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Perspectives on future climate research: a preface to the special collection from the World Climate Research Programme 2023 Open Science Conference

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Since its inception in 1980, the World Climate Research Programme (WCRP) has coordinated and facilitated international climate research to develop, share, and apply the climate knowledge that contributes to societal well-being. Through international science coordination and partnerships, WCRP contributes to advancing our understanding of the multi-scale dynamic interactions between natural and social systems that affect climate. WCRP-supported research builds the climate science that is the basis for IPCC Assessments and Special Reports and underpins the United Nations Framework Convention on Climate Change including national commitments to the 2015 Paris Agreement. It also contributes to the knowledge that supports the 2030 Agenda for Sustainable Development, the Sendai Framework for Disaster Risk Reduction, and multilateral environmental conventions. To shape the future climate science agenda, WCRP organized its second Open Science Conference, which took place between October 23 and 27, 2023 and was hosted by the Rwanda Environment Management Authority (REMA) in Kigali, Rwanda. This once-in-a-decade event took place in a truly hybrid setting, bringing together over 1,400 participants representing scientists from diverse research communities worldwide as well as practitioners, planners, and politicians.

KEYWORDS

World Climate Research Programme, future climate science, climate services, WCRP Open Science Conference, global south

1 The World Climate Research Programme's 2023 second Open Science Conference—Climate science for a sustainable future for all

Since its inception in 1980, the World Climate Research Programme (WCRP) has coordinated and facilitated international climate research to develop, share, and apply the climate knowledge that contributes to societal well-being. Through international science coordination and partnerships, WCRP contributes to advancing our understanding of the multi-scale dynamic interactions between natural and social systems that affect climate. WCRP-supported research builds the climate science that is the basis for IPCC Assessments and Special Reports and underpins the United Nations Framework Convention on Climate Change including national commitments to the 2015 Paris Agreement. It also contributes to the knowledge that supports the 2030 Agenda for Sustainable Development, the Sendai Framework for Disaster Risk Reduction, and multilateral environmental conventions.

To shape the future climate science agenda, WCRP organized its second Open Science Conference, which took place between October 23 and 27, 2023 and was hosted by the Rwanda Environment Management Authority (REMA) in Kigali, Rwanda. This once-in-a-decade event took place in a truly hybrid setting, bringing together over 1,400 participants representing scientists from diverse research communities worldwide as well as practitioners, planners, and politicians.

Conference participants discussed the current state and further evolution of inclusive, international climate science, and the scientifically founded actions urgently needed to mitigate against and adapt to climate change. The Global South remains poorly represented in climate research, where the community of scientists and practitioners experience significant inadequacies in obtaining, accessing and processing data into information, and where the lack of relevant observations is limiting. In recognition of these disparities, the WCRP 2023 Open Science Conference was purposefully held in Africa. The Conference was instrumental in reaching and entraining audiences from the Global South with a vision of a future of a truly global climate science endeavor, attracting many early career scientists from around the world.

The Conference produced the Kigali Declaration (WCRP-Kigali-Declaration-2024-c.pdf) as the official Conference document. Prepared by Conference participants and based on the discussions and deliberations during the Conference, the Kigali Declaration was signed by over 700 climate scientists from around the world. Its signatories acknowledge that because of human-induced climate change and other human impacts on the environment, the world is in a state of polycrises leading to cascading systemic risk and increasing inequality, with failure to limit global warming being one of the greatest threats to humanity.

In the leadup to the Conference, the world's climate science community produced several Concept Papers, which were brought into the Conference discussions as drafts, and subsequently revised and published in *Frontiers* as a Special Collection. These Concept Papers represent community-assessments of the state of knowledge on salient topics in climate science that were not addressed previously through the IPCC Sixth Assessment but require urgent attention. This preface provides a summary of the Conference outcomes together with a discussion of the themes addressed by the Concept Papers.

2 Advancing climate science in support of societal and technological transformation

Increasingly rapid human-induced changes in the Earth's climate are leading to profound and widespread changes in the atmosphere, ocean, cryosphere, land and biosphere. Each of the last three decades has been successively hotter than those before. Global surface temperatures have already breached 1.5°C for individual months, and this threshold will likely be breached frequently, potentially every second year by the 2030s.

Current policies and pledges are vastly inadequate to reduce greenhouse gas (GHG) emissions at the pace and scale required to limit global warming well below 2°C. Instead, if emissions close to today's levels continue in the coming decades, then this would mean that global temperatures would exceed 2°C (above pre-industrial) by the 2050s and close to 3°C by the end of this century. The cumulative effect of GHG emissions, including the committed sea level rise, will require substantial adaptation responses. Continued growth in anthropogenic GHG emissions, combined with systemic changes in land use, atmospheric aerosol content and the resulting changes in the absorption of solar radiation, will further intensify climate change impacts. If continued uninterrupted, these changes and impacts will lead to unprecedented events in the Earth system that will dramatically affect people and life around the world. Any further delays to climate change mitigation and associated societal transformations will exacerbate future impacts.

Conference participants stressed the increasing severity of, and growing concerns about, compound extreme events and cascading hazards; and highlighted the gaps in our current understanding of the drivers and mechanisms of systemic changes and their impacts in different regions.

Many regions of the Global South face a disproportionate burden due to impacts of changes in severe weather events and patterns, including prolonged droughts, heatwaves, devastating floods and landslides, tropical cyclones, and wild/forest fires – all of which are at least partially attributable to climate change. These severe weather events have the potential to cause humanitarian crises that occur alongside conflicts around the globe, with detrimental impacts on economies, water, food security, ecosystems and biodiversity, health, education, migration, and peace. Moreover, current adaptation initiatives in the Global South are insufficient to counter the impacts from climate change - leading to a growing and increasingly large gap in adaptation actions. Adaptation and mitigation decisions benefit from timely, accurate, and contextual climate information.

Unprecedented societal and technological transformation on a global scale is urgently required to achieve net-zero carbon emissions as soon as possible, and to avoid future warming beyond 3°C. Future stabilization of temperatures will rely on reaching net-zero emissions, requiring new technologies, investment, and rapid financial support to vulnerable nations, and commitment by all parties. Good governance and wider leadership by businesses, communities and broader society is essential. A giant leap is also required by societies embarking on a new path to a sustainable world. It requires a fundamental reconfiguration of economies, energy, food, and health systems, so that they work for both people and the planet. Climate science plays a key role in empowering vulnerable nations by providing the evidence base, knowledge and information that underpins these societal and technological transformations.

Recent sudden rises in global temperature highlight that a full system-level understanding of the climate and Earth is still missing, for example: a better understanding of internal variability, tropical-extratropical interactions, ocean-land-atmosphere interactions, eddies, jets, and monsoon systems at the intraseasonal time scales, and a more accurate prediction of extremes, and storms. Knowledge of future circulation changes in the atmosphere and ocean, and the role of internal variability and forced responses which affect changes in regional climate, is required but currently lacking. A better understanding of the complex role of biosphere-atmosphere-climate processes, and their interactions that lead to climate feedbacks, is also needed. A better understanding is also needed for the sources, and impacts of short-lived climate forcers, e.g., novel fluorine gases, secondary organic aerosols, and tropospheric ozone. As there are strong reasons to expect some climate-dependence of climate sensitivity, it is critically important to quantify this if future climate projections and associated risk assessments are to be improved.

3 Understanding the coupled cycles of water, energy, and carbon

Research into the changing water cycle, and its consequences for communities, industry, food security and ecosystem health, needs more attention. This includes how to reduce uncertainties and improve confidence in precipitation and evaporation projections. Beyond problems that exist today, water security will become an increasingly real and pressing problem in the future - in 2030, 85% of the world's population are expected to live in arid regions. The challenges of water can be simply stated as*: too much, too little, too polluted*. The impacts of climate change on water security and availability, and water-related disasters, affect communities differently depending on their resilience and capacity. Extreme weather events – from flooding to compound heatwaves; to droughts and wildfires – are all being increasingly experienced around the world, with human influences contributing to many observed changes.

Observed trends in the water cycle can be attributed to climate drivers in some regions of the world but in most cases these changes are attributed to other anthropogenic factors, such as urbanization or water abstraction. Methods are urgently needed to separate the natural climate and anthropogenic signals in the observed indicators of the continental water cycle, including extremes, and to better understand the role of aerosols on extreme rainfall events. Improved observations of the water cycle; advances in observing and understanding groundwater recharge; and better ways to assess the combined pressures of climate change, water use and demand are all needed.

There have been advances in quantifying changes in the Earth's energy budget and our understanding of the drivers and the importance of anthropogenic forcing for regional precipitation changes. Carbon cycle – climate feedbacks are very important for understanding future Earth System responses. The interannual variability of the ocean carbon sink appears to be higher than previously thought. Clear sky feedback effects (i.e., how the Earth's climate system responds to changes in forcing in the absence of clouds) on the global climate are very robust in climate models and well understood, but questions remain about whether these feedbacks could be altered outside the model range by processes not currently represented.

Trends in effective radiative forcing, driven by increasing GHG, and declining aerosol, levels, are contributing most of the observed changes (i.e., increases) in the Earth's energy budget. Significant longwave and positive shortwave cloud feedbacks yield a non-significant net cloud radiative contribution to the observed increases in the Earth's Energy Imbalance. This implies that cloud could amplify or diminish global warming.

Understanding land use and land degradation is important because of their significant socioeconomic consequences, as well as their impact on climate through changes in the surface fluxes of water, carbon, energy and momentum. Despite research efforts to evaluate the impacts of land use change on surface fluxes, fundamental challenges remain, especially related to understanding the trade-offs and co-benefits of sustainable land management practices, including those related to CO_2 removal and sustainable agriculture. Large uncertainties remain about the size and stability of the land carbon sink, although recent developments illustrate ongoing advances in our knowledge and understanding. Deforestation and land degradation, climatic extremes governing the interannual variability of the land carbon stock, carbon turnover times, and model uncertainties due to gaps in process understanding, all contribute towards this uncertainty. There is a growing need for more advanced land use and land cover change models. Nonetheless, research into land use change and land-based climate solutions, on local to global scales to inform effective climate adaptation strategies, is progressing.

4 The future of observing and simulating the climate system—producing climate information at the scale of people for climate services

With improved observations, methods of attribution and detection, and models, we are starting to see climate change signals emerge from natural climate variability; an improved understanding of jets and eddies in the atmosphere and ocean, from the jet stream in the Northern Hemisphere to the Antarctic Circumpolar Current in the Southern Ocean; and in rapid or irreversible changes in the Earth climate system across the land, ocean and cryosphere and, in particular, their interactions. Novel techniques of model-data fusion are accompanied by advances in high-resolution climate modelling. The problem of longstanding climate model biases remains, notably in regional precipitation and teleconnection patterns. In this context there is a need to close observational gaps and build and maintain sustainable observing systems. At the same time, reducing model deficiencies in simulating internal variability modes at several time scales, tropical-extratropical interactions, and ocean–atmosphere-land interactions are all important goals to improve models.

Major developments are underway that exploit data assimilation and Machine Learning (ML) to improve and replace parameterizations in the atmosphere and ocean, thereby advancing research-based climate forecasting, prediction. For example, with the use of ML to improve parameterizations and other applications, such as model tuning, to simulate scale interactions, major advances in higher resolution modelling are now possible. Along with the use of climate ensembles, these advances may improve the simulation of global-regional scales and local extremes. Progress is being made in developing early warning systems for climate extremes and hazards. Making methods transparent and reproducible, benchmarking data available to ensuring that documentation is accessible and available are all important steps in this context that can be approach. There are further opportunities to improve Earth System Models (ESMs) through better representation of ecosystems and the effects of human activities on land surface processes and the water cycle. New techniques for paleoclimate reconstruction are leading to advances in our knowledge of longer-term changes in the Earth's climate system, climate sensitivity, and to better understand climate variability on longer time scales.

There is a need for urban-resolving climate modeling approaches across scales, that accurately represents urban characteristics and processes and capture the feedback from urban areas to larger weather and climate processes. Urban climate modelling is essential to help plan cities and to manage risks to the health and wellbeing of the urban population. Ideally, urban climate models should include human behavior. Developing climate services for infectious disease control and health will require effective tools, regional collaboration, and access to good quality health data – which remains a challenge. New methods are being developed that can help to overcome the challenges with lack of health data, particularly in the Global South. Urban climate modelling benefits health impact assessments, and benefits from the inclusion of human behavior and more research is needed to better model human processes and behavior.

5 Toward climate justice, equity and action

Monitoring the state of the climate system in near real time and developing operational capabilities for attribution and prediction of emerging changes, are all opportunities that are within reach. Despite emerging opportunities to build sustainable observing systems, there remain major gaps in the quality and amount of our historical observations in all climate components, through which data rescue and research will need to play a key role. Rectifying the mismatch between data gathered in the Global North and South can be achieved through supporting strong relationships across the Global South and North, e.g., at the graduate level where student exchanges can be an effective way of surmounting some of these issues.

Realizing the full potential of sub-seasonal to seasonal and seasonal-to-decadal predictions is within reach, including for extreme events impacts and decision support. Likewise, there are opportunities for more skillful and decision-relevant predictions from forecasts at weekly to sub-seasonal to seasonal time scales, that can be tailored in response to user needs and feedback. Rapid extreme event attribution allows the role of climate change to be communicated and explained at the time when people are interested. Furthermore, there is value in piloting operational impact attribution, even at a basic level.

The climate emergency leads to disproportionate risks and harms to those who have done the least to cause the climate crisis – especially those living in the Global South. Inequities (around climate risks) sit alongside gender, economic, and cultural inequities. There are also regional, national and within country inequities. Future climate actions need to consider equity and justice and must be addressed alongside climate change. We are far away from achieving either of these goals, and vulnerable populations and countries have legitimate development demands and want to see themselves as part of the solution.

Another gap is the effective communication of the results from operational predictive systems that can be used for decision-making. Access to advanced technology to Global South science, along with a lack of Global South data, are also outstanding challenges. Small island states need tools and protocols (and perhaps other support) to do their own attribution studies. There is need for inter- and trans-disciplinary research that connects to those stakeholders who are potentially affected.

The development of regional information continues to evolve – moving closer to decision scales, but there remain challenges in the operationalization of co-production to best align with decision needs. Standards and measures to ensure robustness of climate services are key requirements. Synthesizing individual learning to develop a broader base of understanding is needed and so enable more comprehensive monitoring and evaluation. Research and evidence play a key part of the strategy to ensure that effective climate services for health are developed, implemented, and evaluated in partnership. Cross-cutting opportunities include the co-design of climate services for all and understanding socio-economic vulnerability to climate change. Partnerships are very important, to facilitate access to data and relevant stakeholders.

6 Topics of the special collection—the future of climate science

The following 13 topics are addressed in this special collection on the future of climate science. The respective papers can be grouped into five themes which are essential to advance climate science and to develop solution options.

Theme	Summary	Contributing Concept Papers
1. Advances in Climate Research	The advances in climate science required over the next one to two decades to produce the knowledge base that can help address future mitigation policies and adaptation planning.	Shaw et al. (2024), Friedlingstein et al. (2024), Brasseur et al. (2025), Kageyama et al. (2024)
2. Human Interactions with Climate	Humans are part of the Earth system and so they have a strong two-way interaction with it. To reach Paris climate goals, a better understanding of this interaction is needed to determine the fundamental societal and industrial transformations required to achieve a net-zero global society and economy.	Perkins-Kirkpatrick et al. (2024), Sillmann et al., (2024)
3. Co-produced Climate Services and Solutions	The effective development and use of actionable climate information and climate services requires co-design and co-production between the scientific and stakeholder communities.	Díaz et al. (2025), Jacob et al., 2025)
4. Climate Intervention – Perspectives on Research Challenges and Needs	Halting global warming requires net zero carbon emissions as well as negative emissions and the development of required technologies. Climate intervention research develops the knowledge required to understand the risks and the potential benefits of respective climate intervention technologies and applications.	Haywood et al. (2025), Oschlies et al. (2025), Hurrell et al. (2024)

Theme	Summary	Contributing Concept Papers
5. Climate Science in the Regions: Challenges, Gaps and Priorities	The impacts of climate change will be mostly felt in the regions, which is also the scale of relevant societal decision making. This theme addresses the specifics in selected regions of the global south and their needs from climate science and climate services.	Cavazos et al. (2024), Krishnan et al. (2025)

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DS: Writing – original draft, Writing – review & editing. HC: Writing – review & editing, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Gen AI was used in the creation of this manuscript.

References

Brasseur, G., Stammer, D., Friedlingstein, P., Hegerl, G., Shaw, T., Trenberth, K., et al. (2025). Climate science for 2050. *Front. Clim.* 7:1554685. doi: 10.3389/fclim.2025.1554685

Cavazos, T., Bettolli, M. L., Campbell, D., Sánchez Rodríguez, R. A., Mycoo, M., Arias, P. A., et al. (2024). Challenges for climate change adaptation in Latin America and the Caribbean region. *Front. Clim.* 6:1392033. doi: 10.3389/fclim.2024.1392033

Díaz, L. B., Gulizia, C., Jain, S., Langendijk, G. S., Palanisamy, H., Rabanal, V., et al. (2025). Connecting climate science and society: reflections from early and mid-career researchers at the world climate research Programme Open Science conference 2023. *Front. Clim.* 6:1501216. doi: 10.3389/fclim.2024.1501216

Friedlingstein, P., Artaxo, P., Gallego-Sala, A. V., Jia, G., Jones, C. D., Kawamiya, M., et al. (2024). Earth system responses to different levels of greenhouse gas emissions mitigation. *Front. Clim.* 6:1480208. doi: 10.3389/fclim.2024.1480208

Haywood, J. M., Boucher, O., Lennard, C., Storelvmo, T., Tilmes, S., and Visioni, D. (2025). World climate research programme lighthouse activity: an assessment of major research gaps in solar radiation modification research. *Front. Clim.* 7:1507479. doi: 10.3389/fclim.2025.1507479

Hurrell, J. W., Haywood, J. M., Lawrence, P. J., Lennard, C. J., and Oschlies, A. (2024). Climate intervention research in the world climate research Programme: a perspective. *Front. Clim.* 6:1505860. doi: 10.3389/fclim.2024.1505860

Jacob, D., St. Clair, L. A., Mahon, R., Marsland, S., Ndebele Murisa, M., Buontempo, C., et al. (2025). Co-production of climate services: challenges and enablers. *Front. Clim.* 7:1507759. doi: 10.3389/fclim.2025.1507759

Kageyama, M., Braconnot, P., Chiessi, C. M., Rehfeld, K., Ait Brahim, Y., Dütsch, M., et al. (2024). Lessons from paleoclimates for recent and future climate change: opportunities and insights. *Front. Clim.* 6:1511997. doi: 10.3389/fclim.2024.1511997

Krishnan, R., Dhara, C., Horinouchi, T., Gotangco Gonzales, C. K., Dimri, A. P., Shrestha, M. S., et al. (2025). Compound weather and climate extremes in the Asian region: science-informed recommendations for policy. *Front. Clim.* 6:1504475. doi: 10.3389/fclim.2024.1504475

Oschlies, A., Bach, L. T., Fennel, K., Gattuso, J.-P., and Mengis, N. (2025). Perspectives and challenges of marine carbon dioxide removal. *Front. Clim.* 6:1506181. doi: 10.3389/fclim.2024.1506181

Perkins-Kirkpatrick, S. E., Alexander, L. V., King, A. D., Kew, S. F., Philip, S. Y., Barnes, C., et al. (2024). Frontiers in attributing climate extremes and associated impacts. *Front. Clim.* 6:1455023. doi: 10.3389/fclim.2024.1455023

Shaw, T. A., Arias, P. A., Collins, M., Coumou, D., Diedhiou, A., Garfinkel, C. I., et al. (2024). Regional climate change: consensus, discrepancies, and ways forward. *Front. Clim.* 6:1391634. doi: 10.3389/fclim.2024.1391634

Sillmann, J., Raupach, T. H., Findell, K. L., Donat, M., Alves, L. M., Alexander, L., et al. (2024). Climate extremes and risks: links between climate science and decision-making. *Front. Clim.* 6:1499765. doi: 10.3389/fclim.2024.1499765