PLOS CLIMATE

ESSAY

The physical science basis of climate change empowering transformations, insights from the IPCC AR6 for a climate research agenda grounded in ethics

Valérie Masson-Delmotte*

Institut Pierre Simon Laplace / Laboratoire des Sciences du Climat et de l'Environnement (UMR8212), CEA Saclay, Université Paris Saclay, Gif-sur-Yvette, France

* valerie.masson@lsce.ipsl.fr

This manuscript builds upon a keynote presentation invited at the World Climate Research Programme (WCRP) Open Science Conference in October 2023 [1], at the start of the IPCC 7th Assessment Cycle (AR7).

OPEN ACCESS

Citation: Masson-Delmotte V (2024) The physical science basis of climate change empowering transformations, insights from the IPCC AR6 for a climate research agenda grounded in ethics. PLOS Clim 3(8): e0000451. https://doi.org/10.1371/journal.pclm.0000451

Editor: Jamie Males, PLOS Climate, UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND

Published: August 5, 2024

Funding: The authors received no specific funding for this work.

Competing interests: The author has declared that no competing interests exist.

A fast changing climate and a fast shrinking remaining carbon budget calling for reactivity

As climate scientists, we operate in a changing context. At the start of the IPCC AR6, in 2015, there were major advances in international cooperation towards sustainability, leading to the implementation of several new frameworks, including the UN Sendai Framework for Disaster Risk Reduction, Sustainable Development Goals, New Urban Agenda and the Paris Agreement [2].

Within the AR6 cycle, a strong emphasis was placed on the interplay between climate change, ecosystems and biodiversity with, for the first time, a joint workshop between IPCC and IPBES [3], and the implementation in 2022 of the UN Convention on Biological Diversity Kunming-Montréal Global Biodiversity Framework.

In 2023, the AR6 IPCC Synthesis Report [4] emphasized that the pace and scale of current climate action is not sufficient to limit the escalation of climate-related risks, with a rapidly narrowing window of opportunity to enable climate resilient development, and the key role of sharing knowledges to support transformative changes.

With a fast changing climate (Fig 1), regular updates of the state of climate are critical to inform society–more frequently than IPCC reports, with AR7 outcomes expected by 2028. Such efforts have already been implemented for the global carbon budget [5] and the annual state of climate [6] and extreme events [7, 8]. Grounded in updates in observational datasets and the same methodologies underpinning the AR6 WGI report [9], a new coordinated effort provides annual updates to key indicators of the state of global climate, showing changes in radiative forcing, Earth's energy imbalance, and human-caused global warming occurring at an increasing pace [10]. Such annual updates to attributable global and regional warming now open the possibility of annual updates to observationally-constrained global and regional projections [11, 12].

The remaining carbon budget from 2023 onwards compatible with limiting global warming to 1.5˚C has been reduced by a factor of two compared to its IPCC 2021 estimate [9], shrinking to around 250 GtCO2—expected to be exhausted within around 6 years at the current rate of

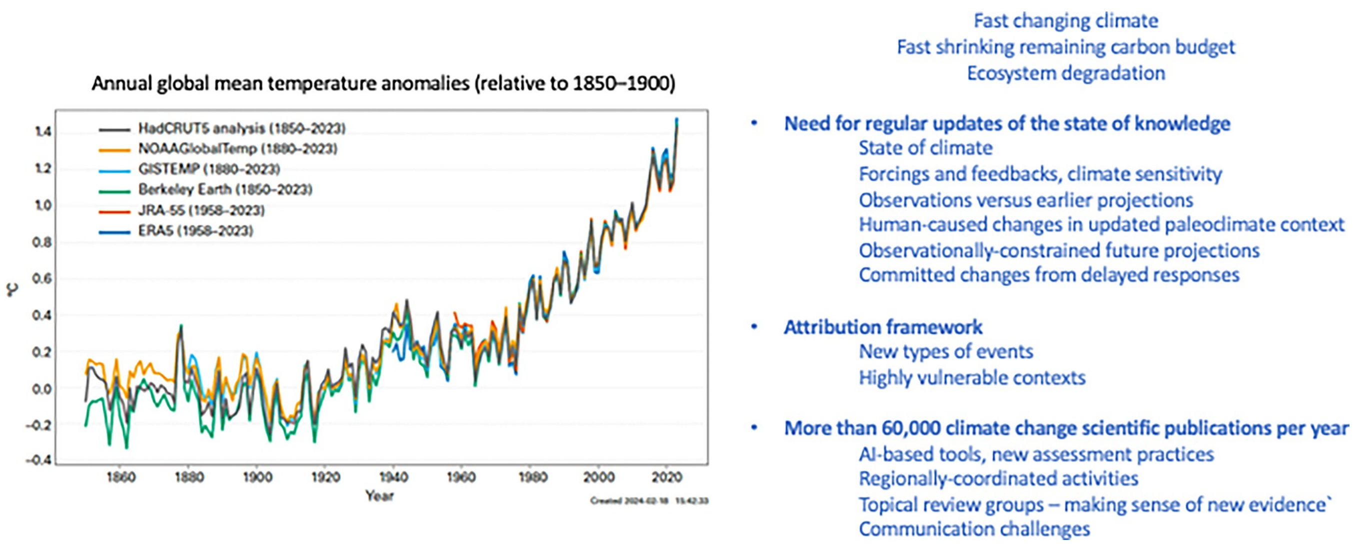

Fig 1. Annual global mean temperature anomalies updated until 2023 from six datasets [76] and needs for regular updates of the state of knowledge.

https://doi.org/10.1371/journal.pclm.0000451.g001

emissions [13], thus inexorably leading to exceed this 1.5˚C level of warming within a decade. Understanding the increased rate of the Earth's energy imbalance [14] also calls for updates in estimates of aerosol forcings, climate feedbacks [15], and carbon cycle consequences of ecosystem degradation [5].

Efforts are also needed to provide regular updates to committed changes from delayed responses of glaciers [16], ice sheets and the deep ocean, and unavoidable sea-level rise [17], and, when onsets can be unequivocally detected, implications of dynamical instabilities in specific Antarctic sectors [18].

Every further increment of global warming brings us further outside of the range of the state of climate of the past recent thousands of years. Systematic approaches to update IPCC assessments of ongoing and projected changes grounded in multiple lines of evidence, including insights from past climates, are also needed [19]. New evidence suggests that the current atmospheric CO_2 concentration is unprecedented in not just the last 3 but the last 14 million years [20]. Recently, new methods have allowed to combine paleoclimate evidence with advanced understanding of climate pattern effects, further narrowing the upper bound of equilibrium climate sensitivity [21].

A major expectation for climate science is making sense of observations, compared to earlier projections [22]. So far, such comparisons with various projections are available based on volunteer individual updates on several science-related blogs [23–25]. Regular updates are needed to understand whether recent observed changes are consistent with the current understanding and modelling of forcings, internal variability and feedbacks, or whether exceptional events do challenge current understanding [26, 27]. By 2023 –the warmest year on instrumental records, observational datasets show that global surface temperature anomalies have increasingly frequently reached or exceeded 1.5˚C above 1850–1900 at the monthly scale, and for the first time close to this level for an annual average [28]. The likelihood of such occurrences will increase with the level of global warming, and is expected to occur every second year by the early 2030s, when such a level of global warming is expected to be reached and exceeded. With natural variability modulating human-driven trends, climate science communication can be challenging–navigating between perceptions of slowdowns and surges [23]. Shared tools are needed to place recent observations within the spread of earlier IPCC constrained projections, and to use attribution outcomes to constrain future global and regional projections [29, 30].

A recent example highlighting the urgent need for such analyses is the sharp decrease in Antarctic sea-ice extent, plausibly a regime shift [31] related to the Southern Ocean heat uptake [32], and with major implications for confidence in future sea-ice projections [33] and risks of irreversible loss of related ecosystems and unique biodiversity [34].

Attribution studies and climate justice

With human-caused climate change exacerbating extreme events, leading to widespread impacts, in every region, we also need regular updates regarding observed regional changes in the frequency and intensity of extreme events, and event attribution outcomes. The "hexagon" figures in recent IPCC reports [4, 9] highlighted knowledge gaps due to limited data availability and lack of studies in regions of high vulnerability—a matter of climate justice and support to the loss and damage mechanism [35, 36]. Knowledge gaps also arise from the length of instrumental records, which could be complemented by paleoclimate evidence, and mismatches between simulations and observations, for instance with European hot extremes increasing twice faster than simulated during recent decades [37].

Since the IPCC 2021 assessment, rapid attribution studies performed within the World Weather Attribution project expand the knowledge basis for high-impact extreme heat, extreme droughts worsened by increased evaporation in a warmer climate, fire weather and extreme rainfall events across multiple regions. However, a framework to bring together studies using different lines of evidence and different attribution methodologies is missing to allow for regular robust updates and their expansion to ocean, cryosphere, compound and cascading extremes [38].

Facing the massive production of peer-review publications in climate science

With a growing production of climate knowledge worldwide, the number of peer-review papers with the keyword "climate change" published every year has doubled within the time span of the IPCC AR6, from around 30,000 per year in 2015 to more than 60,000 per year in 2022 [39], with around 2/3 arising from ocean and atmosphere sciences. While peer review is a key filter for scientific quality, any manuscript currently can currently be published in ever-increasing predatory journals or non-reviewed archive services, independently of its quality. Such challenges are strengthened by recent surges in AI-based tools and new challenges for science integrity [40, 41]. This is overwhelming, and calls our community to sharpen ethics of publications, avoid predatory journals, strengthen open science, open data and open code practices—including transparency related to reviewers, reviews, and accessibility of publications, and explore new publishing models and state of knowledge assessment practices. In this context, regionally coordinated activities are needed to digest and distillate new evidence, including grey literature from climate services, so as to consolidate a robust regionally-relevant evidence basis. Topical review groups are needed to help make sense of new or conflicting evidence and support the maturation of climate science, placing new lines of evidence within a common picture of the current state of knowledge.

This is also a major communication challenge, exacerbated by press releases and sensationalist news headlines exaggerating the alarming or reassuring findings of any single study, which is confusing for the general public and policy makers. This confusing communication towards the general public has been spectacular in 2023 and 2024 on issues associated with deep uncertainty, such as new studies focused on potential instability of sectors of the

Antarctic ice sheet [42, 43], or conditions for abrupt changes of the Atlantic Meridional Overturning Circulation [44–46].

Building on the experience of early career scientists group reviews of AR6 IPCC reports [47], more initiatives are needed to train young scientists from around the world to update the assessment of the state of knowledge on topics that they themselves find exciting, so that a new generation of scientists will be better prepared to sharpen the next IPCC reports, and communicate the updated state of knowledge to the general public.

A changing context at the start of the IPCC AR7—A critical decade

The world in which we operate, as climate scientists, is changing fast (Fig 2). With technological innovation, energy efficiency, and reduced rates of global deforestation, current policies have avoided 4 to 8 billion tons CO_2-eq emissions globally, and made very high future warming pathways less plausible [4]. An optimistic estimate of COP28 outcomes, if all pledges were to be kept, implies global greenhouse gas emissions to decrease from around 10% by 2030, far less than in pathways allowing to limit global warming well below 2˚C or close to 1.5˚C [48].

Inadequate progress towards sustainable development goals, growing food insecurity, and backlashes to climate and environmental policies are widespread. The slow pace of climate action, societal tensions, the escalation of climate change impacts and losses and damages fuel

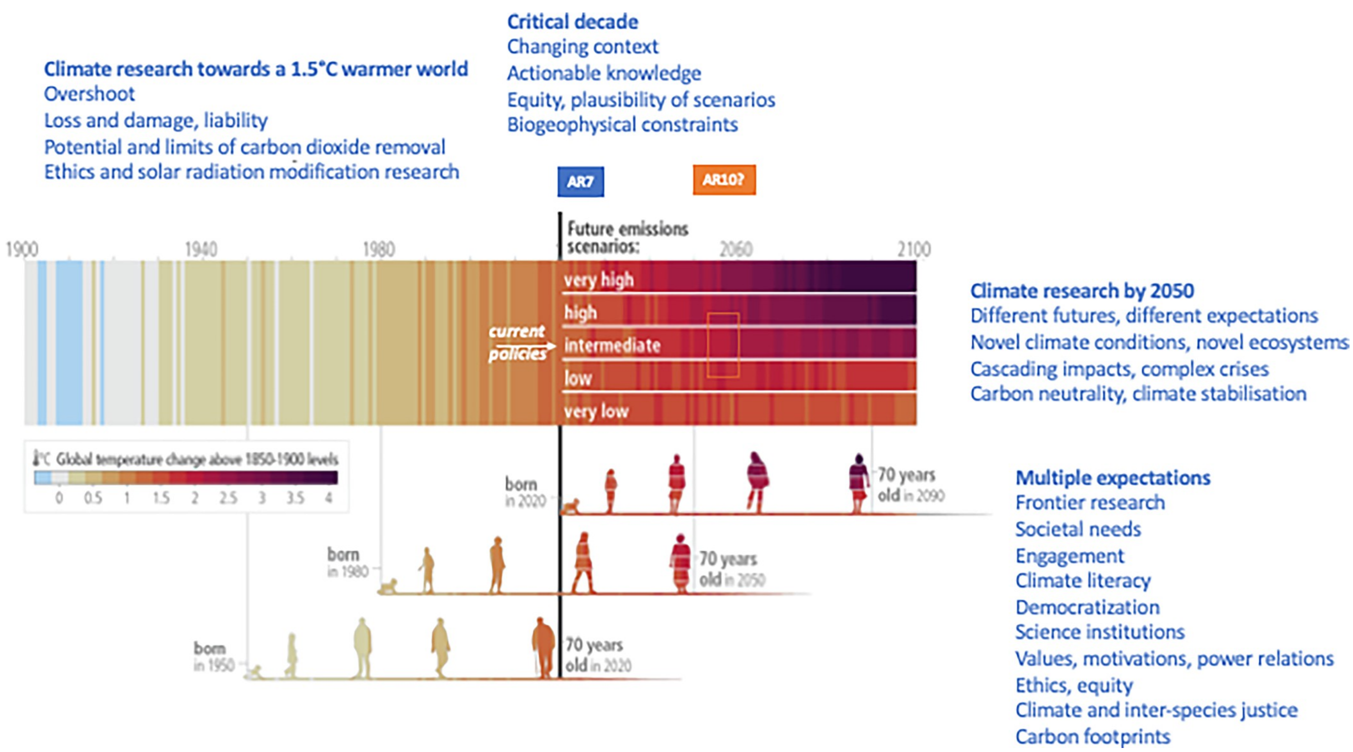

Fig 2. New challenges for climate science in a changing context and critical decade, towards a 1.5˚C warmer world, and projecting climate research towards 2050, with different expectations in different futures. Panel from the IPCC AR6 Synthesis Report [4]. Observed (1900–2020) and projected (2021–2100) changes in global surface temperature (relative to 1850–1900), which are linked to changes in climate conditions and impacts, illustrate how the climate has already changed and will change along the lifespan of three representative generations born in 1950, 1980 and 2020 (including generations of climate scientists). Future projections (2021–2100) of changes in global surface temperature are shown for very low (SSP1-1.9), low (SSP1-2.6), intermediate (SSP2-4.5), high (SSP3-7.0) and very high (SSP5-8.5) GHG emissions scenarios. Very high emission scenarios are considered less plausible due to current policies (closest to SSP2-4.5) and low carbon technological advances [4]. Changes in annual global surface temperatures are presented as 'climate stripes', with future projections showing the human-caused long-term trends and continuing modulation by natural variability (represented here using observed levels of past natural variability).

https://doi.org/10.1371/journal.pclm.0000451.g002

increasing climate anxiety–also affecting the mental health of climate scientists. COVID19 pandemic lockdowns added stress to observing systems which remain challenging to maintain. New obstacles to scientific collaborations, for instance in the Arctic, have emerged following the invasion of Ukraine by Russia. Inflation, growing inequalities, nationalism and populism, declining social coherency fuel political polarization, with populist parties embedding the defamation of scientific expertise, denial of both climate science and the urgency of transformative action within their core values. With social networks, the spread of disinformation and the weight given to opinions above evidence erodes the overall trust in science.

How to best operate, as a scientific community, in that fast changing context? This calls for careful attention to the equity and plausibility of scenarios underpinning future climate projections [49], with due attention to biogeophysical constraints from a warming world–for instance, hard limits for sustainable use of groundwater [50] and forest biomass [51] at regional scales. Reactivity is important in order to develop timely new robust knowledge exploring the climate change and climate action implications of e.g. lockdowns from a pandemic, stratospheric water vapor injection from a volcanic eruption, regulations for shipping fuel sulfur content, or armed conflicts. IPCC could learn from the more flexible IPBES processes allowing to convey timely interdisciplinary workshops and provide relevant peer-review workshop reports [3, 52].

Effective climate action also requires actionable knowledge, including methods to assess the effects of mitigation and adaptation measures, guidance to avoid maladaptation and malmitigation, knowledge to support sustainable use of ocean, land, water, and sustainable cities–including how to maximize climate and air quality benefits. Climate information needs to be specifically coproduced with those most vulnerable, in climate change hotpots [53].

The framework of climatic impact-drivers developed in the IPCC AR6 WGI report was not sufficiently informed by ecosystem and biodiversity stewardship needs [54] calling for robust assessments of methodologies to develop relevant climate information (e.g. climate velocity) at required scales.

The multiple regional consequences of global sea-level rise are emerging, including chronic high-tide flooding [55], extreme sea level events, salinization and coastal erosion–with needs for attribution and confidence in projections of at the scale of settlements. New ethical questions arise from research needs from planned relocation.

Climate research for a 1.5˚C warmer world

Human-driven trends resulting from future emissions are expected to lead to 20-year average global warming overshooting a level of 1.5˚C within around a decade [4]. Informing risk management and adaptation strategies calls for advancing the knowledge basis on the full possible severity of direct consequences, including the low-likelihood, high-risk plausible extreme events and unprecedented combinations of events, accounting for the worse possible combinations of human-caused trends and internal climate variability [56] and long-term outcomes [57]. Better understanding what would be the possible irreversible consequences of various intensities and durations of overshoot are critical to inform global responses, including for committed glacier loss, potential tipping points, sea-level rise, ecosystem degradation and biodiversity losses [58].

Theoretically, returning from a temporary overshoot is conditional on sharp emission reductions, reaching net zero CO_2 emissions with limited cumulative CO_2 emissions, followed by the ability to sustain various magnitudes of net negative CO_2 emissions. Knowledge advances are needed to narrow uncertainties from the response of carbon cycle feedbacks, including biological processes resulting from ecosystem disturbances and degradations, which could also be triggered by natural variability within a 1.5˚C warmer world. While theoretical studies using simplified emulators rely on large-scale carbon dioxide removal to return to 1.5˚C after a temporary overshoot, the plausibility of such pathways lacks a robust evidence basis [59] on feasibility, costs, permanency and risks, accounting for their demands for low-carbon energy, water, biomass and land–in particular when massive amounts of low-carbon energy production are primarily needed to phase-out fossil fuels.

Following COP28, the new resources allocated to loss and damage remain small (around 0.7 billion $) compared to the needs estimated to reach 100 to 400 billion $ per year by 2023. This mismatch highlights the rejection of loss and damage liability by the largest historical and current emitters of greenhouse gases. The framing of solar radiation modification research cannot be restricted to the uncertainties regarding potential interventions and the modelled response of the climate system. Such approaches call for embedding the myriad of ethical questions grounded in its purpose, including the implications of altering the global environment rather than modifying our practices to preserve it, and risk of multi-century legacies of deployment [60]. Ethical questions also arise from the embedded power relations, the values and interests of billionaire philanthropies who chose to fund specifically these research activities [61], at the expense of other climate research directions, and the possible conflicts of interests which encompass space agencies and climate scientists themselves. Consideration of solar radiation modification also needs to explore governance challenges [62, 63], including mechanisms of liability for attributable unintended outcomes.

Projecting climate sciences towards mid-century: Different possible worlds

Today's PhD students will be my age by 2050, when the 10th IPCC assessment cycle would be due. The expectations from climate research would be very different in different 2050 worlds [64]. At the pace of current policies, intermediate or high emissions pathways would lead to exceed a level of 2˚C of global warming by 2050 –uncharted territory for the past millions of years. In a fragmented, uncoordinated world, climate scientists would be monitoring novel climate conditions, and learn from Earth system responses to increasing emissions, loss of ecosystems and nature's contributions to people, cascading impacts, eroding food, water, habitat security, public health, leading to more poverty traps. What would be the science-society relationships with growing public unrest and political destabilization from climate disruptions? Facing complex crises, governments and funding agencies would search for rapidly conceived mitigation plans, without long-term planning, testing, and careful attention to the multiple dimensions of sustainability, with the risk of increased pressures on ecosystems, water and food security–and with fewer ecosystem-based and water-related adaptation response options available.

If different choices are made in the coming decades, the world by 2050 could be on track towards carbon neutrality, and climate science assessments could be monitoring the emergence of climate stabilization–learning from the success story of ozone assessment reports. Advances in climate sciences would support the management of intermittent renewable energy production and energy storage, inform transformative, proactive adaptation measures, support to poor and disadvantaged communities struggling with the growing burden of climate impacts. Transdisciplinary research practices would expand to understand the implications of species movements and novel ecosystems, and inform ecosystem stewardship and durable land and ocean carbon storage. Regular revisions of sea level projections following the detection of onset of ice sheet instability processes would be strongly embedded in deliberations and choices related to sea level rise and coastal management, including planned relocations.

By 2050, in such a world successfully embedding climate action, climate research activities, encompassing monitoring networks, remote sensing, field studies, laboratory analyses and modelling activities would be carbon neutral. This also calls for leadership of climate scientists on reducing now our own carbon footprint at the pace and scale consistent with our own knowledge.

Multiple expectations for the climate research community

WCRP plays a key role to tackle knowledge gaps, including convection and clouds, ocean and atmospheric dynamics, climate variability, Earth system feedbacks and thresholds in a warming world.

The vulnerability of land carbon to climate change and its role for mitigation call for improvements in inventories and processes involving soil organic matter, plant hydraulics and mortality, competition dynamics and disturbance processes–with stronger integration of biological and ecological sciences within climate sciences. Similarly, advances in land surface processes, including plant physiological changes, as well as groundwater recharge and land use and water management changes, are needed to improve future projections of aridity and drought.

Advances in fundamental climate research are the backbone to strengthen the knowledge basis required to address the myriad of expectations from climate sciences: knowledge relevant for mitigation, including air quality, pressure on land and litigation, and knowledge relevant for loss and damage, risk management, humanitarian responses, ecosystem and biodiversity stewardship, sectoral and regional adaptation and climate services.

New pathways have to be designed to offer career paths to scientists who are funded first because of urgent societal needs so that they also have opportunities to contribute to curiosity-driven, frontier research. Developing actionable knowledge, with salience, legitimacy and credibility, calls for in an in-depth understanding of the diverse values, perspectives, power relations and inequalities. Ethics, equity, climate justice and intra-species justice provide strong frameworks to advance the fitness and usefulness of climate information in under-studied regions, and explore the unintended consequences and potential harms emerging from misuses of climate information.

Multiple expectations encompass advancing tools and methods to provide more accurate information on complex and cascading risk which will be the hardest to manage and undermine sustainability aspirations in the near-term, as well as long-term outcomes, over multiple centuries beyond 2100, with due attention to post-forcing recovery and irreversibility, including habitats, ecosystems and biodiversity, and tipping points. Efforts are required towards the maturation of the framework of analysis of e.g. ice sheet instabilities, irreversible retreat, and their implications for pace and magnitude of sea-level rise over decades to centuries. Such a collective framework allowing to make sense of scientific advances and sometimes conflicting evidence arising from different methods is needed to better communicate the evolving state of knowledge with society [57].

Which roles for climate scientists

In a fragmented world, where growing South-North tensions challenge multilateralism, science diplomacy requires strong science-policy institutions and scientific advisory bodies at all governance scales. Institutional approaches play a key role to advance climate knowledge for effective and well-informed decision-making processes.

This also calls for climate scientists to better understand the diverse values and motivations [65], learning from social sciences and humanities [66], understanding powerful economic, political interests, and power relations [61], and to implement structured dialogues with the private sector so that corporate responsible approaches are grounded in the best available science [67]. While corporate responsibility approaches are currently focused on greenhouse gas emissions and transition risks, new knowledge is also required to advance corporate adaptation and resilience strategies, including their supply chains. For instance, the AR6 assessment remained limited for the implications of shifting agroclimate zones for important fiber and tree crops.

Making science meaningful for all is a challenge for effective climate science communication and knowledge co-production processes. Conversational artificial intelligence tools provide new opportunities make the outcomes of scientific assessments more broadly accessible, in plain language and in multiple languages, with the potential for more interactive engagement approaches [68]. IPCC could run an expert meeting on artificial intelligence tools and IPCC assessments, with multiple possible applications to support authors of assessment reports, ranging from systematic literature surveys to translations across multiple languages. Empowerment arises from knowledge, calling for democratization of climate science, with growing experiences from eg. citizen assembly approaches, and the involvement of climate scientists within deliberation processes. Science institutions need to encompass ethics of engagement within academic freedom and responsibility [69], together with resources and support for engaged climate scientists, and valuing their public engagement within their career paths.

While climate literacy is not sufficient to trigger climate action—as illustrated by recurrent discourses of climate delay within the scientific community [70], it is necessary. Trustworthy updated pedagogic classroom resources which can be used by teachers are needed for initial and continued education at all education levels [71]. Climate scientists also have a role to play to overcome current gaps related to the strengthening, monitoring and evaluation of climate literacy.

Evolution of climate science practices within societal transformations

Our changing context also calls for transformation of climate research, strengthening its ethics of research and practice, open science approaches, inclusivity and openness to multiple perspectives and novel ideas. Early and mid-career scientists at the WCRP 2023 Open Science Conference were asking for their voices to be better heard, and be better supported, in terms of professional well-being and mental health.

In a world where climate scientists can still be censored in their public expression, curiosity-driven research, academic freedom, and freedom of communication and engagement needs to be strongly supported.

Finally, climate research needs leadership to reduce the carbon and environmental footprints of research activities, building on shared tools, methodologies [72], collective deliberation processes to make the smartest use of travel [73], field and lab work, and computing resources [74, 75], changing collective academic norms, and strengthening recognition for environmental engagement from funding agencies and for scientific careers.

These are key ingredients for stimulating, meaningful, attractive, rewarding climate research—critical to motivate brilliant minds to advance knowledge.

Acknowledgments

I thank the World Climate Research Programme for inviting me to give this keynote presentation at the Kigali Open Science Conference in October 2023, in Rwanda. I thank members of the IPCC WGI AR6 Bureau and its Technical Support Unit, in particular Anna Pirani and

Sarah Connors, for multiple stimulating exchanges regarding climate science and science-society interplays. Special thanks to Catherine Michaut from the International Support Unit of Institut Pierre Simon Laplace for writing the transcript of my keynote lecture, forming the basis of this article. I also thank Yangyang Xu and two other anonymous reviewers for their constructive review comments.

Author Contributions

Writing – original draft: Valérie Masson-Delmotte.

References

1. World Climate Research Programme, Open Science Conference, Kigali, Rwanda, 2023. Available: https://wcrp-osc2023.org/.
2. Livingston JE, Rummukainen M. Taking science by surprise: The knowledge politics of the IPCC Special Report on 1.5 degrees. Environmental Science & Policy. 2020; 112: 10–16. https://doi.org/10.1016/j.envsci.2020.05.020
3. Pörtner H-O, Scholes RJ, Agard J, Archer E, Arneth A, Bai X, et al. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. Zenodo; 2021 Jun. https://doi.org/10.5281/ZENODO.4659158
4. Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne PW, Trisos C, et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. First. Intergovernmental Panel on Climate Change (IPCC); 2023 Jul. https://doi.org/10.59327/IPCC/AR6-9789291691647
5. Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Bakker DCE, Hauck J, et al. Global Carbon Budget 2023. Earth System Science Data. 2023; 15: 5301–5369. https://doi.org/10.5194/essd-15-5301-2023
6. Blunden J, Boyer T, Bartow-Gillies E. State of the Climate in 2022. Bulletin of the American Meteorological Society. 2023; 104: S1–S516. https://doi.org/10.1175/2023BAMSStateoftheClimate.1
7. Zhang W, Clark R, Zhou T, Li L, Li C, Rivera J, et al. 2023: Weather and Climate Extremes Hitting the Globe with Emerging Features. Advances in Atmospheric Sciences. 2024. https://doi.org/10.1007/s00376-024-4080-3
8. Perkins-Kirkpatrick S, Barriopedro D, Jha R, Wang L, Mondal A, Libonati R, et al. Extreme terrestrial heat in 2023. Nature Reviews Earth & Environment. 2024; 5: 244–246. https://doi.org/10.1038/s43017-024-00536-y
9. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021 –The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2023. https://doi.org/10.1017/9781009157896
10. Forster PM, Smith CJ, Walsh T, Lamb WF, Lamboll R, Hauser M, et al. Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence. Earth Syst Sci Data. 2023; 15: 2295–2327. https://doi.org/10.5194/essd-15-2295-2023
11. Ribes A, Qasmi S, Gillett NP. Making climate projections conditional on historical observations. Science Advances. 7: eabc0671. https://doi.org/10.1126/sciadv.abc0671 PMID: 33523939
12. Ribes A., Tessiot O., Forster P., Gillet N., Masson-Delmotte V., Vautard R., et al. Towards annual updating of attributable warming to date and constrained climate projections. in preparation.
13. Lamboll RD, Nicholls ZRJ, Smith CJ, Kikstra JS, Byers E, Rogelj J. Assessing the size and uncertainty of remaining carbon budgets. Nature Climate Change. 2023; 13: 1360–1367. https://doi.org/10.1038/s41558-023-01848-5
14. Minière A, von Schuckmann K, Sallée J-B, Vogt L. Robust acceleration of Earth system heating observed over the past six decades. Scientific Reports. 2023; 13: 22975. https://doi.org/10.1038/s41598-023-49353-1 PMID: 38151491
15. Raghuraman SP, Paynter D, Menzel R, Ramaswamy V. Forcing, Cloud Feedbacks, Cloud Masking, and Internal Variability in the Cloud Radiative Effect Satellite Record. Journal of Climate. 2023; 36: 4151–4167. https://doi.org/10.1175/JCLI-D-22-0555.1

16. Marzeion B, Kaser G, Maussion F, Champollion N. Limited influence of climate change mitigation on short-term glacier mass loss. Nature Clim Change. 2018; 8: 305–308. https://doi.org/10.1038/s41558-018-0093-1
17. Mengel M, Nauels A, Rogelj J, Schleussner C-F. Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. Nature Communications. 2018; 9: 601. https://doi.org/10.1038/s41467-018-02985-8 PMID: 29463787
18. Coulon V, Klose AK, Kittel C, Edwards T, Turner F, Winkelmann R, et al. Disentangling the drivers of future Antarctic ice loss with a historically calibrated ice-sheet model. The Cryosphere. 2024; 18: 653–681. https://doi.org/10.5194/tc-18-653-2024
19. Esper J, Smerdon JE, Anchukaitis KJ, Allen K, Cook ER, D'Arrigo R, et al. The IPCC's reductive Common Era temperature history. Communications Earth & Environment. 2024; 5: 222. https://doi.org/10.1038/s43247-024-01371-1
20. The Cenozoic CO2 Proxy Integration Project (CenCO2PIP) Consortium*†, Hönisch B, Royer DL, Breecker DO, Polissar PJ, Bowen GJ, et al. Toward a Cenozoic history of atmospheric CO2. Science. 382: eadi5177. https://doi.org/10.1126/science.adi5177 PMID: 38060645
21. Cooper VT, Armour KC, Hakim GJ, Tierney JE, Osman MB, Proistosescu C, et al. Last Glacial Maximum pattern effects reduce climate sensitivity estimates. Science Advances. 10: eadk9461. https://doi.org/10.1126/sciadv.adk9461 PMID: 38630811
22. Hausfather Z, Drake HF, Abbott T, Schmidt GA. Evaluating the Performance of Past Climate Model Projections. Geophysical Research Letters. 2020; 47: e2019GL085378. https://doi.org/10.1029/2019GL085378
23. Hausfather Z. Factcheck: why the recent "acceleration" in global warming is what scientists expect. Available: https://www.carbonbrief.org/factcheck-why-the-recent-acceleration-in-global-warming-is-what-scientists-expect/#.
24. Gavin A. Climate model projections compared to observations. Available: https://www.realclimate.org/index.php/climate-model-projections-compared-to-observations/.
25. Hawkins E. Comparing CMIP5 and observations. In: https://www.climate-lab-book.ac.uk/comparing-cmip5-observations/.
26. Rantanen M, Laaksonen A. The jump in global temperatures in September 2023 is extremely unlikely due to internal climate variability alone. npj Climate and Atmospheric Science. 2024; 7: 34. https://doi.org/10.1038/s41612-024-00582-9
27. Schmidt GA. Why 2023's heat anomaly is worrying scientists. Nature. 627th ed.: 467.
28. https://berkeleyearth.org/global-temperature-report-for-2023/.
29. Kim Y-H, Min S-K, Gillett NP, Notz D, Malinina E. Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. Nat Commun. 2023; 14: 3139. https://doi.org/10.1038/s41467-023-38511-8 PMID: 37280196
30. Ribes A, Boé J, Qasmi S, Dubuisson B, Douville H, Terray L. An updated assessment of past and future warming over France based on a regional observational constraint. Earth System Dynamics. 2022; 13: 1397–1415. https://doi.org/10.5194/esd-13-1397-2022
31. Hobbs W, Spence P, Meyer A, Schroeter S, Fraser AD, Reid P, et al. Observational Evidence for a Regime Shift in Summer Antarctic Sea Ice. Journal of Climate. 2024; 37: 2263–2275. https://doi.org/10.1175/JCLI-D-23-0479.1
32. Purich A, Doddridge EW. Record low Antarctic sea ice coverage indicates a new sea ice state. Communications Earth & Environment. 2023; 4: 314. https://doi.org/10.1038/s43247-023-00961-9
33. Holmes CR, Bracegirdle TJ, Holland PR. Antarctic Sea Ice Projections Constrained by Historical Ice Cover and Future Global Temperature Change. Geophysical Research Letters. 2022;49: e2021GL097413. https://doi.org/10.1029/2021GL097413
34. Fretwell PT, Boutet A, Ratcliffe N. Record low 2022 Antarctic sea ice led to catastrophic breeding failure of emperor penguins. Communications Earth & Environment. 2023; 4: 273. https://doi.org/10.1038/s43247-023-00927-x
35. Thomas A. Research needs for loss and damage. Science. 2024; 383: 798–798. https://doi.org/10.1126/science.adn4697 PMID: 38386738
36. King AD, Grose MR, Kimutai J, Pinto I, Harrington LJ. Event attribution is not ready for a major role in loss and damage. Nature Climate Change. 2023; 13: 415–417. https://doi.org/10.1038/s41558-023-01651-2
37. Vautard R, Cattiaux J, Happé T, Singh J, Bonnet R, Cassou C, et al. Heat extremes in Western Europe increasing faster than simulated due to atmospheric circulation trends. Nature Communications. 2023; 14: 6803. https://doi.org/10.1038/s41467-023-42143-3 PMID: 37884524

38. Martín ML, Calvo-Sancho C, Taszarek M, González-Alemán JJ, Montoro-Mendoza A, Díaz-Fernández J, et al. Major Role of Marine Heatwave and Anthropogenic Climate Change on a Giant Hail Event in Spain. Geophysical Research Letters. 2024; 51: e2023GL107632. https://doi.org/10.1029/2023GL107632
39. (analysis based on Web of Science, in October 2023).
40. Lund BD, Wang T, Mannuru NR, Nie B, Shimray S, Wang Z. ChatGPT and a new academic reality: Artificial Intelligence-written research papers and the ethics of the large language models in scholarly publishing. Journal of the Association for Information Science and Technology. 2023; 74: 570–581. https://doi.org/10.1002/asi.24750
41. Walters WH, Wilder EI. Fabrication and errors in the bibliographic citations generated by ChatGPT. Scientific Reports. 2023; 13: 14045. https://doi.org/10.1038/s41598-023-41032-5 PMID: 37679503
42. Hill EA, Urruty B, Reese R, Garbe J, Gagliardini O, Durand G, et al. The stability of present-day Antarctic grounding lines–Part 1: No indication of marine ice sheet instability in the current geometry. The Cryosphere. 2023; 17: 3739–3759. https://doi.org/10.5194/tc-17-3739-2023
43. van Westen RM, Kliphuis M, Dijkstra HA. Physics-based early warning signal shows that AMOC is on tipping course. Science Advances. 10: eadk1189. https://doi.org/10.1126/sciadv.adk1189 PMID: 38335283
44. Srokosz MA, Holliday NP, Bryden HL. Atlantic overturning: new observations and challenges. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2023; 381: 20220196. https://doi.org/10.1098/rsta.2022.0196 PMID: 37866387
45. Reese R, Garbe J, Hill EA, Urruty B, Naughten KA, Gagliardini O, et al. The stability of present-day Antarctic grounding lines–Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded. The Cryosphere. 2023; 17: 3761–3783. https://doi.org/10.5194/tc-17-3761-2023
46. Jackson LC, Hewitt HT, Bruciaferri D, Calvert D, Graham T, Guiavarc'h C, et al. Challenges simulating the AMOC in climate models. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2023; 381: 20220187. https://doi.org/10.1098/rsta.2022.0187 PMID: 37866390
47. Casado M, Gremion G, Rosenbaum P, Caccavo JA, Aho K, Champollion N, et al. The benefits to climate science of including early-career scientists as reviewers. Geoscience Communication. 2020; 3: 89–97. https://doi.org/10.5194/gc-3-89-2020
48. https://climateactiontracker.org/publications/cop28-initiatives-create-buzz-will-only-reduce-emissions-if-followed-through/.
49. Pirani A, Fuglestvedt JS, Byers E, O'Neill B, Riahi K, Lee J-Y, et al. Scenarios in IPCC assessments: lessons from AR6 and opportunities for AR7. npj Climate Action. 2024; 3: 1. https://doi.org/10.1038/s44168-023-00082-1
50. Kuang X, Liu J, Scanlon BR, Jiao JJ, Jasechko S, Lancia M, et al. The changing nature of groundwater in the global water cycle. Science. 383: eadf0630. https://doi.org/10.1126/science.adf0630 PMID: 38422130
51. Blattert C, Mönkkönen M, Burgas D, Di Fulvio F, Toraño Caicoya A, Vergarechea M, et al. Climate targets in European timber-producing countries conflict with goals on forest ecosystem services and biodiversity. Communications Earth & Environment. 2023; 4: 119. https://doi.org/10.1038/s43247-023-00771-z
52. IPBES. Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). [object Object]; 2020 Oct. https://doi.org/10.5281/ZENODO.4147317
53. Byers E, Gidden M, Leclère D, Balkovic J, Burek P, Ebi K, et al. Global exposure and vulnerability to multi-sector development and climate change hotspots. Environ Res Lett. 2018; 13: 055012. https://doi.org/10.1088/1748-9326/aabf45
54. Trew BT, Maclean IMD. Vulnerability of global biodiversity hotspots to climate change. Global Ecology and Biogeography. 2021; 30: 768–783. https://doi.org/10.1111/geb.13272
55. Thiéblemont R, Le Cozannet G, D'Anna M, Idier D, Belmadani A, Slangen ABA, et al. Chronic flooding events due to sea-level rise in French Guiana. Scientific Reports. 2023; 13: 21695. https://doi.org/10.1038/s41598-023-48807-w PMID: 38066015
56. Baldissera Pacchetti M, Coulter L, Dessai S, Shepherd TG, Sillmann J, Van Den Hurk B. Varieties of approaches to constructing physical climate storylines: A review. WIREs Climate Change. 2024; 15: e869. https://doi.org/10.1002/wcc.869

57. Van De Wal RSW, Nicholls RJ, Behar D, McInnes K, Stammer D, Lowe JA, et al. A High-End Estimate of Sea Level Rise for Practitioners. Earth's Future. 2022; 10: e2022EF002751. https://doi.org/10.1029/2022EF002751 PMID: 36590252
58. Solé R, Levin S. Ecological complexity and the biosphere: the next 30 years. Philosophical Transactions of the Royal Society B: Biological Sciences. 2022; 377: 20210376. https://doi.org/10.1098/rstb.2021.0376 PMID: 35757877
59. Prütz R, Fuss S, Lück S, Stephan L, Rogelj J. A taxonomy to map evidence on the co-benefits, challenges, and limits of carbon dioxide removal. Communications Earth & Environment. 2024; 5: 197. https://doi.org/10.1038/s43247-024-01365-z
60. Baur S, Nauels A, Nicholls Z, Sanderson BM, Schleussner C-F. The deployment length of solar radiation modification: an interplay of mitigation, net-negative emissions and climate uncertainty. Earth Syst Dynam. 2023; 14: 367–381. https://doi.org/10.5194/esd-14-367-2023
61. Sills J, Stephens JC, Kashwan P, McLaren D, Surprise K. The risks of solar geoengineering research. Science. 2021; 372: 1161–1161. https://doi.org/10.1126/science.abj3679 PMID: 34112686
62. Buck HJ. Environmental Peacebuilding and Solar Geoengineering. Frontiers in Climate. 2022;4. https://doi.org/10.3389/fclim.2022.869774
63. Biermann F, Oomen J, Gupta A, Ali SH, Conca K, Hajer MA, et al. Solar geoengineering: The case for an international non-use agreement. WIREs Climate Change. 2022; 13: e754. https://doi.org/10.1002/wcc.754
64. Seneviratne S. and Rogelj J. and Séférian R. and Allen M. R. and Buckerige M. and Ebi C., et al. Cross-Chapter Box 8: 1.5˚C Warmer Worlds. 1st ed. IPCC, 2018: Global Warming of 15˚C An IPCC Special Report on the impacts of global warming of 15˚C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, PR Shukla, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, and Waterfield T(eds)]. 1st ed. Cambridge University Press; 2022. https://doi.org/10.1017/9781009157940
65. Steg L. Psychology of Climate Change. Annu Rev Psychol. 2023; 74: 391–421. https://doi.org/10.1146/annurev-psych-032720-042905 PMID: 36108263
66. https://www.cultureclimatemeeting.org/.
67. https://www.un.org/en/climatechange/high-level-expert-group.
68. https://huggingface.co/spaces/Ekimetrics/climate-question-answering.
69. https://comite-ethique.cnrs.fr/en/comets-opinion-freedom-and-responsibility-academic-researchers-public-advocacy/.
70. Carbou G, Sébastien L. Les discours d'inaction climatique dans la communauté scientifique. Écologie & politique. 2023; 67: 71–91.
71. https://www.oce.global/en.
72. https://labos1point5.org/.
73. Barret D. Estimating, monitoring and minimizing the travel footprint associated with the development of the Athena X-ray Integral Field Unit. Experimental Astronomy. 2020; 49: 183–216. https://doi.org/10.1007/s10686-020-09659-8 PMID: 32836797
74. Acosta MC, Palomas S, Paronuzzi Ticco SV, Utrera G, Biercamp J, Bretonniere P-A, et al. The computational and energy cost of simulation and storage for climate science: lessons from CMIP6. Geoscientific Model Development. 2024; 17: 3081–3098. https://doi.org/10.5194/gmd-17-3081-2024
75. Voosen Paul. Climate modelers grapple with their own carbon emissions. Science. 2024: 494–495.
76. State of the Global Climate 2023. WMO; p. 53. Report No.: 1347. Available: https://library.wmo.int/idurl/4/68835.