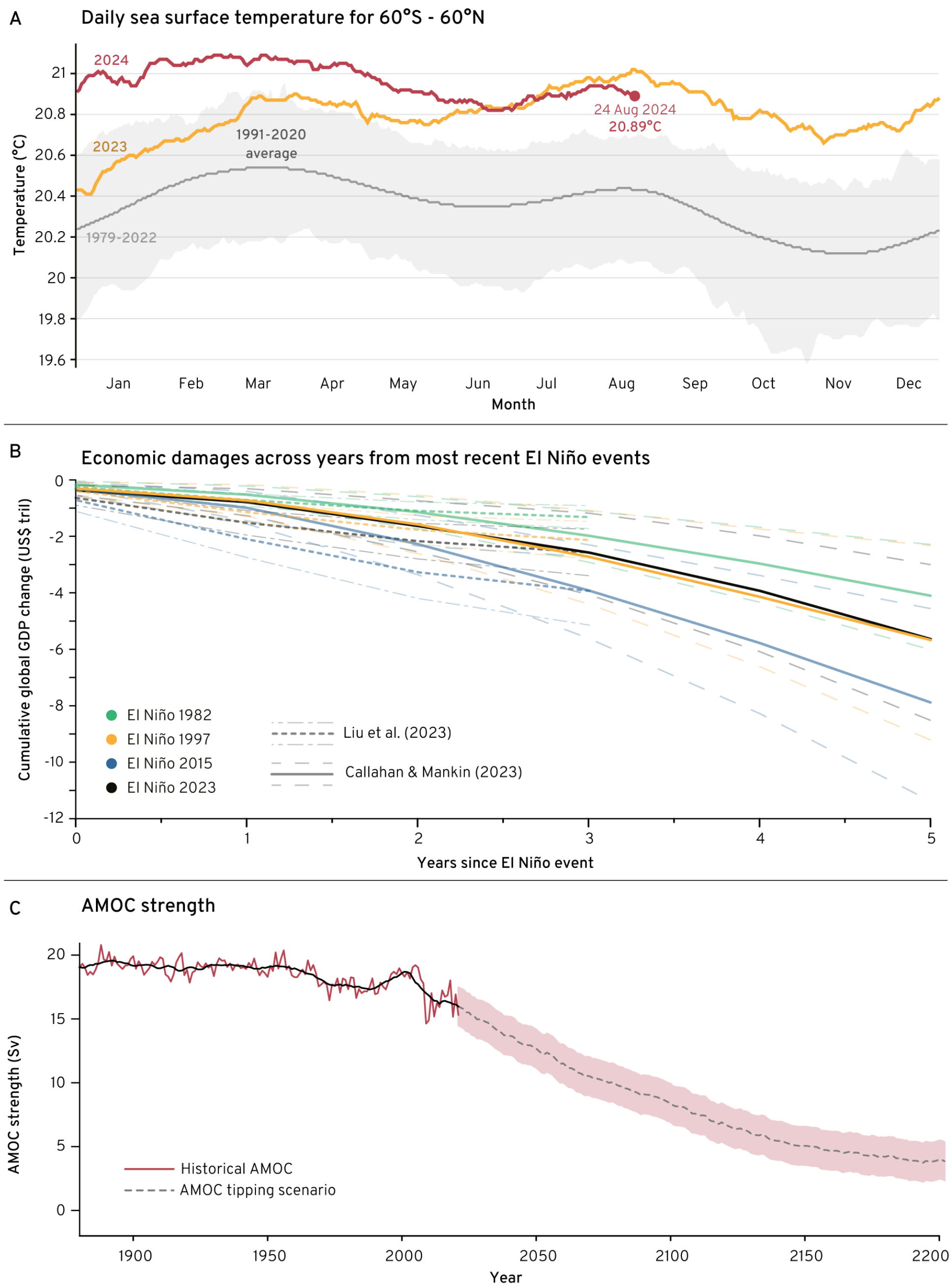

Figure 3. Unprecedented sea surface temperature, El Niño costs, and potential weakening of AMOC
(**A**) The mean daily sea surface temperature across the globe, collected from January 1979 to August 24, 2024 from ERA5.(C3S 2024) (**B**) Economic damages calculated as GDP change for the 3 to 5 years after noteworthy El Niño events with the centre line indicating the mean of the projection and shading shows the 95% Confidence Intervals across regression bootstrap samples.[272,273] 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)[134] shown with 11-year running means (black solid) indicating potential AMOC tipping scenario from 2021-2200 (grey dashed) with shading of interannual variability and uncertainty.[135]

Insight 4. Embracing multiple dimensions of diversity can safeguard the Amazon's resilience

The Amazon basin is a heterogeneous and complex system composed of various types of interconnected aquatic and terrestrial ecosystems, shaped for 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 (Science Panel for the Amazon, 2021). By recycling a tremendous amount of water, it substantially affects the planetary energy balance through the cooling effect that evapotranspiration promotes (Science Panel for the Amazon, 2021). Moreover, it currently stocks as much carbon as has been released as CO2 from global land use change since 1850 (Friedlingstein et al., 2023).

A multitude of human-related drivers have simultaneously altered the Amazon basin vegetation cover,with deforestation and degradation leading the way (Lapola et al., 2023), thereby accelerating and increasing global climate change (Science Panel for the Amazon, 2021). Climate and land use change, together with other human-induced stressors such as fire, have played a fundamental role in gradually impacting and altering the Amazon basin, with their compounding effects often being more harmful than when occurring individually (e.g., Drüke et al., 2023). They synergistically transformed Amazonian basin landscapes with far-reaching consequences that compromise water, energy, and food securities regionally and globally (Science Panel for the Amazon, 2021). With progressing gradual change the concern of a systemic collapse of the Amazon forest constantly rises. This "tipping" can happen due to self-reinforcing feedbacks, e.g. in the water cycle or fire dynamics in the Amazon if forest loss and/or climate change exceed certain thresholds (Flores et al., 2024).

Despite some remaining uncertainty, a large-scale systemic tipping of the Amazon forest is likely resulting from local to regional-scale tipping rather than a synchronous collapse. All tipping dynamics are initially linked to the forest-rainfall feedback whereby forests increase local to regional rainfall by transpiring moisture back to the atmosphere (Flores et al., 2024). In southeastern Amazon, where half of the inland-originated rainfall depends on this regional moisture recycling (Staal et al., 2023), trees are already operating beyond their drought-resistance limits (Tavares et al., 2023) and forests are turning into carbon sources (Gatti et al., 2023). Deforestation and degradation have incrementally dried the Amazon as a whole. Halting these stressors, as well as promoting forest restoration, are priority actions to maintain the forest resilience and preserve the forest-rainfall feedback (Lapola et al., 2023). However, large-scale coordinated actions to increase – and not only to maintain – the resilience of the Amazon system are not yet being actively discussed and planned at the political level needed.

Addressing the impacts of large-scale forest conversion and extreme weather events as compounding impacts is critical to respond to the increasing disturbances in the Amazon basin. Water is thereby an illustrative example on how to integrate social as well as ecological systems to assess critical interdependencies.

Amazon water systems discharge ~16-22% of Earth's river input into oceans (Araujo et al., 2023; SPA 2021), while aerial rivers bring oceanic moisture inflows from eastern portions towards western parts, affecting rainfall downstream. Water enables connectivity, fostering life in heavily populated Amazon cities and in Indigenous local communities living alongside river and lake ecosystems (Science Panel for the Amazon, 2021). Via the water cycle the effects of short to long-term disturbances like extreme droughts, floods, deforestation, mining, and damming propagate through and sustainably change the Amazon basin. 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 (Bottino et al., 2024). Contrasting events such as the 2021 flooding and the subsequent 2023/2024 extreme drought (Espinoza et al., 2024) have substantially affected social-ecological systems throughout the Amazon basin. Impacts were registered on both people (e.g., displacement, transportation shortages) and ecosystems (e.g., reduced productivity) (Ottoni et al., 2023). Not surprisingly, as climate and land use change increase so are such impacts expected to increase in the future (Uribe et al., 2023). As atmospheric moisture flows interconnect the whole continent ensuring supply of rainfall (Flores et al., 2024) acknowledging international inter-dependence of and responsibility between socio-ecological systems is key for a continental scale resilience strategy for humans and nature.

The diversity of the Amazon basin is crucial for the resilience of the ecosystem, especially in the face of disturbances mentioned above [Figure 4]. These disturbances are unevenly distributed in space and time and are pushing the system towards different thresholds (temperature, rainfall, seasonality, dry season length and deforestation) at different times (Flores et al., 2024). Recent studies have shown that temperature thresholds can significantly influence photosynthesis efficiency, pushing the forest closer to its physiological limits (Doughty et al., 2023). The presence of a richer functional diversity enhances resilience of the Amazon to climate change, suggesting that conserving biodiversity is essential for bolstering forest resilience (Rius et al., 2023; Sakschewski et al., 2016; Weiskopf et al., 2024) (Weiskopf et al. 2024).

Indigenous peoples have played a vital role in shaping the Amazonian ecosystem for at least 12,000 years. Their presence contributes to the biocultural diversity of the region, which is the variety of life resulting from the interaction and co-evolution of biological, cultural, and linguistic components. This diversity fosters a range of responses to different combinations of disturbances, making the ecosystem more resilient. Indigenous ecological knowledge and practices, such as the creation of nutrient-rich soils and food forests, have significantly enhanced the diversity of soils and plant communities, benefiting both local and global societies (Levis et al., 2024). These practices illustrate the potential of Indigenous knowledge to maintain forest resilience and mitigate the risk of an Amazon forest systemic tipping point (Flores et al., 2024).

BOX: social-ecological “hope spots”

Despite the challenges, social-ecological “hope spots”, conservation models are emerging across Amazonian Indigenous and local communities. These hope spots demonstrate successful cases of biocultural conservation, such as the Xingu hope spot and protected areas in the Cerrado-Amazon ecotone (Almada et al., 2024; Levis et al., 2024). These areas are crucial for maintaining the multiple dimensions of biocultural diversity and their interactive functions (Langhammer et al., 2024). By acting as buffers against large-scale deforestation and degradation, Indigenous territories and protected areas play a critical role in preserving the Amazon's resilience and biodiversity (Levis et al., 2024).

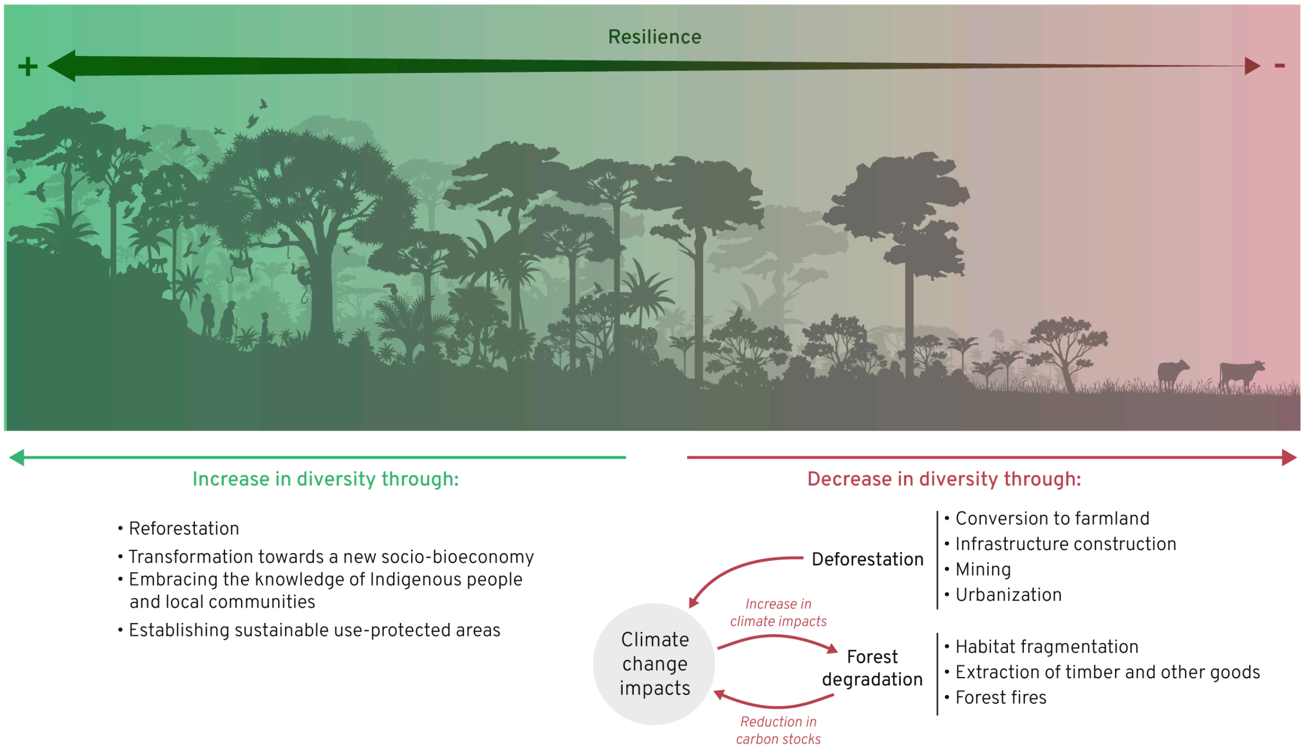

Figure 4. Amazon's biological and cultural diversity enhance its resilience to climate change
A high biodiversity landscape, both biological and biocultural, has higher resilience to climate change impacts, compared to less diverse landscapes. Climate change and forest degradation are self-reinforcing feedbacks reducing the diversity of the Amazon system. Reforestation, a transformation towards 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.

Insight 5. A growing fraction of the planet is at risk of becoming uninhabitable

Habitability refers to the livability of a setting: whether it is suitable for and can support human life in a productive and sustainable manner (Horton et al., 2021). Access to adequate resources (e.g. food, clean water, safe shelter, and healthcare) and comfortable environmental conditions (e.g. livable temperatures and humidity, and clean air) are some important determinants (Horton et al., 2021). At a global scale, habitability can be considered in terms of the so-called ‘human climate niche’. A simplified way to define the human climate niche is to look at the climatic conditions where most people choose/want to live. Archaeological records and climate reconstructions reveal that since neolithic times (~6000 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 ~1000 mm (Xu et al., 2020). In present-day societies, most people, agricultural, and economic output are within this same “human climate niche” (Xu et al., 2020). Human-induced climate changes we are currently facing are pushing areas outside habitable climatic conditions (Horton et al., 2021; IPCC, 2022b). A recent study estimates that at the current ~1°C warming level, >600 million people already live outside the human climate niche, and this study projects that every degree of future warming could further push >10% of the world’s population outside the niche (Lenton et al., 2023) (Figure 5).

While mean annual temperature and precipitation have the advantage of data availability for characterising and projecting the human climate niche, habitability can more simply be defined by how humans are able to withstand extreme events (these measures of niche are often strongly correlated, (Lenton et al., 2023)). Extreme heat is a key hazard threatening habitability, and in the future most regions of the world will likely experience an increased frequency, duration, and magnitude of extreme heat (Domeisen et al., 2023). High temperatures can result in heat-related illnesses - strokes, severe headaches, vital organs damage, decreased metabolic activity, and in severe cases, mortality. The occurrence of heatwaves alongside humid conditions is particularly dangerous, hindering evaporative cooling and reducing the ability to regulate core temperature (Figure 5). Recent empirical studies indicate that 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 theorised (Vecellio et al., 2023). Other heat impacts include reduced work capacity (Parsons et al., 1 2022), especially for outdoor workers (Nelson et al., 2024). 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 (see Insight 7). Other vulnerable groups include the elderly and young children; people with chronic cardiovascular, respiratory, and cerebrovascular conditions; people with pre-existing mental illness; and people with cognitive and/or physical impairments. Non-direct impacts also occur, e.g., with increasing temperatures the amount of dissolved chlorine in water reduces, increasing the likelihood of waterborne bacteria (Roy et al., 2016); climate warming may also amplify the risk of algae blooms and its spillover from aquatic ecosystems to the atmosphere, increasing human exposure to cyanotoxins (Sun et al. 2023). Different communities experience the same impacts at different climatic limits, like urban heat island effects lead to cities experiencing higher temperatures compared to rural surroundings.

Although a limit can be defined whereby humans can no longer thermoregulate, impacts of heat extremes affect different regions and population groups differently - depending on factors, including the current record temperatures experienced (Thompson et al., 12 2023). This is because adaptation measures are often administered after particularly impactful extremes, often only to the level of that event. The world is not warming evenly, some regions are becoming exposed to extreme heat more rapidly (Figure 5, inset of West Africa in particular). Powis et al. (2023) show that regions including South Asia and the Persian Gulf already experience deadly heat. Ramsay et al. (1 2024) show 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, deadly heat events are expected in India, Pakistan, and Bangladesh (Ramsay et al., 1 2024; Zachariah et al., 2023). Global-scale analyses suggest that heat extremes will be concentrated in low-latitude regions, which disproportionately include many Global South countries (Lenton et al., 2023).

Record-breaking extremes can push a region outside of habitable conditions for the first time. Superimposed on global warming, El Niño can exacerbate record-breaking heat, especially humid-heatwaves (Zhang et al., 4 2024). Understanding when, and by what margin, such events are likely to occur is vital for adaptation planning. A variety of climate modelling methods can investigate the physical characteristics of possible unprecedented extremes in current and future climates, allowing plausible adaptation levels to be determined. This include evaluating large ensembles of climate models and initialising model simulations of past events at future GHG conditions. Recently, ensemble boosting has been developed, whereby a large ensemble with perturbed initial conditions allow evaluation of possible record-breaking margins; this has been used to show the plausibility of unprecedented heatwaves (Fischer et al., 12 2023).

Habitability is not only an individual, physiological concept, but also one dictated by the suitability of the surrounding environment to live and thrive in, and the availability of food. In the changing climate, drought-heatwave and humid-heatwave events are increasingly occurring, impacting agriculture, influencing food security globally (Bustamante et al., 2023; Tripathy et al., 2023). Extreme heatwave-drought events significantly impact staple crop yields, like maize (Simanjuntak et al., 12 2023). During growing seasons which coincide with El Niño events , in many areas, like southern Africa and Australia, more frequent and intense heat generally coincides with drier-than-normal conditions, leading to greater impacts on crop and livestock production; this was observed during 2015/16 and 2023/24.

While environmental indicators show a shift towards uninhabitable conditions, there is substantial heterogeneity in different types of adaptive capacity across populations; Vecellio et al. (2023)'s results were from temperate, northeastern United States climates not normally characterised by long durations of extreme heat. Physiological adaptation occurs in populations chronically exposed to warmer conditions, reducing health impacts (Tobías et al., 2021). On the other hand, vulnerable populations, such as the elderly, have lower physiological thresholds for extreme heat (Wolf et al., 12 2023). More research is needed to determine limits in populations living in climates routinely exposed to extreme temperatures. Additionally, in contrast with higher-income countries in vulnerable regions (e.g. Singapore and Saudi Arabia) can afford required technological adaptation and lifestyle changes to withstand the worst effects of extreme heat.

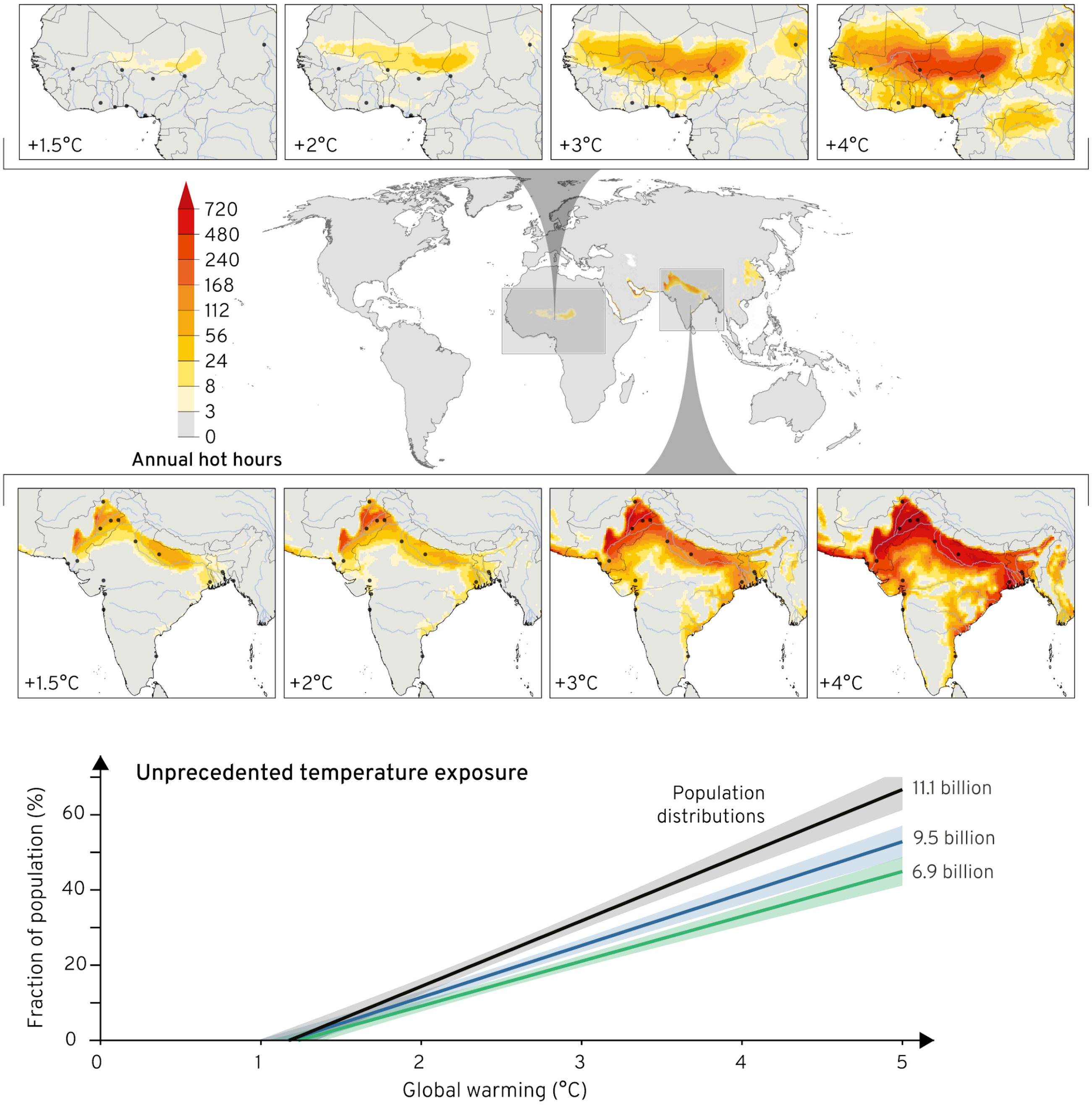

Figure 5. Increasing exposure to prolonged heat at different levels of global warming

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°, 2°, 3°, and 4°C warming).13 Bottom left plot: Projection of fraction of humanity exposed to unprecedented temperatures10: 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 (grey).

Insight 6. Climate extremes are harming maternal and reproductive well-being

Changing climate patterns are impacting pregnant women worldwide, with more severe impacts in climate vulnerable regions with limited access to resources (Rekha et al., 2024). Now more than ever, highlighting the impacts of climate change on maternal and reproductive health (MRH) has become critical. Direct and indirect cause-effect pathways are being established between climate change and increased pregnancy loss, preterm births, severe maternal morbidity, gender-based violence, and more (Afzal et al., 2024) [Figure 6], yet policy responses remain insufficient (Bonell et al., 2024). Researchers also highlight gaps in higher education and training on the topic of climate change on health across the medical community, reducing their preparedness in addressing these challenges (Létourneau et al., 2023; Pandipati et al., 2023). Inaction risks a reverse in the progress made in MRH over the recent decades.

Multiple studies were published last year on the impact of extreme weather events on MRH in low and middle income nations. Rekha et al. (2024) explore the impact of occupational heat stress on 800 pregnant women in India, the first publication of its kind. Results show that nearly 50% of the women reported heat stress and 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 India, where millions of pregnant women experience occupational heat stress on an annual basis (Rekha et al., 2024). In their study of over 400,000 pregnancies in Southern California, Jiao et al. (2023), 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 (Ye et al., 2024). Analysing urban green infrastructure combined with social determinants of health adds to our understanding of prevention options. Bonell et al., (2024) 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, confirmed an association between gestational flood exposure and pregnancy loss. They estimate that flood events are responsible for over 107,000 excess pregnancy losses annually across the studied regions, with the highest loss calculated in South Asia. The study also reports elevated odds of pregnancy loss for women dependent on surface water and those with the lowest income and education levels (He et al., 2024).

Through indirect pathways, climate change can magnify these direct impacts, for example affecting health systems and infrastructures (see Insight 8) and exposing societal weaknesses (Afzal et al., 2024). 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 (Lusambili et al., 2024). Research from Kenya and Burkina Faso show that extreme heat can impact MRH, due to the added discomfort which discourages important behaviours: Studies report a decline in breastfeeding frequency, mother-child bonding (e.g., ‘Kangaroo Mother Care’), travelling for antenatal and postnatal care, and use of mosquito nets, hence increasing exposure to vector-borne diseases (Kadio et al., 2024; Lusambili et al., 2024; Scorgie et al., 2023). 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 (Sundaresan et al., 2023).

Overall, the full magnitude of climate change impacts on MRH remains underexplored (Bonell et al., 2024). Urgent action is required to avoid further deterioration of health in pregnant women and of future generations. More research from regions highly vulnerable to climate change is needed to better understand the direct and indirect pathways, and the socio-economic conditions that amplify risks to MRH, which will also shed light on how different climatic seasonalities influence these outcomes. This will help set in place the needed policies, awareness programs, and standards to protect MRH from the impacts of climate change.

BOX. Addressing impacts of climate change on MRH through a justice and gender approach
Solutions to addressing the direct and indirect impacts of climate change on MRH cannot be separate from justice and gender-based rights approaches. For example, it is known that women of colour, low income and low education levels are exposed to harsher environments, face more impacts of climate change and have limited access to healthcare services (Bekkar et al., 2023). 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 justice lens that ensures equitable access to health resources to all pregnant women (Bekkar et al., 2023). Increasing gender-based domestic violence is also another indirect cause of climate change on MRH. A study by Zhu et al. (2023) 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 (Afzal et al., 2024; Sundaresan et al., 2023). Scorgie et al. (2023) in Kenya report that in areas where heat is normalised and behavioural changes conflict with gender norms, pregnant women often continue their physical activities during extreme heat events. This lack of change in behaviour due to entrenched gender norms and labour conditions is concerning as it indicates that communities may not be able to adequately respond to the risks heat poses to maternal health. Gender must be a key consideration when tackling this problem and empowering communities to recognize unique heat risks to MRH ((Kadio et al., 2024; Lusambili et al., 2024; Scorgie et al., 2023)). In addition, climate change impacts to MRH are also intergenerational as they can have subsequent impacts on a baby’s development through indirect pathways. For example, pregnancy exposure to extreme weather events have been linked to long-term behavioural and cognitive impacts on offspring.This evidence further adds to the existing and growing intergenerational justice concerns of climate change (Pandipati et al., 2023).

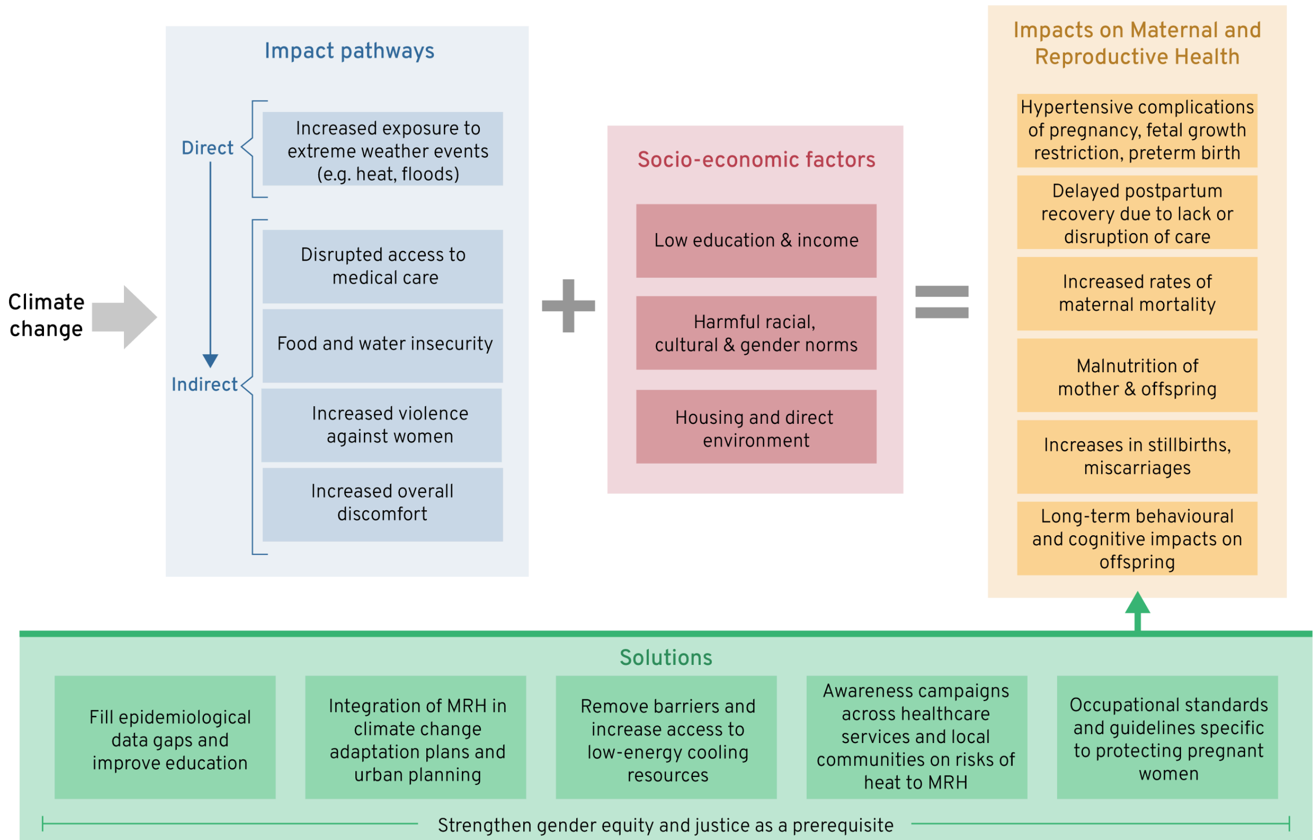

Figure 6. Direct and indirect pathways of how climate change impacts maternal and reproductive health. Impacts are further amplified by socio-economic factors in a given setting. To strengthen preparedness and protect maternal and reproductive health in a changing climate, solutions must address existing challenges in climate adaptation plans, data, education, gender and socio-economic norms, and be driven by gender equity and reproductive justice.

Insight 7. Cities and Climate Resilient Development - challenges and options

Emerging, rapidly growing, established, and shrinking cities across the globe are dealing with the impacts of climate change, calling for the need to adapt and mitigate (Sharifi, 2021). As climate change intensifies, billions of people clustered in cities will be at risk from climate-related hazards, including flooding, heatwaves, sea-level rise, and droughts. Out of 100 of the fastest growing cities in the world already classified to be at “high risk”, 80 are in Asia and Africa (commercially important cities such as Jakarta, Lagos, and Addis Ababa are in top 10) (C40, 2023). Cities face other systemic challenges such as, ageing populations leading to shrinking cities (Jarzebski et al., 2021), which reduce residents’ ability to withstand and adapt to shocks, as well as to rebuild after extreme events (Jarzebski et al., 2021). Planning is needed to increase resilience and prevent loss and damage in cities worldwide.

Despite the urgency, few cities combine mitigation and adaptation in their Action Plans. Among those that do, most plans show only a moderate level of integration (Aboagye and Sharifi, 2024) and a meta-analysis of cities found that often efforts to mitigate are misdirected (Burley Farr et al., 2023). Based on data from the Carbon Disclosure Project, the most frequently identified mitigation actions in cities were building energy efficiency measures (1444 actions), and on-site renewable production (644), while the most common actions for adaptation were tree planting (283) and flood mapping (Sebestyén et al., 2023); however, challenges remain for mitigation and adaptation to happen at the speed necessary in cities.

Climate-resilient development (Figure 7)**,** is a process essential for cities to implement local-level climate action together with urgent developmental and sustainability concerns (Sánchez Rodríguez and Fernández Carril, 2024; Simpson et al., 2023). This process becomes even more important amidst the urgency to ramp up climate action and to ensure that vulnerable populations are not left behind (Krigel et al., 2023). Yet progress towards operationalizing climate-resilient development faces significant barriers, with urban governance and planning at the heart of the issue (Asadzadeh et al., 2023). Some cities also lack mechanisms to stop development in areas with high climate risk, to deal with formal and informal housing located in hazardous areas, as well as to compensate landowners for maintaining regulating services for cities (e.g. maintenance of green areas). The absence of regulatory, legal, and guiding frameworks in some cities pose significant challenges to just transition for climate resilient planning. Examples of barriers that lead to low climate resilient development are: (1) struggles to identify priorities among many frequently changing issues in cities and when priorities are identified, they change over time (Sharifi, 2023), (2) trade-offs amidst competing priorities (such as for public health, economic growth, social uplift...) with priorities given to low hanging fruits that focus on single (e.g., social, or ecological) or two-dimensional sub-systems (e.g., social-ecological) (Chester et al., 2023; Sharifi, 2023), and (3) lack of socio-economic capabilities prevent many cities from anticipatory decision making (Chester et al., 2023).

To deal with such barriers, research points at systems approaches that consider urban areas as dynamic and open social-ecological-technological systems (SETS) (Chester et al., 2023). The SETS approach helps to minimise trade-offs that may emerge when isolated or bilateral social, ecological, or technological measures are taken (Sharifi, 2023). By examining the interactions and interdependencies of these system domains, this approach broadens the spectrum of options available for interventions and potential to achieve co-benefits (for adaptation, mitigation, biodiversity, health, equity, etc.). Efforts that could prevent increases in such GHG emissions include methane capture in sewage, greywater and organic waste management. Further adoption of SETS can emphasise the integration of smart technologies, nature-based solutions, and grey/traditional infrastructure as an approach to reduce urban heat island effect and provide energy needed for cooling in cities (Irfeey et al., 2023). In particular, it allows city practitioners to evaluate co-benefits among highly competing sectors and sub-systems in cities by aiming for integrated approaches (e.g. with nature-based solutions (Hahn et al., 2023). 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 (Liu et al., 2022). Innovative mechanisms that encompass all components of SETS may be able to deal with conflict between development and conservation for "high risk" areas. 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 (Aboagye and Sharifi, 2024). In doing so, cities can move towards climate-resilient development based on transformative decisions (Nath, 2024).

Rapidly growing cities in low- and middle-income countries need more support to develop critical infrastructure because of a lack of socio-economic capabilities (Lorencová et al., 2021), especially if they are classified as "high risk". Smaller cities also lack city-specific climate-related funding streams, leading to an overreliance on central government budgets, which delays planning processes (Birchall and Bonnett, 2021).

BOX: City of Cape Town, South Africa based on Simpson et al. 2023

The City of Cape Town's 2022 - 2027 Integrated Development Plan (IDP) offers an example of a planning process that aims to mainstream climate mitigation and adaptation actions into an inclusive development pathway for the city. The IDP is organised around six priorities. The most important of which is inclusive economic growth to reduce poverty. A 'Resilient City' is a cross-cutting foundational principle that includes a Climate Change Strategy, a Resilience Strategy, and a Disaster Risk management plan, all in support of the IDP's six priorities. The plan recognizes in alignment with SETS the need to address social, ecological, and infrastructural dimensions to reduce vulnerability to climate change. The plan is considering aspects such as informal settlements, energy, and environment and biodiversity, among others. Yet, it remains to be seen the extent to which the interdependencies among these domains will be successful once fully implemented. With this approach, the City of Cape Town has taken important steps to outline a development strategy with elements consistent to a climate-resilient development process.

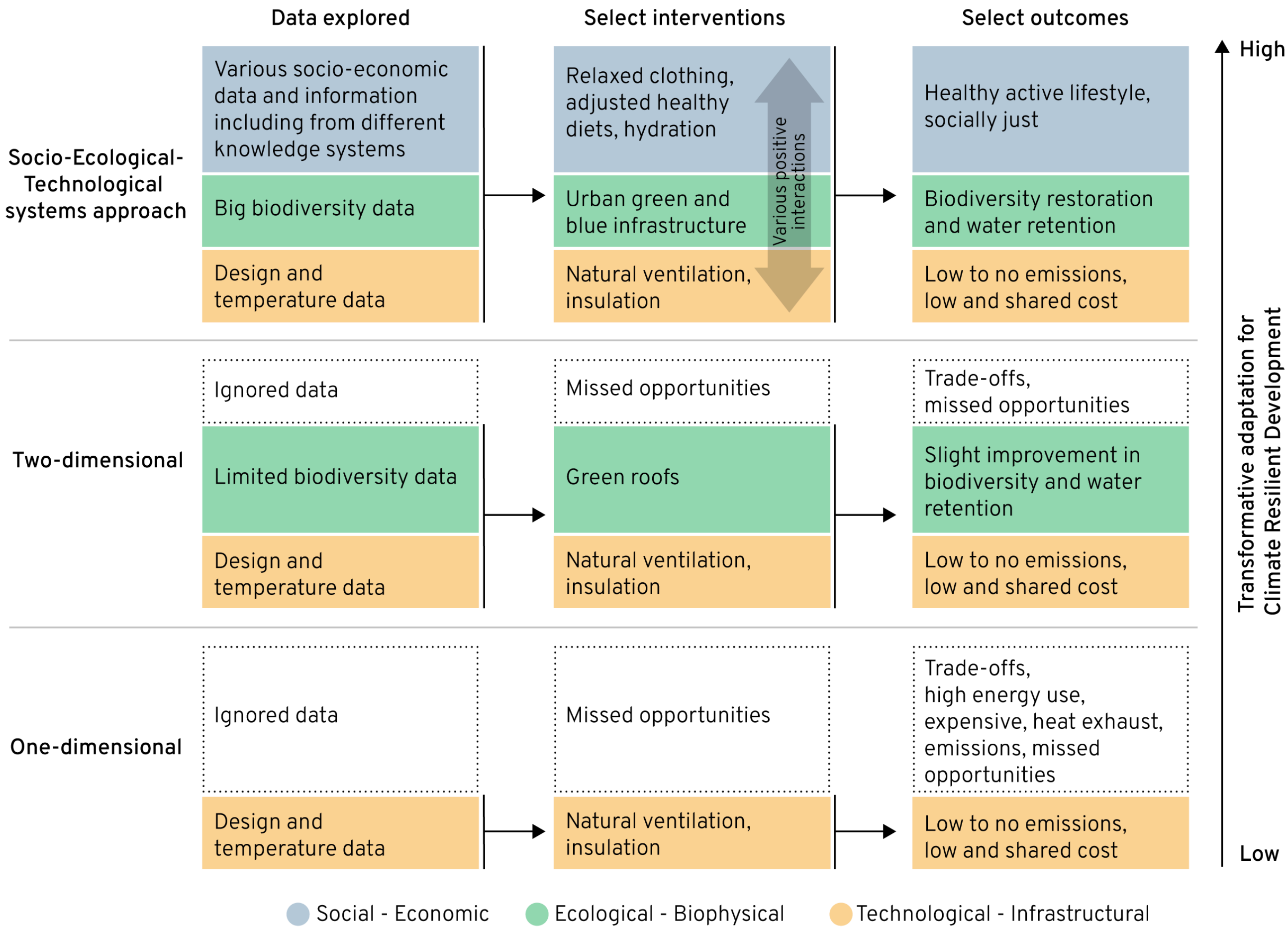

Figure 7. Social-ecological-technological systems (SETS) approach to urban heat
Illustrated solutions to urban heat using a social-ecological-technological systems (SETS) approach McPhearson et al. 2022) compared to conventional approaches, to guide planning and integrate policies with co-benefits

Insight 8. Critical infrastructure under pressure from climate change

The escalating challenges posed by climate change exert significant pressure on the resilience of 'critical infrastructure'— including assets, network or systems, [or a part of] necessary for the provision of essential services, i.e. those that are crucial for the maintenance of vital social and economic functions, including public health and safety (EU Directive on the Resilience of Critical Entities). Services classified as essential include power generation and transmission, potable water supply, waste collection and treatment, transport and telecommunication networks, and the systems of healthcare provision and food supply. The term 'critical infrastructure' encompasses essential physical facilities, such as power plants and water treatment centres, as well as organisational structures that ensure the continuous and secure operation of vital governmental and economic activities. Should these infrastructures suffer damage, even briefly, the functionality of society could be notably disrupted. The IPCC in its latest WG2 report (2022b, chap. 6), underlines the heightened vulnerability of these systems to climate change related hazards. Threats from extreme weather events are becoming more frequent and severe, increasing the risk of significant disruptions (IPCC, 2021, chap. 11).

The impacts of climate change on critical infrastructure can manifest in various forms and affect critical infrastructure dynamically. Hazards may occur as single events or as compound or coincident weather events, and their impacts can cascade through interconnected systems (Barquet et al., 2024), see Box. Further, interdependencies between critical infrastructure systems, like energy distribution and healthcare, or food supply and transport, can intensify these vulnerabilities, causing a domino effect where the failure of one system disrupts others (Nyangon, 2024; Nyangon and Byrne, 2023) [Figure 8]. Assessing climate change vulnerability requires considering location-specific conditions due to varying exposure, sensitivity, and adaptive capacity influenced by historical practices, socioeconomic trends, and legacy factors ((Nyangon, 2024; Nyangon and Byrne, 2023)). These localised nuances affect how each system responds to climate impacts, necessitating the need for tailored strategies for robust resilience and adaptation. Three stages described by Perera and Hong (2023), go from 1) a single isolated disruption of a facility/asset, that then 2) spreads through the specific system (within the sector), and 3) eventually extends beyond the sector disrupting other interconnected systems.

Stage 1: Direct impacts disrupting physical infrastructure locally, such as a drought interrupting hydroelectric power or a wildfire season disrupting transmission systems. Managing such disruptions locally is vital as it reduces the wide-scale impact.

Stage 2: Severe direct impact spread over a large area may move beyond a local issue to the next level, if poor local management, and/or vulnerable design and operation of the infrastructure. Considering the electricity sector, renewable energy technologies, which notably reduce grid inertia, may increase the risk unless proper measures are taken. To avoid such a wide-scale spread, public safety power shutdowns (Lesage-Landry et al., 2023), grid hardening (Anvari and Vogt, 2024), and microgrids are introduced (Perera et al., 2023b; Wang et al., 2023).

Stage 3: There are many interdependencies in critical infrastructure. For example, the natural gas network depends on the electricity grid to operate the compressors (transport natural gas), while the electricity grid depends on the natural gas network to generate electricity using gas turbine power plants. Similarly, the electricity sector and the communication network are interconnected. The widespread disruptions (discussed in Stage 2) prevail for a reasonable time (time interval may depend on the sector) in one sector (ex: electricity) may lead to disruption of the other connected infrastructure (ex: natural gas, communication). Such events have a multi-dimensional impact on society and take more time for full or partial recovery. Most of such events end up as billion-dollar disasters due to the widespread impact (NOAA-NCEI, 2024a).

Much research has been published lately on the vulnerability/resilience of the energy sector to climate related hazards (e.g., Lesage-Landry et al., 2023; Perera et al., 2023b; Wang et al., 2023; Xu et al., 2024), and a range of solutions have been proposed (Anvari and Vogt, 2024). In some cases, very targeted interventions can substantially increase the resilience of these networks, as illustrated by study of Texas's power grid demonstrated that identifying and protecting critical transmission lines, representing only 1% of the total, significantly reduced hurricane-induced power outages by a factor of 5 to 20 ((Anvari and Vogt, 2024). One area of active research worth highlighting are ‘smart grids’ powered by artificial intelligence (AI), machine learning (ML), and predictive analytics (Nyangon, 2024). These technologies are essential for the power industry to adapt to a rapidly changing climate, and build resilience in the energy infrastructure. AI/ML-based tools can support efficient predictive maintenance systems, accurate renewable energy forecasting models, and robust cybersecurity algorithms, fundamentally upgrading 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, energy distribution management, and environmental management, optimising energy distribution, reducing costs, and enhancing energy efficiency while ensuring a reliable energy supply in a constantly evolving environment. Beyond the energy sector, these tools can also enhance the resilience of critical infrastructure systems in other sectors, including water management, transportation, and telecommunications, by providing advanced analytics, predictive capabilities, and efficient resource management.

Research on critical infrastructure and its resilience/vulnerability amidst climate change is closely related with research on adaptation in urban settings (see Insight 8). Indeed, the title of the chapter in the latest IPCC WG2 report (2022b) is “Cities, settlements and key infrastructure”. But this is not only an issue of co-location: The defining characteristics of urbanisation actually can shape the intensity of hazards. One striking example is the trend towards more dense ‘urban morphology’, which underlies the urban heat island effect (Harmay and Choi, 2023; Karimi et al., 2023) and in turn leads to a significant increase in cooling demand (30-40% in the EU, Perera et al., 2023a). Urban heat islanding, adding to the impact of extreme heat events will further strain energy grids and make urban energy transition challenging (Javanroodi et al., 2023). Simultaneous increases in population and economic activities (up to 80% of global GDP will be generated in urban areas) will demand resource concentration towards urban areas. These supply chains, including the electricity grid, may become more vulnerable to extreme climate events. Addressing these bottlenecks is essential as the population in urban areas is expected to double by 2050 (compared to 2023), and more than 1 billion people will live in informal settlements that are particularly vulnerable to extreme events, especially heat waves. Detailed climate risk and vulnerability assessment in urban areas at the municipality level is required to prepare for extreme climate events especially considering the underserved and marginalised communities (Hartinger et al. 2024; Zhu et al. 2024 report). Co-optimizing urban function, urban form, urban infrastructure, and networks (sectoral and spatial interactions) could help to enhance the sufficiency level of urban areas (Perera et al. 2021). Increased attention is being paid to nature-based solutions that have 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 (Iungman et al., 2023), as well as mitigate flood risk, exhibiting both social and ecological benefits (Huang et al., 2020)

BOX: Resilience planning for critical infrastructure and the private-public interplay

Despite the high level of privatisation in many sectors, adaptation requires engagement from both private and public sectors, within which perceptions of risks and capabilities for risk assessments can vary (Juhola et al., 2024). These risk perceptions and policy signals both drive adaptation in private companies. Adaptation with the aim of long term resilience may not be prioritised, if no significant incentives can be identified. Here, adaptation policy instruments to steer the private sector become important, and yet they are mostly lacking from national and local adaptation strategies. One notable exception is the United Kingdom's Adaptation Reporting Power, which mandates reporting on adaptation of infrastructure providers (Romsdahl et al., 2017).

Insight 9. Responsible Energy Transition Mineral Value Chain: Closing the Governance Gap

Examining the energy transition minerals (ETM) value chain is crucial given the anticipated surge in demand for these minerals as part of decarbonization initiatives (Fikru and Kilinc-Ata, 2024). ETMs, often called critical minerals, include minerals and metals that are essential inputs for the energy transition and clean energy technologies (IRENA, 2023). These include, but are not limited to, cobalt, copper, graphite, lithium, nickel, and some rare earth elements. Considerable attention is often given to technological aspects and ensuring an adequate and cost-effective supply of ETMs. However, ensuring a just and equitable transition for producer countries in the Global South and achieving an energy transition within planetary boundaries have not received enough attention. In this context, responsible mineral value chains emerge as a critical policy area for energy transition and net-zero emission reduction goals (Janardhanan et al., 2023). Responsible mineral value chains focus on minimising environmental impacts, upholding high labour standards, and engaging local communities throughout the extraction, processing, and distribution stages. Achieving this is a continuous and dynamic process that includes community benefit plans, local consultations, respect for cultural assets, minimising resource use, ensuring transparency, and managing ESG risks.

Key concerns surrounding ETMs are multifaceted, encompassing trade dynamics and value chain-related impacts. While there is consensus that the demand for ETM will continue to increase alongside these initiatives, there are differing forecasts on the extent, timeframe, and rate of this increase (Calderon et al., 2024). The projected global increase in mineral demand, along with potential supply disruptions and price fluctuation, is expected to shape new geopolitical dynamics in international relations (IRENA, 2023) and trigger strategic responses from governments, such as offering tax credits, imposing mineral import bans, and forming alliances to preserve supply security. This surge in demand is also expected to prompt the development of newer mines to meet the growing demand. However, under current conditions—such as the known reserves, market prices, technological capabilities, and policy goals—the mineral intensity of the energy transition could lead to high supply risk for some minerals (Savinova et al., 2023), meaning that the supply of these minerals may not meet the growing demand, potentially causing shortages or disruptions. Additionally, misalignment between national resource inventories and the implementation of policy actions required to make these mineral resources available could lead to global-scale delays in advancing the energy transition and mitigating climate change (Owen et al., 2023). As the demand for finite mineral resources rises, their prices may increase, leading to higher production costs for clean energy technologies.

The search for new mineral sources and reserves could adversely affect communities in the vicinity of these sites and be met with strong opposition and resistance, including refusal to extend social licences to operate if these projects are perceived as imposing high costs on the community compared to the benefits they offer. A recent study found that 69% of over 5,000 global ETM projects are located on or near land classified as Indigenous peoples' or peasant land (Owen et al., 2022). 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. For instance, while cobalt mines are predominantly located in the Democratic Republic of Congo (DRC), less than 5% of production is controlled by DRC-owned companies (IEA, 2024a). While there are initiatives to improve transparency, community participation, and due diligence across the supply chain, comprehensive governance mechanisms remain extremely limited. These mechanisms struggle to balance geopolitical interests, address the security-sustainability nexus (Riofrancos, 2023), harmonise trade and climate perspectives, and ensure civil society's involvement beyond private sustainability standards.

Mineral extraction and processing have wide-ranging impacts, such as biodiversity loss, land degradation, water scarcity, pollution, and resource depletion. These effects are particularly felt in resource-rich, Global South countries and can exacerbate socio-economic disparities through effects on agri-food systems, public health issues, and disruptions to local livelihoods. Technical challenges, such as suboptimal processing and recycling methods, worsen environmental harm, highlighting the need for improved technological solutions and responsible practices throughout the value chain. A business-as-usual approach could substantially increase waste, estimated at 2,000 Gt by 2050 (Valenta et al., 2023). The ETM value chain is influenced by and influences the political economy, geopolitics, economics, environmental, and societal impacts. While surface-level concerns are acknowledged by governments and corporations, other more specific, complex, and intersecting issues like gender and violence against women (Mishra et al., 2024), Indigenous land rights and cultural heritage, impacts on agri-food systems, and transition risks for businesses are often overlooked in policy debates (Figure 9).

Challenges for a just energy transition arise from a lack of economic diversification, limited technological capacity, and heavy reliance on extractive sectors in energy transition mineral-rich countries. Kramarz et al. (2021) developed a typology of displacement that includes displacement through commodity-dependent development, defined as a path-dependent process that locks individuals, communities, and economies into a particular trajectory. Additionally, corporate accountability challenges and disparities in regulatory access and dispute resolution mechanisms, including double standards in trade policies and investment dispute settlements, present significant barriers for Global South countries in advancing energy transition solutions, thus delaying climate action (IRENA, 2023). For instance, mineral stockpiling by Global North countries can exacerbate supply chain constraints, inflate prices, and contribute to an inequitable energy transition. However, no formal mechanisms exist to penalise such actions. On the other hand, mineral export restrictions by Global South countries, as seen in Indonesia’s attempts to regulate its nickel reserves through export limitations and domestic processing requirements (dispute settlement, WTO, 2022).(dispute settlement, WTO, 2022), can lead to high-level disputes and be penalised.

In the context of a mining rush, competitive dynamics, and increasing public opposition, there is a critical need to find mechanisms to balance benefits with trade-offs, uphold the highest standards of social equity and environmental stewardship, and offer long-term and context-specific measures rather than providing blanket solutions for all mineral commodities and nations (Fikru and Kilinc-Ata, 2024).

More research is needed to identify discrepancies in rules and decisions across regulatory mechanisms, agreements, and forums, particularly those related to trade, investment, and climate commitments. This should include examining regulations on technology transfers, local content, and factors affecting investors' profit expectations. New research should identify ways to enhance capacities and access patents and technologies, especially in the Global South, to ensure that energy transition solutions do not perpetuate existing asymmetries. Understanding these intricate relations is essential for informing effective governance for a just and equitable transition to sustainable energy and climate neutrality.

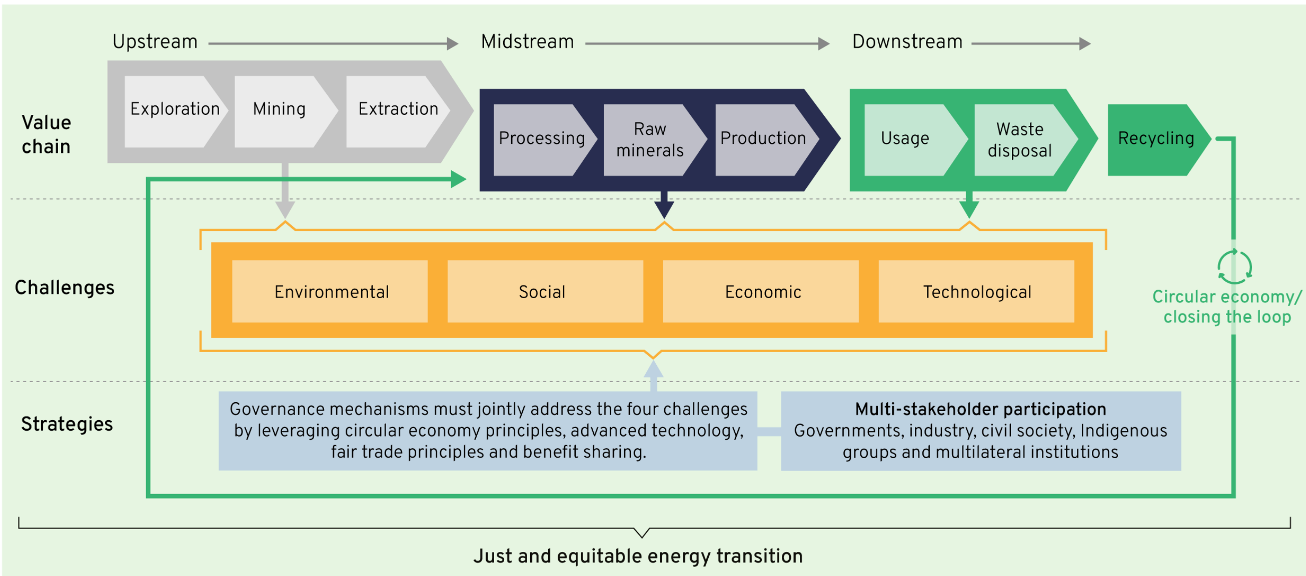

Figure 9: Addressing challenges of ETM value chain to achieve a just and equitable energy transition
The ETM value chain and the challenges different stages present across environmental, social, economic and technological domains.

Insight 10. Bringing everyone on board: navigating resistance to and acceptance of climate policies

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 mobilisation, and civil unrest. Examples include the Yellow Vests in France, recent European farmer's protests, and 'quiet' resistance by disadvantaged populations worldwide (Brink et al., 2023). 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. Lately, certain political parties have also been fueling and shaping public opinion for a backlash against climate politics to align with perceived sentiments in the general public (Huber et al., 2021; Kulin et al., 2021).

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, economic conditions, and policy types (Brink et al., 2023). Considerations of cultural factors should also include country-specific political-economic factors, which are crucial elements for the success of climate policies (Jones and Cardinale, 2023) [Figure 10]. Across this evidence, the issue of (un)fairness emerges as a central determinant of acceptance and resistance. 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 (Bergquist et al., 2022). Resistance can stem from a perceived unfair distribution of economic costs, job insecurity, cultural identity, and social justice concerns resulting from climate policy (Vargas Falla et al., 2024).

Fairness concerns the distributional aspects of specific policy instruments and the procedural elements of policy adoption. In the energy sector, for example, creating transition areas, fostering deliberative processes for adaptability, and promoting gender equality are crucial to increasing social support for new energy systems and inclusive and sustainable transition strategies (Biresselioglu et al., 2024). 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 appear to generate a similar level of public resistance (Harring et al., 2023). 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 (Sælen and Kallbekken, 2011), while other recent studies conducted in the Global South support cash transfers to poor or vulnerable groups (Dechezleprêtre et al., 2022) and investments in social programmes (Harring et al., 2024).

People's perceptions of fairness vary, including concerns about higher fuel prices, freedom, and living standards, affecting not only vulnerable groups (Povitkina et al., 2021) 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 marginalised 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 (Vargas Falla et al., 2024). Examples include relocation programmes 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 learnt, historically entangled, and linked to issues beyond climate policies, such as lack of trust in the state (Brink et al., 2023). 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 (Vargas Falla et al., 2024). 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 (Dechezleprêtre et al., 2022). However, standard macro- and microeconomic analysis methods need to be complemented with the mesoeconomic analyses of sectors (Cardinale, 2019; Vargas Falla et al., 2024) and social groups (Tatham and Peters, 2023). 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 labour unions advocated for exemptions on public transport fare increases (Jones and Cardinale, 2023).

Maintaining a balance between specific and general interests within countries has proven increasingly difficult in recent years. Previous national reforms, such as liberalisation and privatisation, as well as the degree of integration into the global economy, 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.

There are still gaps in the literature, notably women's opposition and role in resistance to low-carbon transitions (Biresselioglu et al., 2024), highlighting the need for more comprehensive research. 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 (Brink et al., 2023; Inchauste and Victor, 2017; Tatham and Peters, 2023). There are also perception gaps: studies have highlighted widespread public support for climate action, with nearly 70% of respondents willing to allocate 1% of their income and almost 90% desiring increased government efforts, but they often underestimate their fellow citizens' willingness to contribute (Andre et al., 2024). 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 (Hulme, 2020).

Overcoming resistance requires inclusive, democratic processes and bottom-up approaches that involve local communities and authorities in decision-making (Biresselioglu et al., 2024; Vargas Falla et al., 2024). 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 (Jones and Cardinale, 2023). However, not all resistance should be overcome, as it can represent an alternative form of political participation (Vargas Falla et al., 2024). One viable perspective is to recognise and utilise resistance as a means to highlight and debate potentially overlooked needs in society, particularly those of marginalised 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.

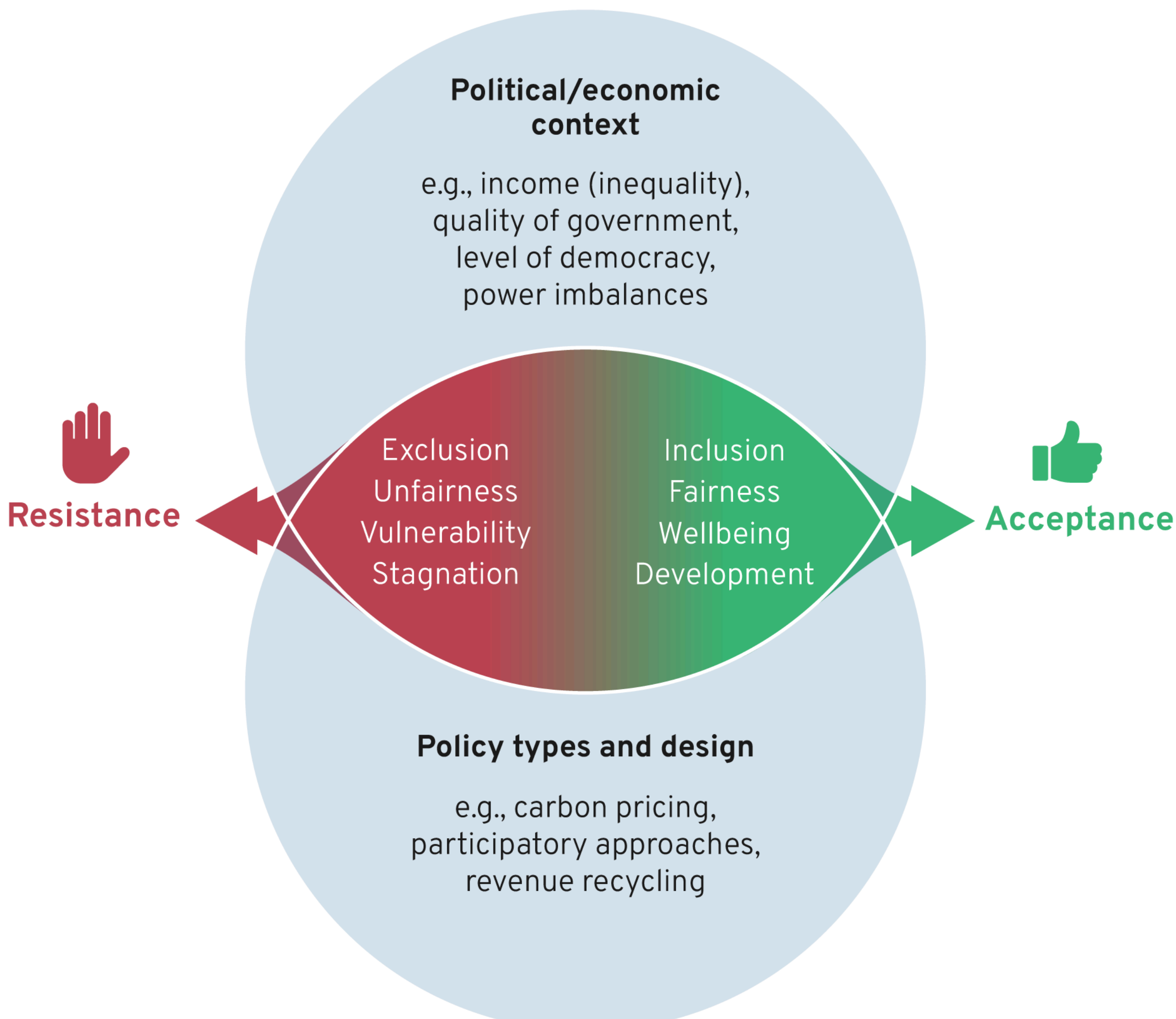

Figure 10. Interaction factors leading to climate policy resistance or acceptance.
The interaction between political-economic contexts and policy designs can either lead to exclusion, injustice and vulnerability– resulting in popular resistance – or to inclusion, fairness and development – resulting in popular acceptance.

Discussion

The heat anomaly of 2023 was striking not only because it broke consecutive monthly records since July (now extending well into 2024), but even more so because of how perplexing this sharp temperature rise has been for climate scientists. Climate models cannot fully account for this behaviour, which suggests a significant knowledge gap and the possibility that global warming is already fundamentally altering the climate, putting the world in “uncharted territory” (Schmidt, 2024). Now, it is more likely than not that 2024 will be even warmer (NOAA-NCEI, 2024b). The Insights featured in this review are essential pieces to make sense of the current situation and inform priority actions on mitigation and adaptation.

The first Insights presented in this paper focus on emissions in the atmosphere of non-CO2 gases with major implications for the Paris Agreement warming limits: Aerosols declining (Insight 1) and methane soaring (Insight 2). While the factors underlying the former are known, the consequences are much harder to foresee (IPCC, 2021, chap. 6; Mahowald et al., 2024). Conversely, the exact sources of the increasing methane emissions might not be fully established yet, but the consequences of the rising trend are clear and hugely problematic, as they further reduce the remaining carbon budget aligned with the Paris Agreement (Rogelj and Lamboll, 2024). While the reduction of anthropogenic aerosol emissions has been hugely beneficial for public health, it has also “de-masked” the true level of warming produced by the accumulation of anthropogenic GHG emissions (IPCC, 2021, chap. 7). At the same time, GHG emissions continue to rise, and in the case of methane even accelerate (Lan and Dlugokencky, 2024; Nisbet et al., 2023; Saunois et al., 2024 [submitted]) . An additional concern is the likely effect of climate feedback mechanisms, further amplifying methane emissions from natural ecosystems (Insight 4 in Bustamante et al., 2023). Understanding the processes stemming from and leading to these changing atmospheric concentrations is crucial for developing adequate mitigation strategies. Here again, there is a clear rationale for prioritising emission reductions from the fossil fuel industry: health co-benefits associated with reduction of aerosol emissions, and the cost-effectiveness of addressing methane emissions.

As the atmosphere changes, other processes and components of the Earth system change too. Amidst the yet unexplained heat anomalies of 2023, a major concern is the risk of the destabilisation of Earth system elements, such as key ocean-climate processes (Insight 3) and the Amazon forests (Insight 4). It is useful to consider how much the impacts of El Niño events mirror those of global warming (i.e., amplified droughts and floods, and temperature extremes). On one hand, this means that investing in socio-ecological resilience to El Niño events, means also enhanced resilience to future climate change. On the other hand, the vulnerability of the global economy to ENSO ((Callahan and Mankin, 2023; Liu et al., 2023) also suggests a broader latent vulnerability to future climate change. Furthermore, whereas the impacts of ENSO are something to which societies today are inured to (even if poorly adapted), other risks in the horizon, such as the potential collapse of AMOC (Ditlevsen and Ditlevsen, 2023; van Westen et al., 2024), could result in changes beyond the scope of societal experience. In the case of the Amazon forests, it is not only climate change but also land use change that threatens their stability. More specifically, these gradual drivers are weakening the forest-rainfall feedback (Lapola et al., 2023), and progressively increasing the risk of a systemic collapse of the Amazon forests (Flores et al., 2024). Enhancing the resilience of the Amazon must be a global priority, and recent research highlights the crucial role of functional and response diversity, as well as bio-cultural diversity, in achieving this goal (Levis et al., 2024; Rius et al., 2023). Precaution, rather than certainty about exact tipping points or the timing of a potential collapse, should be enough to galvanise decisive collective action to stabilise these land-atmosphere and ocean-atmosphere processes.

Four Insights form a cluster on climate change impacts, primarily related to heat extremes, that affect fundamental aspects of social life. These Insights point to available adaptation options, but in some cases losses and damages are already a stark reality. For example, at just 1°C of warning above pre-industrial levels, over 600 million people are already living under conditions outside the narrow range in which humans have concentrated since Neolithic times (Lenton et al., 2023). In the coming decades, a growing fraction of the Earth's surface is projected to be under conditions deemed 'uninhabitable' (Insight 5). The increased intensity, frequency and duration of extreme heat is a direct threat to livelihoods, significantly interfering with outdoor labour (Nelson et al., 2024). While most of the potential migration and displacement associated with climate change impacts is bound to happen domestically, anticipatory governance will be important to facilitate mobility and social integration (Insight 4 in Martin et al., 2022; Scheffer et al., 2024 [accepted]). Extreme heat is also a key hazard to maternal and reproductive health (MRH), one that gathered increasing attention in climate-health research, uncovering evidence on various mechanisms (Insight 6), including multiple direct physiological effects, as well as indirect effects through changes in individual and social behaviours ((Afzal et al., 2024); Scorgie et al., (2023); (Sundaresan et al., 2023); Zhu et al., (2023)). Unless comprehensive adaptation plans are implemented, there is a serious risk of reversing the progress made in MRH over the recent decades. Justice and gender-based rights approaches are highlighted. Priority actions to prepare for increasing risks of heat stress include the establishment of early warning systems and revisions of outdoor labour guidelines. Cities are crucial foci for the implementation of these actions. Climate-resilient development is now seen as a priority, recognising the outsized role of cities for climate mitigation and their needs for adaptation, while continuing to pursue development goals for the greater well-being of all inhabitants (Sánchez Rodríguez and Fernández Carril, 2024). Insight 7 highlights the SETS approach to guide governance efforts, facilitating the identification of strategies that maximise co-benefits and minimise trade-offs (Chester et al., 2023; Sharifi, 2023). Closely related is the issue of the vulnerability of critical infrastructure to climate related hazards (Insight 8).This Insight features the known risk of disruptions propagating across multiple critical infrastructure systems and networks. It zooms in on the example of the energy sector to highlight available technological solutions to enhance resilience of power grids.

The two final Insights highlight two areas of governance and policy design on which much of the success of climate action will hinge: Robust and responsible governance of the globalised energy transition minerals value chain (Insight 9) and improving the social acceptance of climate policies (Insight 10). The rapid deployment of clean energy has been at the root of the "structural slowdown" of CO_2 emissions (IEA, 2024b), and high expectations continue following the COP28 goal of tripling renewables' capacity by 2030. Yet, risks abound for the supply of key minerals (Savinova et al., 2023), exacerbated by policy misalignment, which could delay the transition (Owen et al. 2023). Moreover, known socio-environmental conflicts are a recurrent feature of mining operations, imposing a disproportionate burden on producer countries in the Global South. Responsible mineral value chains will require comprehensive, context-specific and enforceable mechanisms that uphold social equity and environmental standards, and ensure transparency towards a just transition to climate neutrality.. Relatedly, the perception of (un)fairness is at the core of resistance to or acceptance of climate policy (Bergquist et al., 2022), both for mitigation and for adaptation (Insight 10). This stems from the distributional consequences of specific policy instruments as well as the procedural elements of policy adoption, but it also depends fundamentally on the political-economic context (Vargas Falla et al., 2024). Governments could make use of lessons from political science to inform the design and deployment of climate policies with higher levels of public acceptability. These include considerations about framing, information, and participation, policy sequencing, policy packaging, among others (Heyen and Wicki, 2024). For example ‘revenue recycling’, by which revenue from a new carbon tax or a removed fossil fuel subsidy is allocated to offset impacts perceived as unfair.

Climate action is embedded in a challenging socio- and geopolitical context in 2024. Ongoing and escalating armed conflicts within and across state boundaries consume the public's attention and focus of policymakers, diminish political will, increase polarisation and drain financial flows. These are challenging times for multilateral cooperation. Much of the policy direction of the future years hinges on the outcomes of national elections in 50 countries, including the United States, India, and the European Union, amidst concerns over public resistance to ambitious climate policies. As we approach the halfway mark of this crucial decade for the implementation of robust climate policies, scientific communities have a key role to play in ensuring the accountability of all parties towards fulfilling their commitments to the Paris Agreement.

Methods

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 described below builds directly on the one described by (Bustamante et al., 2023). Around mid-January, an open call for expert input is distributed as an online questionnaire, 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 very 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 197 individuals, totaling 216 suggestions.

The suggestions or 'entries' collected were screened based on predefined inclusion criteria; each individual entry was screened by at least two team members. 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 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 was then evaluated in a three-stage process by our editorial board, consisting of17 well-established international climate change researchers from various disciplines, who constitute our editorial board. First, the 62 themes were categorised into four broad categories: (i) the Earth system, (ii) impacts, (iii) action needed, and (iv) barriers. The editorial board members then individually prioritised 4–20 themes (1-4 per category) which they considered most relevant overall. Second, building on the outcomes of the individual prioritisation of themes, the editorial board members gathered virtually for a workshop to deliberate and collectively prioritise the themes, leading to a preliminary set of candidate insights. Finally, the candidate insights were examined more deeply, with editorial board members providing further input and arguments. Based on this final round of input, the editorial board members approved the final list of ten insights. With a brief initial outline for each Insight, ten international groups were recruited (each composed of 3-7 topic experts) to synthesise the key messages from recent academic literature for the chosen Insight.

Supplemental Information

Supplementary information includes: (1) a flow diagram of the process, (2) the questionnaire for the 'open call for expert input', (3) the inclusion/exclusion criteria used to screen entries, (4) the results of the complementary literature scan, and (5) the list of resulting themes. It can be found online at: https://xxx *[NOTE: provided as separate files for reviewers]*

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Author contributions

WB, MBu, JGC, SFu, ATG, TYJ, JK, JM, AM, ÅP, JRoc, JRoy, RS, ELFS, PS, YS, and DT constituted to the editorial board, selected the insights to be highlighted, and provided initial guidance on the outlines. DO, PMi, and RS led the overall writing. Investigations and writing for each insight: PA, GP, IR, BHS, and YY (insight 1); SFe, ÖG, JDM, CM, ET, JW, and ZZ (insight 2), WC, MPA, PD, JYL, JSM, and RMW (insight 3); AA, MH, DL, CL, and BS (insight 4); SR, VT, DJV, CX, and MZ (insight 5); MBo, CH, AL, and SP (insight 6); UE, TAME, ZN, AS, and WYS (insight 7); MA, SJ, SK, JN, ATDP, and GZ (insight 8), MGF, NJ, PMa, and (insight 9); and MEB, EB, RC, NH, and AMVF (insight 10). Additional investigation and writing, as well as coordination for each insight: TB (insight 1), SH (insight 2), HCW (insights 3 and 10), AH and MM (insight 4), AR (insight 5), NK (insight 6), GBS (insight 7), SS (insight 8), and PMi (insight 9). DO and PMi. coordinated the overall process.

Declaration of Interests

The authors declare no competing interests.

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