WORLD CLIMATE RESEARCH PROGRAMME

WHITE PAPER

Beyond the Horizon: Our Vision

Research Directions for WCRP Beyond the 2019–2028 Strategic Plan

Prepared for the WCRP Scientific Community

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Executive Summary

The World Climate Research Programme (WCRP) has, since its inception in 1980, stood as the premier international body coordinating research on the physical basis of the climate system. Its Strategic Plan (SP) 2019–2028[1] establishes four overarching scientific objectives spanning fundamental understanding, near-term predictions, longer-term projections and their translation into decision ready information for bridging the science to societal needs. A Science and Implementation Plan (SIP)[2] to deliver the strategy, together with key partners, evolved between 2020-2025 and defines the goals, connections and implementation pathways for six Core Projects and six Lighthouse Activities. It also includes an Academy to support the training and development of Early to Mid-Career Researchers (ECMRs).

The implementation of these Plans have resulted in transformative progress. Several key indicators of the state of the climate system are now better observed, understood, simulated, projected and communicated. Moreover, this framework has facilitated the co-ordination of international assessments (e.g. ECS, TCRE, Tipping dynamics), modeling experiments (CMIP, CORDEX, ISMIP), and impactful workshops/conferences (Kigali OSC) critically-needed for input to IPCC reports, addressing priorities of WMO, ISC and UNESCO-IOC member countries, and global climate fora such as UNFCCC. As the programme approaches the end of that planning horizon, the scientific community must now look beyond 2028 and chart the research directions that will define the next era of climate science.

This white paper draws on the latest scientific directions, priorities, and gaps following consultation with the WCRP Leadership and the wider community, reports, partner strategies, and the WCRP SIP (2025) to provide a vision and starting point for WCRP's science strategy and directions beyond 2028. The following priority research areas are being proposed:

1. multi-scale earth system dynamics;
2. water cycle and hydrological extremes;
3. Machine Learning (ML) and Artificial Intelligence (AI) in climate modelling and prediction across time scales;
4. the rapidly disappearing cryosphere and its impacts;
5. the accelerating impacts of sea-level rise on coastal and island communities;
6. extreme events and compounding hazards;
7. carbon cycle science in service of net-zero pathways;
8. risk assessment and building resilience.

[1] https://www.wcrp-climate.org/images/documents/WCRP_Strategic_Plan_2019/WCRP-Strategic-Plan-2019-2028-FINAL-c.pdf
[2] https://www.wcrp-climate.org/WCRP-publications/2025/WCRP-SIP-Final-c.pdf

Crosscutting themes of capability development and training, digital infrastructure, open science, and regional equity and justice need to be established and will help facilitate connections between future activities and deliver on priority research areas.

We propose that WCRP must evolve from a programme primarily focused on process understanding towards one that integrates physical science, data science, and societal impact as equal pillars — delivering knowledge that is not only scientifically excellent but directly actionable for decision-makers worldwide.

The following factors should be taken into consideration in the development of WCRP's future science directions.

- The current and future geopolitical landscape.
- WCRP's resource landscape including flexibility (pathways for a resource constrained future, but also value-add activities if funding can be mobilized).
- The balance between fundamental, innovative and applied science.
- Training and development priorities and needs.
- Delivery of actionable information that is usable and used through co-design, co-production, collaboration and partnerships.
- Alignment with, rather than duplication of, research, products and services.
- Identification of areas that are working well and remain a high priority. Identification of areas of lower impact, need and priority
- Identification of new opportunities, and those that would be attractive to co-funding partnerships or fundraising.
- Identification of any structural changes that may facilitate better and more efficient internal and external collaboration and impact.

The JSC has approved a task team[3] that will undertake an assessment of the scientific delivery and impacts from the current SP & SIP and make recommendations on future science priorities and the next steps for the production of Strategic and Implementation plans for 2029-2039. The report will be delivered at the 48th Session of the WCRP Joint Scientific Committee (JSC-48).

We also provide some recommendations, here, for the pathway forward and propose that a community workshop be held in 2027 (perhaps in conjunction with JSC-48) to help build the next Strategic and Implementation plans.

1. Introduction

Climate change is no longer a distant projection — it is the defining physical reality of the twenty-first century. Indeed, the nexus of the climate crisis, environmental degradation and biodiversity loss accounts for the top three global risks in the World Economic Forum's decadal

[3] Link to TT ToRs and participants to go here.

outlook[4]. Observations from satellites, *in-situ* networks, and reanalysis products consistently document that the pace of change is outrunning mid-range scenario projections: global mean surface temperatures have risen by approximately 1.2°C above pre-industrial levels; the global ocean has absorbed more than 90% of the excess heat; sea levels are rising at an accelerating rate; and extreme events are intensifying across all inhabited regions.

Against this backdrop, the WCRP SIP 2019–2028 articulated four scientific objectives: advancing fundamental understanding of climate processes; predicting the near-term evolution of the climate system; refining projections of future climate trajectories; and supporting the development of climate theory and practice. Overarching scientific priorities — on basic climate knowledge; climate observations and modeling; predicting earth system change; climate extremes and risks; cycles budgets and stocktake; tipping points; safe landing climates; climate intervention; and climate information— channelled community effort into high-impact research.

By 2025, WCRP had also launched six Lighthouse Activities — Digital Earths, Explaining and Predicting Earth System Change, My Climate Risk, Safe Landing Climates, Global Precipitation Experiment and the Research on Climate Intervention — representing a new mode of working that is more integrated, interdisciplinary, and solution-oriented. The SIP provides the operational framework bridging the current strategic plan to a post-2028 future.

This white paper builds on the foundations laid by the SP and the SIP and draws on the future research priorities and gaps identified in the Report and Declaration from WCRP Open Science Conference held in Kigali, Rwanda in 2023[5] to articulate a set of research directions for the period 2029–2039. It is addressed primarily to the research community — climate scientists, modelers, data scientists, earth system scientists, social scientists and providers of actionable science information — while remaining relevant to the funding agencies and intergovernmental bodies that support WCRP's mission.

Finally, we note that this White Paper is not an all encompassing list of priorities, it is our synthesis of the priorities and directions we think WCRP should take, within its constraints and boundaries. It is not prescriptive, but rather is provided to stimulate discussion and offer a starting point,

[4] https://www.weforum.org/publications/global-risks-report-2026/
[5] https://www.wcrp-climate.org/conferences/WCRP-OSC-2023/KD/WCRP-Kigali-Declaration-2024-c.pdf

2. Research Priority Areas

Understanding multi-scale earth system dynamics

Our understanding of how every sphere of the Earth system interacts with each other remains incomplete. Research efforts are needed to deepen our understanding of the non-linear, multi-scale processes governing the interactions among the ocean, atmosphere, cryosphere, and land surface — including the transport and exchange of heat, water, and carbon within and between each component. Internal variability, biogeochemical interactions leading to climate feedbacks, and external forcing are recognized as critical drivers of regional climate change, though their relative roles remain incompletely understood. As demand grows for reliable regional predictions spanning weeks to years, a deeper grasp of natural variability becomes increasingly critical, given that this variability itself is likely to shift in response to large-scale climate change.

Future research priorities could (or should) include: (i) better characterization of internal variability; (ii) tropical-extratropical interactions across multiple time scales; (iii) the role of stratosphere on intraseasonal timescales; (iv) ocean-land-atmosphere-dynamics; and (V) monsoon systems, with goal of enhanced predictability at regional scale.

Water cycle and hydrological extremes

Water is fundamental to life and climate, yet our understanding of its behavior across the atmosphere, oceans, cryosphere, and biosphere remains surprisingly incomplete. Long-term observations of clouds, precipitation, and evaporation are often inadequate, leaving critical gaps in our ability to track how water moves through the Earth system — and how that movement is changing. Bridging these gaps requires integrated hydrological research that combines observational data with modeling across every element of the Earth system, including the frequently overlooked domain of groundwater. Perhaps the most societally urgent research gap concerns hydrological extremes. Floods and droughts are not merely intensified versions or ordinary conditions; they emerge from nonlinear interactions among atmospheric dynamics, land surface states, and human water management. Current models tend to underestimate the frequency and magnitude of extreme precipitation events. Similarly, compound events (see below) — where drought is followed by fire and then intense rain causes floods - are poorly represented in risk assessments that treat hazards in isolation.

Future research priorities should involve an approach that cuts across atmospheric science, hydrology, ecology, and disaster risk research. The path forward demands integration: of observations systems spanning, satellites, sensors, and citizen science networks; of interdisciplinary modeling frameworks; and of international data-sharing that makes hydrological knowledge a global commons. Many of these priorities are articulated by the 7 research imperatives in the GEWEX Project[6] and fundamental understanding of process modeling will

[6] https://www.gewex.org/about/science/seven-gewex-imperatives/

continue to be relevant, but focussed assessments and research on key challenges of societal concern should be encouraged, as well as integration with other research priority areas (RPAs) outlined here.

The rapidly disappearing cryosphere: improving knowledge of processes, projections and impacts.

As Earth continues to warm, the loss of ice, snow, and permafrost is occurring at unprecedented rates leading to committed and irreversible global consequences, with 3 billion people estimated to be directly impacted by the end of the century. These changes in the cryosphere — including but not limited to substantial loss of sea ice in both hemispheres, continental ice sheets in Greenland and Antarctica, Antarctic ice shelves, and mountain glaciers — have significant impacts. These impacts include (i) coastlines through sea-level rise driven flooding and erosion, (ii) high mountain regions through natural hazards (e.g. glacial outburst floods; GLOFS), regional water, food and energy security, (iii) Arctic communities through loss of food, shelter and transport routes, and (iv) global climate through interactions and feedbacks.

Future research priorities are outlined in the new CliC strategic plan and include: (i) better understanding future polar ice sheet contributions to sea-level rise (also feeds into RPA below); (ii) explain the causes and effects of sea-ice variability and retreat in the Arctic and Antarctic to improve predictability, as well as understand the impact of sea ice on the wider Earth system; (iii) improve understanding of the rates of snow and ice loss in high mountain regions; (iv) better understand how snowfall and atmospheric frozen cloud processes influence the Earth's hydrological cycle and albedo feedbacks (also relevant to RPA above); (v) improve understanding of the processes of permafrost thawing in the Arctic, Antarctic, and mountain cryosphere for better predictability of spatial scale, rate and timing of methane and carbon dioxide release to the atmosphere and its influence on global warming and infrastructure and hazards, such as landslides.

The accelerating impacts of sea-level rise on coastal and island communities: From Projections to Action.

Future sea-level rise is unavoidable, yet its magnitude, rate, and regional expression remain deeply uncertain. These uncertainties, beyond scenario dependencies, are due to knowledge gaps in rate-determining processes, feedbacks and potential instabilities controlling the mass loss of polar ice sheets. This uncertain response to warming and overshoot pathways, together with inherent pathway uncertainty, limit the utility of current projections for coastal risk assessment and adaptation planning.

While the JSC approved Task Team on Sea-Level Rise[7] will undertake an assessment of future directions and next steps, it is important to note that increasingly, stakeholders are requesting:

[7] Insert lint to TT ToR

(i) reduced uncertainty in global drivers - especially the land ice contribution (see RPA above); (ii) more granular relative sea-level projections and information to adequately assess the evolving local impacts (e.g. flooding, erosion, groundwater inundation, salinisation, compound hazards) and risks, that account for vertical land movements, local hydrodynamics, coastal geomorphology and changing frequency of extreme sea-levels; (iii) consistency in actionable information for decision and-making and planning, which requires co-production between researcher, stakeholder and user communities.

The transformative application of Machine Learning (ML) and Artificial Intelligence (AI) in climate modelling and prediction across time scales

The convergence of unprecedented volumes of Earth observation data, dramatic reductions in high-performance computing costs, and rapid methodological advances in machine learning and artificial intelligence is creating a genuinely transformative moment for climate science. AI-based weather forecasting systems — including GraphCast (Google DeepMind), Pangu-Weather (Huawei), FourCastNet (NVIDIA), AIFS (ECMWF), and Aurora (Microsoft) — have achieved skill comparable to or exceeding that of state-of-the-art operational numerical weather prediction (NWP) models at a fraction of the computational cost. Large-scale foundation models such as ClimaX and ACE2 are extending these capabilities to climate timescales, learning subseasonal to decadal atmospheric variability and forced responses. Simultaneously, ML methods are accelerating the emulation of expensive Earth System Model (ESM) components, enabling ensemble approaches previously computationally prohibitive.

Yet critical challenges remain. ML models trained on historical climate statistics may not extrapolate reliably to climatic states beyond their training distribution — a fundamental limitation when projecting into a world 2–4°C warmer. Interpretability and physical consistency are also concerns: some simpler, physics-informed approaches have been shown to outperform deep learning in certain extrapolation scenarios, highlighting the need for hybrid methods.

Future research priorities cloud (or should) include: (i) physics-informed and hybrid modeling; (ii) foundation models for climate, democratization and capacity building; (iii) trustworthy and explainable AI.

Next-generation understanding and prediction of extreme events, compound hazards, and high impact events in the Earth System

Our fast-warming, non-stationary, climate raises a number of scientific challenges as it drives the Earth System into states that are unprecedented in human history. The intensification of extreme weather events — including heatwaves, compound flooding events, tropical cyclones, droughts, and wildfires — is among the most societally consequential projections of climate science (connections with RPA above, hydrologic extremes). Additionally, the recognition that global warming increases the risk of crossing threshold temperatures associated with several tipping systems, together with growing public interest, and concern from decision makers, led the WCRP and IPCC to convene an expert workshop on this topic in Paris, November, 2025[8]. IPCC WGI AR7 have also a dedicated chapter on "Abrupt changes, low-likelihood high impact events and critical thresholds, including tipping points, in the Earth system" (Chapter 8). Such changes in Earth system components and their ecosystems (e.g. ice sheets, ocean circulation, rainforests, coral reefs, permafrost, and monsoons) can greatly amplify climate risks, as they can trigger large, often irreversible shifts that have dangerous local and regional consequences. They are an additional danger to the already growing risks of heat waves, droughts, extreme sea levels, increased occurrence and intensity of several other extreme event types, all of which constitute multiple reasons for future research. Under the 2019–2028 SP, the activities have made significant progress in improving the predictive skill of the near-time evolution of hydrological extremes, including compound events, and in identifying longer term safe landing climates. This was achieved by focusing on ways in which the non-stationarity of the Earth System interacts with fast and slow extremes.

The post-2028 agenda must go further: from mechanistic understanding to attribution, prediction, and impact quantification. Future research should focus on bridging the gap between raw physical data and actionable, local-scale warnings including: (i) improving model representation of regional processes; (ii) advance high-resolution regional modeling and downscaling approaches; (iii) emphasize strengthening subseasonal-to-decadal (S2D) forecasting; (iv) address the predictability of "unknown" likelihood, high-impact events, tipping systems, cascades and their consequences; (v) co-create actionable, context-specific knowledge for disaster risk reduction.

Carbon cycle science in service of net-zero pathways

Understanding and predicting the carbon cycle - the suite of physical, chemical, biological, and human processes that determine atmospheric concentrations of CO2, CH4, and other greenhouse gases — is fundamental to both climate projections and climate mitigation policy. The remaining carbon budget for 1.5^{0}C is measured in years, and natural carbon sinks are showing signs of weakening under current heat, drought, and fire stress. Post-2028 WCRP research should prioritize the characterization of non-linear and threshold-crossing carbon cycle feedback, including permafrost thaw and associated CH4 release, tropical forest dieback, expansion or contraction of wetlands, and the saturation of ocean carbon sinks. These feedbacks are inadequately constrained in current Earth System Models and represent a primary source of uncertainty in long-term climate projections. Close coordination with the Global carbon project and with IPCC Working Group I is essential.

8 https://wmo.int/media/magazine-article/wcrp-and-ipcc-join-forces-high-impact-events-tipping-points-and-their-consequences

Future research priorities should include: (i) observation-constrained carbon budgets (ii) carbon dioxide removal (CDR) science; (iii) climate-carbon interactions under overshoot scenarios.

Improved regional information for assessing climate impacts, risk and building resilience

The demand for regionally specific, actionable information has become central to effective risk assessment and resilience planning. Decision-makers across sectors require granular data that distinguishes between different categories of climate risk operating on different time scales. Chronic risks, unfolding over decades (e.g., heat stress, water stress, sea-level rise) gradually reshape habitability, agricultural viability, and coastal infrastructure. Acute risks, by contrast, manifest on sub-seasonal and interannual timescales and encompass extreme heat events, droughts, tropical cyclones, severe convective storms, cold air outbreaks, floods of pluvial, fluvial, and coastal origins, landslides, and wildfires. Transitional risks emerge over decades as societies undertake adaptation (e.g., the cost of decarbonization), generating economic, regulatory, and technological disruptions that cascade through markets and communities. Systemic risks arise where the hazards interact with interconnected human systems - supply chains, financial networks, food systems, and public health infrastructure- producing compound failures.

Research priorities could include: (i) developing high-resolution regional climate projections that resolve mesoscale processes and local feedbacks for chronic risk assessment; (ii) advancing event attribution science to quantify how climate change alters the frequency, intensity, and spatial footprint of acute hazards; (iii) use of AI for improving sub-seasonal to decadal prediction systems that bridge the gap between weather forecasts and long-term projections to support operational decision-making; and (iv) modeling systemic risk propagation through interconnected infrastructure, financial, food, and supply-chain systems to identify tipping points and cross-sectoral vulnerabilities.

The relationship between climate change and human health is one of the most rapidly emerging and societally urgent frontiers in Earth system science. Heat stress, vector-borne disease expansion, air quality deterioration, food and water insecurity, and the mental health consequences of climate-related disasters collectively constitute a major and growing public health burden. Climate science has, historically, maintained a distance from health research; the post-2028 period offers an opportunity to close this gap. Building on the methodologies developed for physical extreme event attribution, the post-2028 WCRP agenda should invest in the development of end-to-end attribution frameworks that connect specific climate forcing to specific health outcomes — excess mortality from heatwaves, hospital admissions related to air quality episodes, or food insecurity crises linked to drought. This requires close collaboration with epidemiologists, public health agencies, and the health modelling community.

Research priorities could include: (i) attributing health outcomes to climate change; (ii) climate services for health decision-making; and (iii) mental health and climate anxiety.

3. Cross-Cutting Themes and Enabling Priorities

3.1 Digital Infrastructure and Open Science

The post-2028 WCRP agenda will be computationally demanding. Coordinated access to exascale and cloud-based high-performance computing, community-governed data repositories, standardized data formats, and reproducibility infrastructure are prerequisites for the scientific programme described in this paper. WCRP should advocate strongly for the development of a federated, internationally governed climate data commons, with data citation standards, persistent identifiers, and machine-readable provenance.

3.2 Regional Relevance and Climate Justice

The communities most vulnerable to the impacts described in this paper — low-lying coastal nations, mountain communities dependent on glacial meltwater, tropical regions facing compound heat and humidity extremes — are, in many cases, the least represented in WCRP's scientific community and governance structures. Post-2028, WCRP must embed regional equity as a structural principle: through co-designed regional research programmes, genuine partnerships with scientists from the Global South, capacity-building investments, and the integration of indigenous and local knowledge into research design.

3.3 Earth System Modelling and CMIP7+

The Coupled Model Intercomparison Project (CMIP) has been one of WCRP's most impactful contributions to climate science and policy, providing the model ensemble underlying successive IPCC Assessment Reports. Post-2028 CMIP activities must adapt to the new realities of km-scale modelling, AI-hybrid approaches, and the expanded scope of WCRP's agenda to include human system interactions. A CMIP 'next generation' design process should begin no later than 2027 to ensure readiness for AR7 and beyond.

3.4 Observational Strategy and Space Agency Partnerships

World-class observational infrastructure is the lifeblood of climate science. WCRP should renew and strengthen its engagement with space agencies — particularly European Space Agency (ESA), National Aeronautics and Space Agency (NASA), Japan Exploration Space Agency (JAXA), Indian Space Research Organisation (ISRO), and China National Space Administration (CNSA) — to ensure that the satellite constellation required for post-2028 science priorities is planned, launched, and calibrated in time. Priority missions should include next-generation sea level altimetry, high-resolution ice sheet radar, hyperspectral greenhouse gas monitoring, and a global sub-daily precipitation measurement system.

4. Recommendations

Based on the analysis presented in this White Paper, the following recommendations are made to the WCRP Joint Scientific Committee and sponsoring bodies for the development of a post-2028 strategic framework:

- Initiate a formal post-2028 strategic planning process no later than 2027, based on the report of the Science Strategy, Directions and Future Priorities Task Team[9], with broad community consultation and explicit engagement of the Global South.
- Establish community standards for AI/ML in climate science — covering validation, benchmarking, transparency, and reproducibility — modelled on the success of the CMIP protocol.
- Launch a CMIP Next Generation design process by 2027 to prepare the modelling community for the computational, methodological, and scientific demands of the post-2028 era.

The following factors will need to be taken into consideration in the development of WCRP's future strategic direction.

- The current and future geopolitical landscape.
- WCRP's resource landscape including flexibility (pathways for a resource constrained future, but also value-add activities if funding can be found).
- A focus increasing the quality and accuracy of predictions/projections at regional/local scale.
- The balance between fundamental, innovative and applied science (within Core Activities &, Lighthouse Activities) needed to deliver on a balanced portfolio of physical science, data science, and societal needs
- Training and development priorities and needs (e.g. Academy and core activity initiatives)
- Delivery of actionable information that is usable and used through co-design, co-production, collaboration and partnerships.
- Alignment with, rather than duplication of, research, products and services.
- Identification of areas that are working well and remain a high priority (if it isn't broken don't fix it).
- Identification of areas of lower impact, need and priority (all research in the current SP/SIP is relevant, but we will have to choose and elevate certain topics)
- Identification of new opportunities, and those that would be attractive to co-funding partnerships or fundraising.
- Identification of any structural changes that may facilitate better and more efficient internal and external collaboration and impact.

Last but least, based on the above considerations, prioritise where effort and resources are best used.

[9] Terms of Reference_WCRP_ScienceDirections.docx

5. Conclusions

The decade 2029–2039 will be a period of extraordinary consequence for both climate science and the societies it serves. The physical changes set in motion by past emissions will intensify regardless of future mitigation choices; the science community must be prepared to characterise, predict, and attribute these changes with ever-greater precision. At the same time, the emergence of artificial intelligence as a climate science tool, the imperatives of the net-zero transition, and the growing demand for regionally specific, decision-relevant climate information are opening new scientific and practical frontiers.

WCRP is uniquely positioned to coordinate the global scientific response to these challenges. Its convening power, its relationships with WMO, IOC-UNESCO, and ISC, its track record through CMIP, and its emerging Lighthouse Activities provide a strong foundation. But realising the vision articulated in this white paper will require deliberate choices: to invest in the science of sea-level rise and coastal impacts at a scale commensurate with the human stakes; to embrace and govern the AI transformation of climate modelling; to extend the programme's reach into extreme events, carbon science, the cryosphere, and human health; and to ensure that the benefits of world-class climate science are shared equitably across all regions of the world.

The next strategic plan of WCRP should be not merely a plan for research, but a plan for impact — grounded in the conviction that rigorous, coordinated, and open science, freely shared across borders and disciplines, is among humanity's most powerful tools for navigating the climate challenges ahead.

Key References and Further Reading

The following sources informed the preparation of this white paper:

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- WCRP Grand Challenge on Regional Sea-Level Change and Coastal Impacts: https://www.wcrp-climate.org/gc-sea-level.