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Website: **wcrp-climate.org**

Contact information
All enquiries regarding this report should be directed to wcrp@wmo.int or:

World Climate Research Programme
c/o World Meteorological Organization
7 bis, Avenue de la Paix
Case Postale 2300
CH-1211 Geneva 2
Switzerland

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Impressum
The WCRP Science and Implementation Plan, Edition 2025, was prepared by the WCRP Joint Scientific Committee (JSC) with extensive community consultation. The JSC members involved were:

WCRP Joint Scientific Committee (JSC) 2023–2024: Detlef Stammer, Pascale Braconnot, James Hurrell, Lisa Alexander, Pierre Friedlingstein, Tercio Ambrizzi, Eleanor Blyth, Susanna Corti, Amadou Gaye, Maria Ivanova, Tim Naish, Krishnan Raghavan, Roberto Sánchez-Rodríguez , Cristiana Stan, Ken Takahashi, Huijun Wang.

In addition from, WCRP Joint Scientific Committee (JSC) 2021 and 2022: Helen Cleugh, Jens Hesselbjerg Christensen, Pedro Montiero, Thomas Peter, Igor Shkolnik, Martin Visbeck.

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Preface

JSC Chair, Detlef Stammer (Top). JSC Vice-Chairs, Helen Cleugh (2019–22) (Middle) and Pascale Braconnot (2023–24) (Bottom).

When the World Climate Research Programme (WCRP) was established in 1980, it aimed to address the overarching questions of (i) to what extent the global climate can be predicted, and (ii) how humans influence the climate. Answering these questions has led to scientific activities around the world providing deep understanding of the processes acting in the Earth system, particularly with respect to climate variability and the interactions and feedbacks between its components, including the key physical, biological, and chemical processes. It also spawned and guided the development of climate observing systems, as well as a climate model infrastructure that, today, is being used to simulate the Earth's climate. WCRP's scientific advances continue to generate the knowledge that the Intergovernmental Panel on Climate Change (IPCC) draws on for their climate change assessments. Insights gained through WCRP unambiguously point to the fact that our climate is changing, and that changes observed since the mid-20th century are largely due to human activities.

Today, after more than 40 years since its inception, especially in the context of the twenty-first session of the Conference of the Parties (COP21) held in Paris in 2015 and the United Nations 2030 Agenda for Sustainable Development adopted in 2015, WCRP's climate research remains as important as it was at its beginning. However, its charge has evolved from the initial research questions and is now oriented not only towards addressing basic scientific understanding, such as the causes of climate change and climate predictability, but also towards identifying associated impacts and finding solutions as part of mitigation and adaptation strategies. WCRP remains uniquely positioned to establish fundamental scientific knowledge about the climate system, its variability, and how it is changing at global and regional scales. However, WCRP, in close collaboration with other research programmes, now also leads and facilitates developing the knowledge and information required by society to tackle future challenges related to anthropogenic climate change and the climate dimension of sustainable development. WCRP's future work will be based on further expanded cooperation and collaboration between natural and social scientists, civil society, and political leadership at every level to deliver information in support of solutions.

WCRP's Strategic Plan 2019 - 2028 articulates the new challenges and requirements for climate science by defining a vision and mission that reflects the new direction of the Programme and by setting future priorities through four Scientific Objectives. In a second step, this Science and Implementation Plan describes WCRP's new science priorities and presents the Programme's new structure and operational information required to support the new science priorities. Thus, this Science and Implementation Plan is intended to document the implementation of the WCRP Strategic Plan, its science priorities, as well as providing a guide to the operation and governance

of WCRP. The document is written for multiple audiences, from the WCRP community, including the co-sponsoring organizations, to the agencies and funding bodies from around the world.

This First Edition of WCRP's Science and Implementation Plan is intended to cover the period of the Strategic Plan, i.e., to the end of 2028 but will also be a living document that will be revised and updated as necessary. As such, it is intended to be a dynamic document that informs WCRP members as well as funding agencies and official programmes about WCRP and that can be periodically updated to remain relevant for the decades ahead.

We would like to thank all members of the WCRP community who contributed to the preparation of this plan. We also acknowledge the continuous support by the World Meteorological Organization, by the Intergovernmental Oceanographic Commission of UNESCO, and the International Science Council, as WCRP's enduring and committed co-sponsors.

Detlef Stammer
JSC Chair

Helen Cleugh
JSC Vice-Chair (2019–22)

Pascale Braconnot
JSC Vice-Chair (2023–24)

Contents

1. Introduction

The World Climate Research Programme (WCRP) was established in 1980 to advance climate research with the specific charge to (i) to what extent the global climate can be predicted and (ii) investigate how humans have influenced the climate. It is sponsored by three parent organizations, the World Meteorological Organization (WMO), the International Science Council (ISC), and the Intergovernmental Oceanographic Commission of the United National Educational, Scientific, and Cultural Organization (IOC-UNESCO). WCRP has made enormous contributions in advancing climate knowledge since its establishment four decades ago. The significant improvement in our understanding of the coupled climate system goes back to WCRP's internationally coordinated efforts in establishing a comprehensive observing system and building increasingly complete and accurate climate modeling tools capable of delivering climate change projections that extend beyond the 21st century, considering various greenhouse gas emission scenarios.

Understanding climate processes and quantifying climate variability required the establishment of various core research projects dealing with the atmosphere, the ocean, the cryosphere, and land surface processes, as well as all their interactions. At the same time, seasonal, multi-year and regional prediction capabilities had to be developed in close collaboration with the weather, oceanographic and other communities. Largely through WCRP's efforts, it is now possible to monitor, simulate and project global climate, to provide climate information for use by governments for policymaking, decision-making, and to support a wide range of practical end-user applications. WCRP provided the insights and information that led to the unequivocal agreement by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report that human activities have led to a continuing warming of the Earth's climate which, by 2010 – 2019, reached 1.07°C compared to 1850 – 1900, through the release of climatically active constituents (mostly fossil Carbon Dioxide).

At the 21st Conference of the Parties (COP21) in 2015, governments around the world accepted the scientific evidence that human activities affected the climate system, and that society needed to act to limit the associated warming to 2°C or less. The 2015 Paris Agreement, which identified the need for climate mitigation and adaptation solutions, also meant that climate research needed to evolve to put more emphasis on these broad societal needs and challenges as well as creating fundamental knowledge and understanding. Moreover, the World Climate Conference-3 (WCC- 3) made the leap to put climate science in the service of society. The focus on "climate prediction and information for decision-making" enabled the Conference to identify critical components of a Global Framework for Climate Services (GFCS), where WCRP plays an important research and development role.

Since COP21, the need for WCRP's leadership role in defining and coordinating international climate science remains more important than ever, to ensure that the global, regional, and national climate research communities continue to create the enduring, rigorous, and scientific foundation required to meet society's demand for robust and useful climate information.

The WCRP Strategic Plan 2019 – 2028 (https://www.wcrp-climate.org/wcrp-sp) recognizes and addresses this need through its vision and mission:

Our Vision

A world that uses sound, relevant, and timely climate science to ensure a more resilient present and sustainable future for humankind.

Our Mission

The World Climate Research Programme (WCRP) coordinates and facilitates international climate research to develop, share, and apply the climate knowledge that contributes to societal well-being.

The WCRP Strategic Plan ensures that the Programme continues to provide the science, knowledge and understanding needed to target and provide answers to frontier problems – such as disaster risk reduction, climate change adaptation, mitigation, and intervention strategies – to develop, share, and enable the application of climate knowledge that contributes to societal well-being. Anthropogenic climate change already brings significant challenges and risks that affect almost all aspects of life on Earth. Droughts, heavy rain and flooding, heatwaves, extreme fire weather, and coastal inundation are just a few examples of what is already occurring and where amplified risks and impacts in the future will threaten achieving many of the United Nations Sustainable Development Goals (SDGs).

WCRP's unique role in advancing climate science and providing information to decision makers (partly communicated through the IPCC process) continues through international coordination to identify and pursue new and evolving frontier scientific questions related to the climate system that are too large and too complex to be tackled by a single nation, agency, institution, or scientific discipline. In doing so, WCRP brings together scientists from around the world, at all stages of their careers, to advance our understanding of the multi-scale dynamic interactions between components of the climate system, to investigate climate predictions from intra-seasonal to multi-decadal time scales, to understand the response to external forcing anomalies, as well as to address and study the role of humans on climate. Solutions to address the causes and impacts of climate change in the future must be based on a collaborative dialog between WCRP and its partners, bringing together natural and social scientists, civil society, and political leadership at every level. WCRP also works with nations and funding agencies to ensure that required resources are mobilized. This is especially true to secure the resources needed to ensure that the Global South (in terms of "Least Developed Countries", "Landlocked Developing Countries", and "Small Island Developing States") is fully included in the scientific community.

WCRP's Strategic Plan broadly defines four overarching Scientific Objectives (Figure 1) that guide WCRP's climate science until at least 2028. These objectives reflect the most pressing contemporary climate knowledge needs, as well as the core science and capability that are needed to anticipate and prepare for the challenges that society cannot yet foresee.

Objective 1: **Fundamental understanding of the climate system**: support and facilitate the advancement of sciences enabling an integrated and fundamental understanding of the climate, its variations, and its changes, as part of a coupled physical, biogeochemical, and socio-economic system.

Objective 2: **Prediction of the near-term evolution of the climate system**: push the frontiers of climate predictions and quantify the associated uncertainties for sub-seasonal to decadal time scales across all climate system components.

Objective 3: **Long-term response of the climate system**: quantify the responses, feedbacks, and associated uncertainties intrinsic to the changing climate system on decadal to centennial timescales.

Objective 4: **Bridging climate science and society**: support innovation in the generation of decision-relevant information and knowledge about the evolving Earth system.

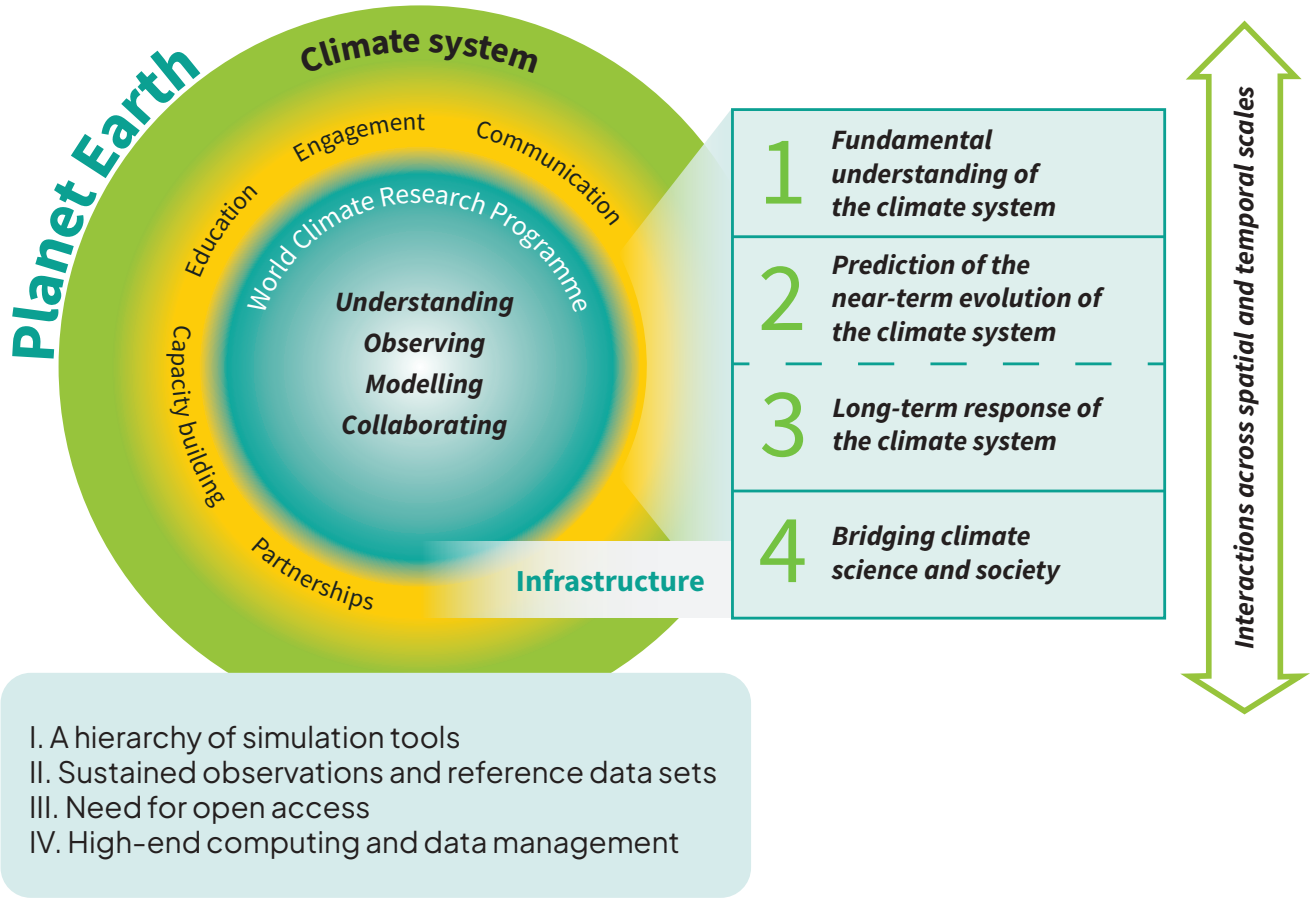

Figure 1: The four Scientific Objectives as outlined in the WCRP Strategic Plan 2019–2028 (www.wcrp-climate.org/wcrp-sp)

The focus of WCRP's community during the implementation of the strategic plan has been on identifying research priorities to guide the scientific advances needed; promoting technologies and institutional frameworks required to achieve WCRP's vision; and establishing a new science programme and a structure that better supports WCRP's new goals, science objectives and priorities. Example priorities are highlighted in Figure 2. These will continuously evolve as new and urgent scientific and knowledge gaps arise and WCRP aligns its research priorities with the agendas and priorities of international scientific research agencies. By addressing these priorities, WCRP will make fundamental and significant contributions to humankind's ability to understand and predict climate change, and its impacts, on different time horizons.

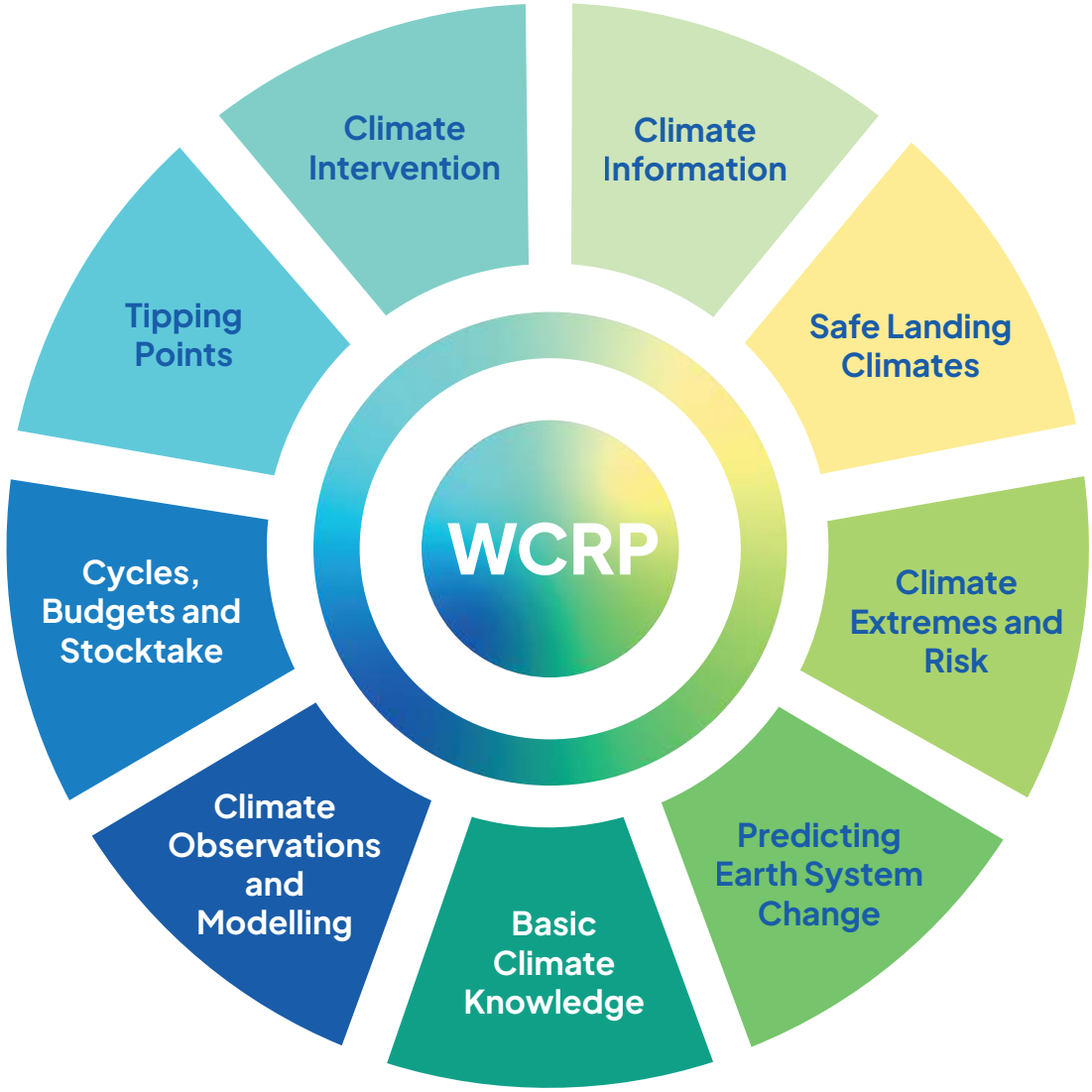

Figure 2: Examples of WCRP's overarching scientific priorities.

This **Science and Implementation Plan** documents six key implementation elements:

- Research priorities that guide the science we do – to advance knowledge (discovery), provide societally-relevant information, and inform public policy
- A new structure to support WCRP's mission, and strategic goals
- Partnerships with other research programmes and funding agencies – partners with whom WCRP needs to collaborate and, where appropriate, co-design research
- New science activities, as well as ongoing research programmes
- Operational elements: governance; financial plans; communication, coordination and engagement principles and plans; and capability (people and infrastructure) plans
- Success measures, milestones, and timelines

The following sections provide further details on each of the elements listed above, starting from the overall vision, a detailed description of the activities, and the different levels of organization.

2. Implementing WCRP's strategy

Implementing WCRP's new strategy and addressing WCRP's Scientific Objectives rely on the global community working together and collaborating to advance climate science, including improved understanding, enhanced prediction skills and expanded context-relevant information. The basis for this is sustaining and expanding observations, analysis and modeling approaches and efforts required to deliver its outcomes. During the implementation process, WCRP critically reviewed and refined past science activities to align future activities with the strategic plan, ensure continuous consultation and engagement across WCRP's research community, co-sponsors, partners, and with WCRP's user and stakeholder communities. Two overarching priorities served as guidelines during this process to underpin these Scientific Objectives and guide the definition and implementation of science priorities for WCRP:

1. **Foster and deliver scientific advances and future technologies**, to advance understanding of the multi-scale dynamics of Earth's climate system; and to quantify climate risks and opportunities. Furthermore, WCRP's stakeholders are asking for climate information that helps quantify risks associated with a changing climate.

2. **Develop new institutional and scientific approaches**, to co-produce cross-disciplinary global to regional to local climate information for decision support and adaptation; and to inform and evaluate mitigation strategies based on the latest and best quality climate science – alongside other sciences and technologies.

Implementing the new WCRP strategy required the development of a new "fit-for-purpose" structure to effectively support and enable WCRP's Scientific Objectives, to address new challenges and to develop new opportunities in an agile and nimble way. Meeting WCRP's research priorities requires discipline-based communities to work together to advance multi-disciplinary research: these communities require a home where their capabilities are sustained, as well as platforms where "big problems" can be addressed together in an integrative and interdisciplinary way.

The resulting new organizational structure of WCRP is shown in Figure 3. The major elements of the WCRP structure are:

1. **Joint Scientific Committee (JSC)**: The JSC is the highest-level committee of WCRP, responsible for overseeing and steering all science and certain high-level organization aspects of WCRP. "Joint" refers to the fact that the WCRP has three sponsors: WMO, ISC, and IOC-UNESCO.

2. **Core Projects:** Core Projects (see Table 1 for a list) are long-term activities that are dedicated to specific aspects of climate science within WCRP as specified in their terms of reference. Each Core Project has a Scientific Steering Group (SSG), approved by the JSC. The Core Projects are WCRP's foundation and are home to various scientific communities – across oceans, cryosphere, land, and atmospheric science domains; process studies, modeling, and observations; and regional climate information. They develop and deliver important foundational knowledge and understanding and foster scientific discovery as well as applications and regional climate information through process studies, modeling, and observations; They identify key research questions and gaps as well as emerging issues. They facilitate exchanges amongst scientists and relevant external stakeholders and promote international cooperation. They also communicate their related science to policymakers, funding agencies and the public.

International Project Offices (IPOs) support the Core Projects and work closely with the WCRP Secretariat.

3. **Lighthouse Activities:** The WCRP Lighthouse Activities (see Table 2 for a list) are designed to be ambitious and interdisciplinary, integrating across WCRP, in particular across the Core Projects, and collaborating with partners, so that they can rapidly advance new science, technologies, and institutional frameworks that are needed to manage climate risk and meet society's urgent need for robust and actionable climate information more effectively. Work within the Lighthouse Activities is performed in collaboration with the WCRP Core Projects, helping to complement and rapidly advance some of the Core Project goals. They have their own SSGs (or equivalent), approved by the JSC, and can form working groups, approved by the SSG, as required. As of 2023, there are six Lighthouse Activities. Their scope encompasses building new knowledge of the Earth's climate system, its near-term predictability, and longer-term trajectories by harnessing emerging technologies to better simulate the Earth system via digital "twins", as well as exploring new approaches for managing climate risk that start with the decision context and user needs. The two more recent Lighthouse Activities focus on the science behind climate intervention and on the development of a global precipitation experiment.

4. **The WCRP Academy**: The Academy is the research training advisory and coordination arm of WCRP. Its mission is to equip current and future climate scientists with the knowledge, skills, and attributes required to tackle the world's most pressing and challenging climate research questions. As with other WCRP Core Activities, the Academy has a SSG, approved by the JSC. The WCRP Academy was previously a Lighthouse Activity but was made part of the permanent structure of WCRP in 2023, as its character is different from that of the Lighthouse Activities.

5. **The WCRP Secretariat**: Primarily located at WMO Headquarters in Geneva, with secondments outside of WMO, the Secretariat supports the JSC as well as WCRP's Core Projects, Lighthouse Activities, other research activities and groups.

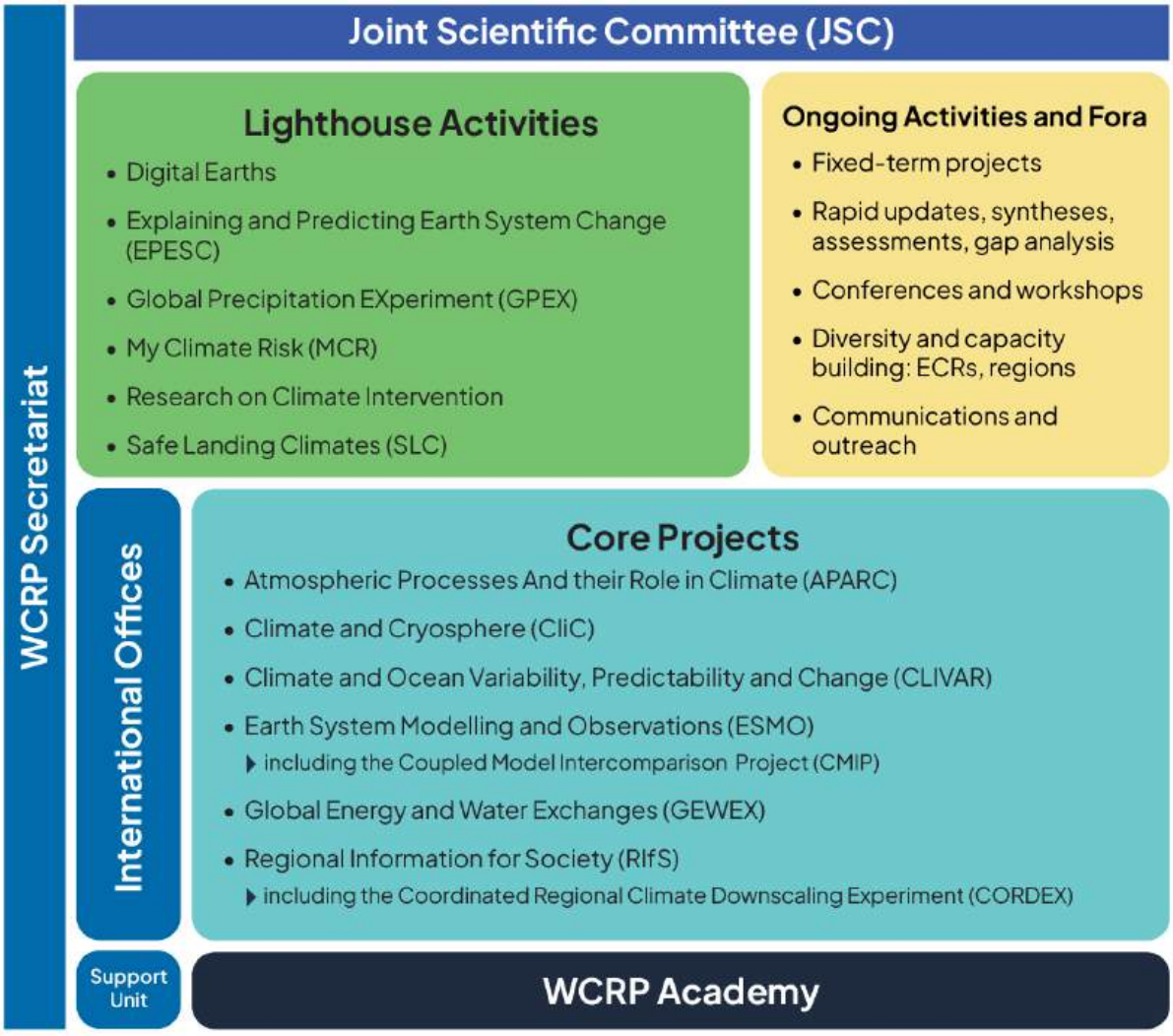

Figure 3: WCRP organizational structure

Table 1: WCRP's six Core Projects

Core Project	Role within WCRP
Atmosphere Processes and their Role in Climate (APARC)	APARC coordinates international research efforts to improve our understanding of how atmospheric dynamical, chemical and physical processes interact with Earth's climate system.
Climate and Cryosphere (CliC)	CliC improves the understanding of the processes in the cryosphere (polar seas, frozen and snow-covered land, ice sheets and mountainous regions) and its interaction with the climate system.
Climate and Ocean Variability, Predictability and Change (CLIVAR)	CLIVAR investigates the dynamics, the interaction, and the predictability of the climate system with emphasis on ocean-atmosphere interactions. It facilitates observations, analysis, predictions of variability and changes in the climate system.
Earth System Modeling and Observations (ESMO)	ESMO coordinates modeling, data assimilation and observational activities within WCRP, working jointly with all other WCRP core activities. It provides a seamless approach across all Earth system components, disciplines, and scales.
Global Energy and Water Exchanges (GEWEX)	GEWEX is dedicated to understanding Earth's water cycle and energy fluxes at and below the land surface and in the global atmosphere. It facilitates improvement of observations, process understanding and model improvements.
Regional Information for Society (RIfS)	RIfS facilitates research related to the provision of actionable information about climate variability and change in support of adaptation and mitigation. RIfS uses the application context to inform research on aspects of understanding the climate system, the collation and/or generation of relevant data and the construction of context-relevant actionable information.

Table 2: WCRP's six Lighthouse Activities

Lighthouse Activity	Role within WCRP
Digital Earths	Digital Earths aims to facilitate the research required to build quantitative frontier climate information systems and to support the international community engaged in developing and implementing them.
Explaining and Predicting Earth System Change (EPESC)	The overarching goal is to develop an integrated capability to understand, attribute, and predict annual to decadal (A2D) changes in the Earth system, including capabilities for early warning of potential high impact changes and events.
Global Precipitation Experiment (GPEX)	GPEX makes progress in understanding phenomena and processes critical to precipitation; and improves precipitation prediction by leveraging existing WCRP projects and community capabilities in observation, modelling, and research. It conducts focused activities, including planning for the WCRP Year of Precipitation.
My Climate Risk (MCR)	The activity develops a 'bottom-up' approach to regional climate risk, which starts with the requirements of decision-makers. By 'risk' we mean the combination of hazard, vulnerability, and exposure that is particular to a given regional context.
Research on Climate Intervention (RCI)	The activity aims to identify scientific knowledge gaps and remaining uncertainties with respect to scaled-up climate interventions. It is critical to comprehensively evaluate not only potential benefits and risks like environmental consequences of RCI, but also remaining research questions to provide an overview of the current research as a foundation for governance and decision making.
Safe Landing Climates (SLC)	Explores routes to "safe landing" spaces for human and natural systems. It will explore future pathways that avoid dangerous climate change while simultaneously contributing to the United Nations Sustainable Development Goals (SDGs), including those of climate action, clean water, good health and well-being, affordable and clean energy, and healthy ecosystems above and below water.

3. WCRP science: goals and priorities

WCRP's Core Activities, consisting of Core Projects (see Table 1) and Lighthouse Activities (see Table 2), facilitate and coordinate climate research in specific areas in accordance with their strategic goals and science plans developed by their SSGs, which adhere to the overarching WCRP Strategic Plan. In this section, we describe the goals and research priorities of each Core Activity and explain how they interact and collaborate with each other. Section 4 describes WCRP's collaborations with other programmes. Governance aspects of the Core Activities are addressed in Section 5. For further details, please also consult the web pages of each activity at https://www.wcrp-climate.org.

3.1. Core Projects

3.1.1. Atmospheric Processes And their Role in Climate (APARC)

Science goals and objectives

Founded in 1992 as the Stratosphere-troposphere Processes And their Role in Climate (SPARC) Core Project, this activity renamed itself in early 2024 to Atmospheric Processes And their Role in Climate (APARC), to better reflect its role within WCRP of a providing fundamental understanding of the role of the atmosphere in the Earth's climate system. APARC coordinates research improving our understanding of how atmospheric dynamical, chemical, radiative and physical processes interact with the rest of the climate system. In doing so, APARC addresses

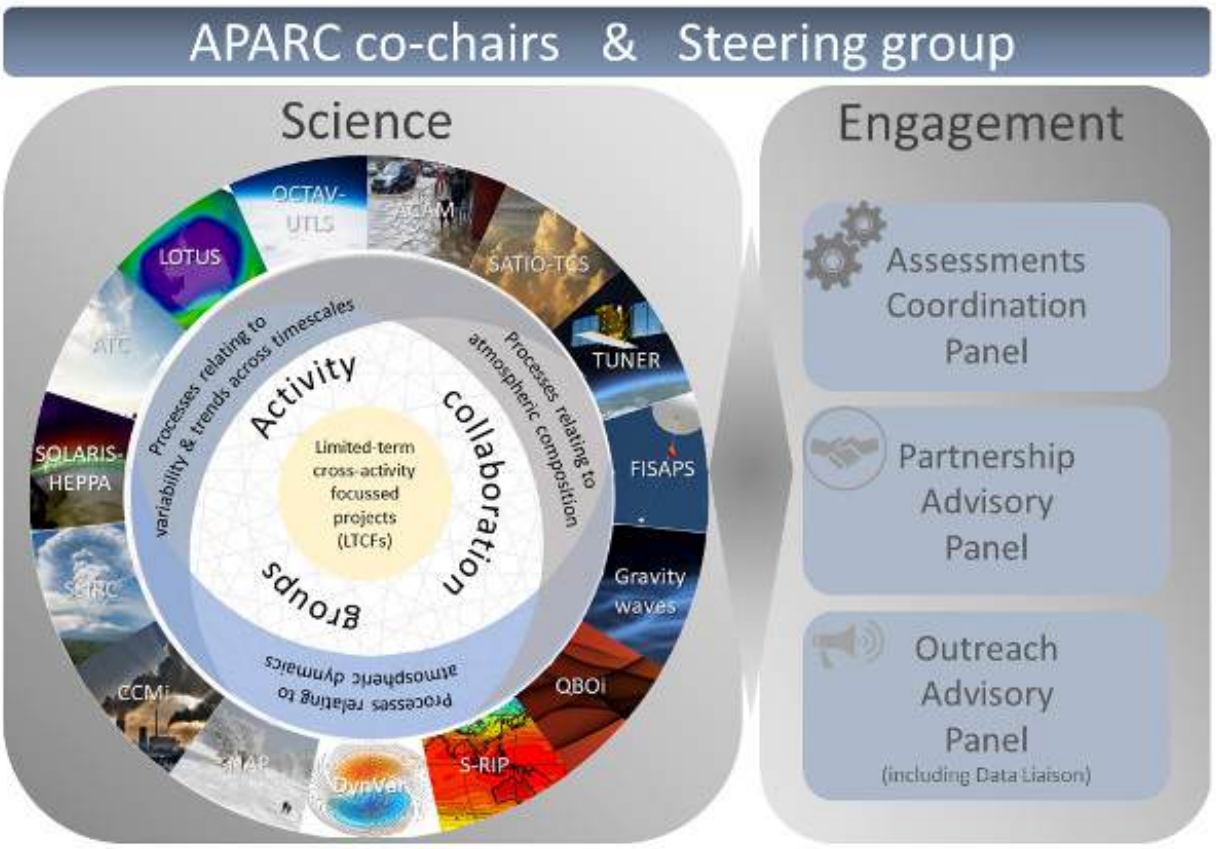

Figure 4: Organizational structure of APARC.

all of WCRP's overarching objectives. In addition, it supports the scientific and user/policy communities in addressing science questions relevant to our changing planet. In terms of the generation of decision-relevant information, APARC has a longstanding role in supporting international scientific assessment reports, such as the WMO/United Nations Environment Programme (UNEP) Ozone Assessment Reports. APARC's objectives are:

- To advance understanding of the role of the atmosphere in the Earth's climate system.
- To promote innovative research in atmospheric science that addresses questions and knowledge gaps across the breadth of atmospheric science topics.
- To deliver rapid, timely, and coordinated responses to emerging atmospheric science topics in support of WCRP's 'science for society' ethos.
- To assess and advocate for future measurement needs in relation to composition studies.

To facilitate engagement, APARC has established three panels (Figure 4): (1) An Assessments Coordination Panel, to unite scientists from the APARC community who are supporting international assessments; (2) A Partnerships Advisory Panel to facilitate engagement and collaboration with external organizations, groups and other projects; and (3) an Outreach Advisory Panel to take strategic responsibility for APARC's outreach and engagement, capacity building, training, and open science.

Ongoing and planned research for the next 5 – 10 years

APARC's work is organized into three science themes:

- Processes relating to atmospheric composition, to improve understanding of fundamental processes that control composition and feedbacks associated with composition, including those related to atmospheric chemistry, radiation and dynamics.
- Processes related to atmospheric dynamics, focused on leveraging observations, reanalyses, models, and innovative analysis and attribution methods to demonstrate new understanding of the climate system, its changes and drivers.
- Processes related to variability and trends across timescales, including research related to atmospheric and climate prediction, and occurrence and attribution of extreme events.

APARC has also developed Limited-Term Cross-activity Focused projects (LTCFs), the first of which is on the January 2022 Hunga Tonga Eruption and aims to produce a special assessment report on the eruption ahead of the 2026 WMO/UNEP Ozone Assessment. After finalizing its new strategy for the next 5 to 10 years, APARC is working with its SSG and IPO to implement its new structure.

In the longer term, there are several emerging science themes that have been identified as relevant but are not currently a focus of APARC. APARC will undertake a scoping exercise to establish the wider community representation around emerging topics and identify whether APARC can provide a scientific home and support for groups of researchers interested in those topics.

New topics and collaborations with other WCRP Core Projects include:

- APARC/ Climate and Ocean Variability, Predictability and Change (CLIVAR) / Global Energy and Water Exchanges (GEWEX) joint activity on extratropical cyclones and climate: Extratropical cyclones are a key feature of the general circulation. They are frequently

associated with impactful events.

- APARC/CLIVAR/GEWEX joint activity on convective organization: This could be a follow-up to the "Clouds, Circulation and Climate Sensitivity" Grand Challenge" which had a focus on convective organization and has established an international community around clouds, circulation and climate sensitivity.
- APARC/CLIVAR joint activity on Rossby waves: Rossby waves are a fundamental part of the general circulation. Rossby waves are involved with many aspects of weather and climate, e.g., teleconnections, stratosphere-troposphere coupling, atmospheric blocking, and compound extremes. However, there remain fundamental questions about Rossby wave dynamics, their representation in models and the response to external forcing.
- APARC activity on multi-variate atmospheric trends: APARC has supported several activities focused on atmospheric trends. These were separate activities with distinct scientific foci. Deeper understanding can be gained by viewing these trends holistically as interconnected aspects of the coupled atmospheric system.

3.1.2. Climate and Cryosphere (CliC)

Science goals and objectives

The aim of the Climate and Cryosphere (CliC) Core Project is to provide vision and leadership to facilitate an improved understanding of how the cryosphere (polar oceans and seas, frozen and snow-covered land, glaciated regions including ice sheets and mountainous regions) operates, is changing, and its interaction with the other components of the climate system. CliC identifies key research questions, emerging issues, priorities, and gaps, and coordinates international collaborative research activities to help address them. This involves collaboration amongst scientists, and developing relationships with relevant external stakeholders, promoting international cooperation and the development of Early Career Researchers (ECRs).

CliC also facilitates co-design, co-production, and communication of cryospheric science, information, and outcomes with stakeholders, policymakers, funding agencies, and the general public. To achieve this, CliC works closely with other WCRP Core Projects and Lighthouse Activities, and has developed strong external science partnerships (e.g., with the Scientific Committee on Antarctic Research (SCAR), the International Arctic Science Committee (IASC), and the International Association of Cryospheric Science (IACS)) and relationships with stakeholders.

With respect to the WCRP overarching Scientific Objectives, CliC has a unique role in advancing our fundamental understanding of the climate system, with a focus on all aspects of the cryosphere. CliC also provides input into WCRP's prediction and projection activities, particularly on longer time scales, and contributes to bridging climate science and society.

Actionable science is critically needed to identify future safe landing pathways for the cryosphere in response to planetary heating, to minimize risks associated with cryospheric loss, and to enable effective anticipation of the hazards and flow-on impacts to ecosystems and society. Therefore, CliC has identified four key science objectives:

1. Improve understanding of the rates and (ir)reversibility of polar land ice loss and its contribution to sea level rise, including:
    a. Understand the rate determining processes affecting the dynamic loss of Antarctic

Figure 5: Organizational Structure and Activities of CliC

ice mass and their incorporation into models for projections, so that confidence can be increased, and deep uncertainty reduced in sea-level projections;

b. The identification of key cryosphere-related thresholds and tipping points;

c. Improved knowledge of the processes of Greenland ice mass loss and its relationship with North Atlantic regional climate variations through a better understanding of atmospheric circulation changes and their links with polar amplification;

2. Improve understanding of the drivers of sea-ice variability and retreat in the Arctic and Antarctic to improve predictability, including longer-term changes in sea-ice state, in order that future heat and carbon budgets, and their consequences for the Earth System, can be better predicted, including impacts on ecosystems, human communities and cryospheric services;

3. Improve understanding of the rates and (ir)reversibility of snow and ice loss in high mountain regions, and the implications for water availability, food production, ecosystem services and related natural hazards;

4. Improve understanding of the processes of permafrost thawing in the Arctic and Antarctic

for better predictability of spatial scale, rate and timing of methane and carbon dioxide release to the atmosphere and its influence on global warming.

CliC's structure and current activities are depicted in Figure 5. Examples of past CliC efforts include modeling and projections within Model Intercomparison Projects (MIPs) aligned with the Coupled Model Intercomparison Project (CMIP) Phase 6 (CMIP6) cycle for ice sheets, snow, and glaciers as well as coordinated observations of Arctic and Antarctic sea ice, and permafrost regions. These projects were organized under the umbrella of the WCRP's Grand Challenges on "Melting Ice and Global Consequences" and "Regional Sea level Change and Coastal Impacts" and in collaboration with other WCRP Core Projects. Many of these initiatives will continue within CliC and in close association with the Earth System Modelling and Observations (ESMO), CLIVAR, and Regional Information for Society (RIfS) Core Projects and the Safe Landing Climates (SLC) Lighthouse Activity. For example, the Ice Sheet Model Intercomparison Project (ISMIP) Phase 7 team are developing their next generation of experiments of land-ice contribution to sea-level rise with ESMO, large European research consortia such as PROTECT, and SCAR's INStabilities and Thresholds in ANTarctica (INSTANT) Programme. The local and regional implications and impacts of cryospheric change contribute to work streams in SLC, RIfS, and the My Climate Risk (MCR) Lighthouse Activity.

Ongoing and planned research for the next 5 – 10 years

CliC is in the process of developing a new 10-year strategy and implementation plan that will address the highest priority research issues and needs concerning the changing cryosphere and its societal impacts. This will involve sunsetting some of its current activities, continuing others and developing new ones. CliC is also in the process of soliciting information from the global community for ongoing and new activities that will promote collaboration and co-ordination of interdisciplinary regional (including applied) research targeting CliC priorities, as outlined above. CliC aims to improve inclusion of, and opportunities for, ECRs and scientists from under-represented regions. CliC activities will address priorities in a time-sensitive and limited manner aimed at specific outcomes and deliverables. Groups, projects, and activities are to be regularly reviewed and assessed. Where the research is applied, CliC aims to co-produce the application of the research and outcomes in the form of case studies with stakeholder and user groups, such as indigenous communities, planners, practitioners, and policy makers.

Examples of future foci include:

- Lead a series of hands-on workshops to address gaps in observing networks and knowledge at regional level, involving local scientists and communities. These workshops lead to synthesis of scientific papers, grant proposals, capacity building, and other team building and co-production efforts.
- Promote activities to establish and sustain long-term monitoring of key cryospheric parameters in regions of poor data coverage by local communities with limited funding.
- Develop capacity in cryospheric science through supporting ECRs, working closely with WCRP Academy, and other groups e.g., Association of Polar Early Career Scientists (APECS).
- Develop collaborative opportunities with WCRP Lighthouse Activities and other WCRP activities.

Over the next five years CliC has identified the following critical needs:

- Promote improved understanding of cryosphere processes.
- Promote increased capacity to acquire urgently needed observations of the cryosphere in regions where change is occurring quickly and is critical to achieving the point above.
- Incorporate improved understanding of the cryosphere boundary conditions and process into models to improve accuracy of predictions and projections and reduce uncertainty.
- Facilitate interdisciplinary research that contributes to an improved integrated understanding of cryosphere systems and their interactions in the climate system across multiple components and disciplines that bridges the natural and social sciences. This will enable services provided by ice and snow, and hazards associated with their loss as well as the societal cost of their damage.
- Deliver and translate actionable climate information to support the development of decision tools and engagement with stakeholders that can help establish signposts for decision-makers that can assist more effective adaptation strategies, and safe landing pathways for the cryosphere.

3.1.3. Climate and Ocean: Variability, Predictability and Change (CLIVAR)

Science goals and objectives

The Climate and Ocean: Variability, Predictability and Change (CLIVAR) Core Project was launched in 1995, building on the success of the Tropical Ocean - Global Atmosphere Project (TOGA) and the World Ocean Circulation Experiment (WOCE) to further understand the ocean circulation and the atmosphere-ocean interactions. CLIVAR's mission is to understand the dynamics, the interaction, and the predictability of the climate system with emphasis on ocean-atmosphere interactions. To this end it facilitates observations, analysis, predictions and projections of variability and changes in the Earth's climate system, enabling better understanding of climate variability and dynamics, predictability, and change, to the benefit of society and the environment in which we live.

Covering all WCRP Objectives, CLIVAR provides fundamental knowledge about the drivers of variability and predictability in the coupled climate system with emphasis on the ocean. It has a focus on detection, attribution and quantification of climate variability and change as well as the development and evaluation of climate simulations and predictive capabilities, emphasizing the combined use of models and observations to develop understanding and benefit society.

The CLIVAR SSG oversees a number of quasi-permanent panels as well as temporary Research Foci, Working Groups, and Task Teams (Figure 6). Research Foci are focused research activities on topics (1) with high potential for significant progress in a 3–5–year time scale, and (2) that would benefit from enhanced international coordination. Research Foci have proven to be effective means to initiate a bottom-up effort and invigorate progress in areas that are of high priority to the climate research community, thereby fostering cross panel, cross WCRP community collaboration, while also providing opportunities to entrain new scientists into CLIVAR. New Research Foci will be established continuously in a bottom-up process through proposals from members of the CLIVAR and WCRP communities.

CLIVAR Working Groups and Task Teams are established on an ad hoc basis to work on the synthesis of key questions, current understanding and gaps, and opportunities for future

improvement towards a specific research topic that is at the frontier of the science and/or has large uncertainty that impedes our ability in understanding and predicting the Earth's ocean and climate system. Examples for working groups are understanding and prediction of El Niño–Southern Oscillation (ENSO) and Pacific decadal variability by the Pacific Regional Panel and understanding of the Atlantic Meridional Overturning Circulation by the Atlantic Regional Panel. A CLIVAR Task Team is a cooperative effort across CLIVAR groups, and usually is in collaboration with other partner programmes. A Task Team coordinates international efforts and cooperation on important phenomena and/or processes that are identified by the international community with strong relevance to society.

Ongoing and planned research for the next 5 – 10 years

Organized through its panels and Research Foci and in cooperation with partners, CLIVAR provides fundamental knowledge about the drivers of variability and predictability in the coupled climate system with emphasis on the ocean, which is a key subsystem that regulates the Earth's climate. CLIVAR also stimulates the development of ocean and coupled modeling capacity and model intercomparison projects, which advances the understanding of the climate system's response to anthropogenic forcing, with highlighted work on CMIP, the Ocean Model Intercomparison Project (OMIP) and the Coordinated Ocean-ice Reference Experiment (CORE) -I and II.

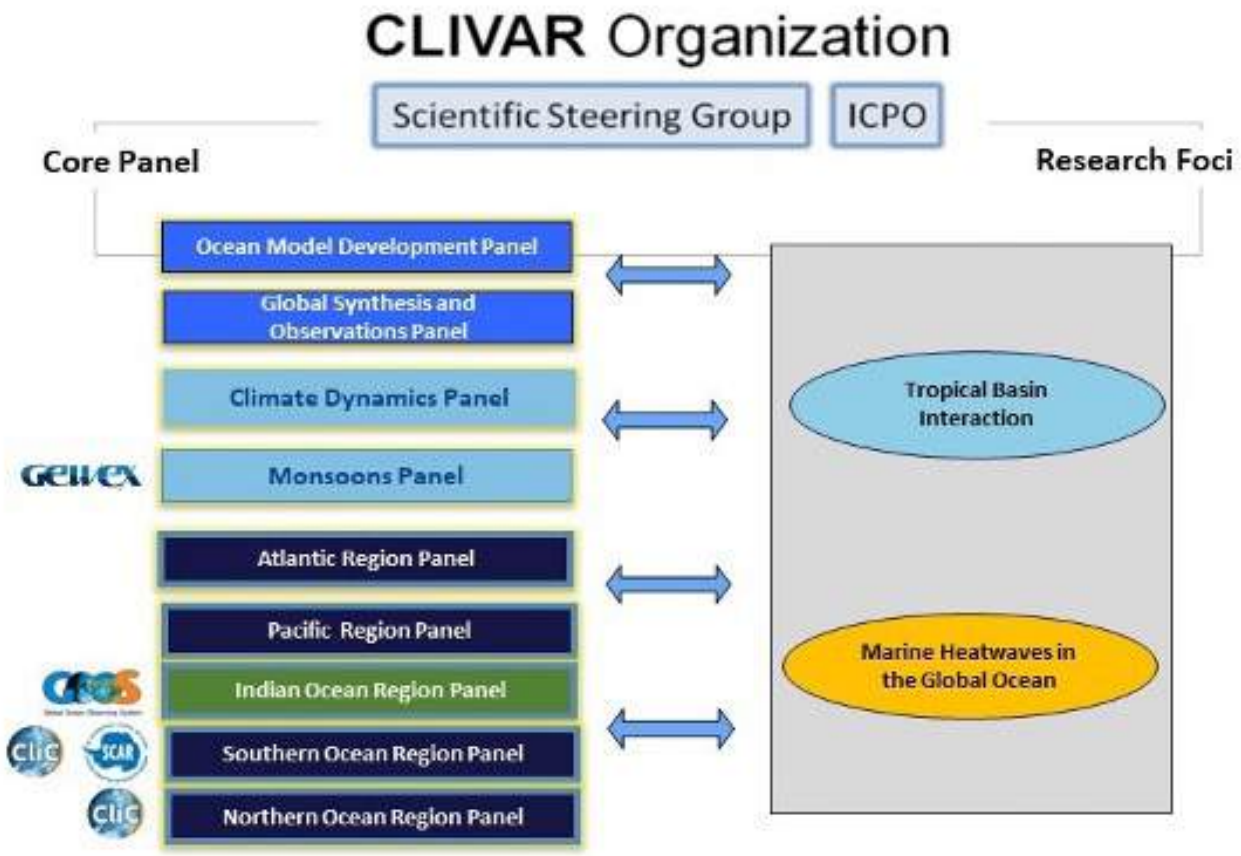

Figure 6: Organizational structure of CLIVAR showing the Scientific Steering Group, International CLIVAR Project Office (ICPO), Panels and Research Foci. Logos on the left hand side of the Panels indicate those Panels that are joint with other activities: GOOS for the Indian Ocean Regional Panel, CliC and SCAR for the Southern Ocean Regional Panel and CliC for the Nortnern Ocean Regional Panel.

CLIVAR supports the strategic development of the global in situ and satellite observing networks, such as Argo and GO-SHIP, as well as the regional ocean observation system design and implementation, such as the Indian Ocean Observing System (IndOOS), the Tropical Atlantic Observing System (TAOS) and the Tropical Pacific Observing System (TPOS) 2020. CLIVAR shows significant leadership in synthesis of global ocean, atmosphere and coupled climate information with highlighted activities on the International Quality Controlled Ocean Database (IQuOD) and the endorsement of several Ocean Reanalysis Intercomparison Projects (ORA-IP).

CLIVAR, through its structure and activities, promotes international collaboration and cooperation, increasing the global scientific capacity beyond regional and institutional capabilities. Intra group/panel collaboration is promoted alongside liaisons with GEWEX, CliC and APARC. Some panels and groups are organized jointly with other WCRP components and partner organizations, such as the Global Ocean Observing System (GOOS).

CLIVAR contributes to new WCRP science by covering the following overarching topics:

- Understanding the ocean's role in climate variability, change, and transient sensitivity;
- Understanding the ocean's role in shaping the hydrological cycle and distribution of precipitation at global and regional scales;
- Understanding the drivers of regional climate phenomena that provide predictability on different time scale;
- Provision of coordinated observations, analyses and predictions of variability and change in the Earth's climate system;
- Detection, attribution and quantification of climate variability and change;
- Development and evaluation of climate simulations and predictive capabilities.

Through its Panels, Research Foci, workshops, summer schools and conferences, CLIVAR continues to bring together researchers from all over the world. In doing so, CLIVAR develops a strong, multidisciplinary international community of scientists at all stages of their career who coordinate efforts required to measure, simulate, and understand coupled ocean-atmosphere dynamics, and identify processes responsible for climate variability, change and predictability.

CLIVAR will continue to work toward its scientific goals through the activities of panels, Research Foci, workshops and summer schools. In the short term, summer schools have been organized in alternate years at the First Institute of Oceanography (China) and the International Center for Theoretical Physics (Italy).

Links between CLIVAR and the Lighthouse Activities have been developed and will be further strengthened with short-term plans including the implementation of three hubs on ocean extremes in collaboration with the MCR Lighthouse Activity. Links across panels will be strengthened through cross-panel activities, particularly emphasizing the combined use of models and observations to develop understanding and benefit society.

Long-term plans include strengthening ocean observing systems from the open ocean through to the coastal zones, engaging with user communities such as ocean rim nations and small island nations, making ocean and climate information more accessible and relevant to stakeholders, and bridging between ocean climate science and society.

3.1.4. Earth System Modeling and Observations (ESMO)

Science goals and objectives

The Earth System Modeling and Observations (ESMO) Core Project coordinates and advances modeling, data assimilation and observational activities within WCRP. ESMO works jointly with all other WCRP Core Projects and activities and provides strategic connections to related external programmes. It promotes a seamless approach across all Earth system components, disciplines, and scales in an effort to join communities to address key problems and potential for innovation.

ESMO's activities are key to all of WCRP's Scientific Objectives, with a particular focus on improving process understanding, as well as predictions and projections of the climate system. It's activities also pertain to developing actionable climate information for society.

The modeling and observational activities under ESMO are central to the provision of science-based climate information to support adaptation planning and decision-making, local and regional climate impact assessments, and national and international mitigation and adaptation policies. Understanding, adapting to, and mitigating climate change requires taking a holistic perspective of our Earth system. The strong interplays between carbon, energy and water cycles are just one well-known example of the global nature of climate research where linkages among communities that study each cycle offer potential for advancement. An immediate consequence of these complex interconnections is that the monitoring, modeling, and analysis of the various climate components need to be carried out in a consistent and coordinated manner. ESMO will contribute to improving the understanding, predictive skills, and projections across all components of the climate system.

ESMO has developed the following three scientific objectives that will underpin and integrate the next decade of climate science modeling, data assimilation and observational activities (Figure 7). The objectives are informed by the most pressing shortcomings in our ability to monitor, predict, and provide projections of the climate system from weeks to centuries and from local to global spatial scales with an aim to advance the core capabilities of the Project.

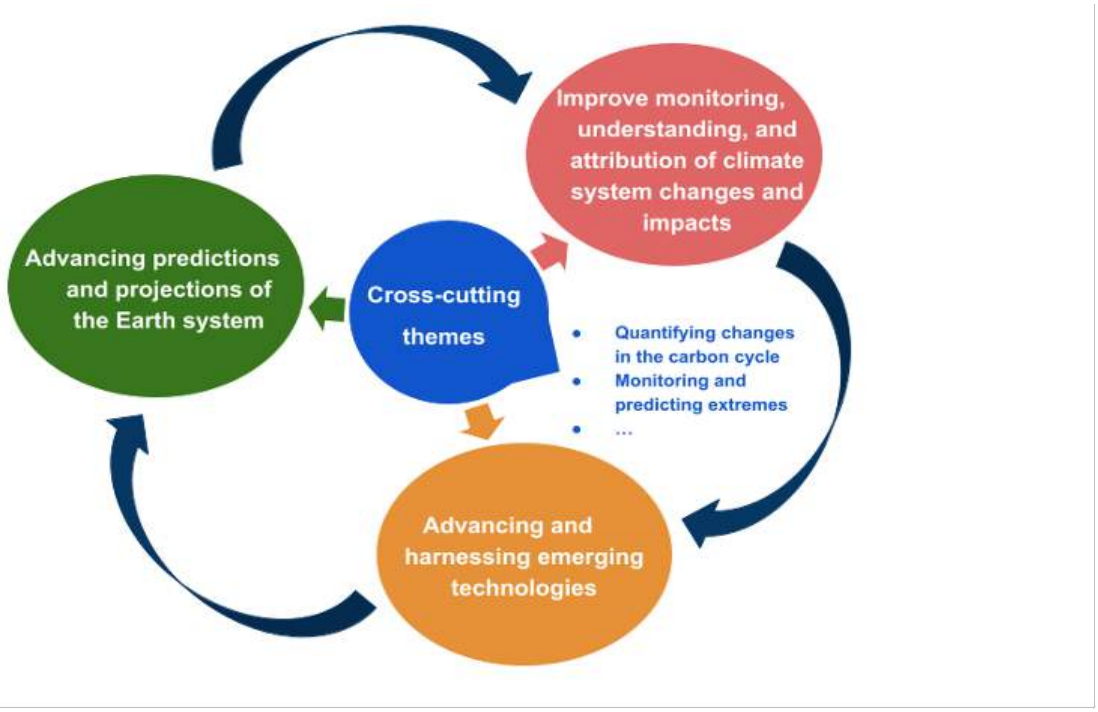

Figure 7: ESMO objectives and Initial cross-cutting themes.

1. Advancing predictions and projections of the Earth system

Improved predictions and projections of the evolution of the climate system on time scales from weeks to centuries are the focus of the first objective. The provision of science-based climate predictions and projections requires a coordinated model hierarchy connecting models at various scales from process models at cm-scale to global kilometer-scale models to Earth System Models (ESMs). Such a model hierarchy should be aligned in an integrative framework making use of Earth system observations and data assimilation practices to evaluate model prediction and projection skill and address an ever-expanding suite of applications. The use of satellite data needs to be strengthened, as its potential has not been fully exploited to date.

Many of the challenges that will drive this objective are already being addressed in the modeling Working Groups and observational panels that sit under ESMO and in other Core Projects and Lighthouse Activities. These range from process understanding and development of component models (e.g., the Global Atmospheric System Studies (GASS) within GEWEX and the Ocean Model Development Panel (OMDP) within CLIVAR) to assessment, intercomparison and evaluation of ESMs (e.g., CMIP (see box below) within the Working Group on Coupled Modeling (WGCM)). ESMO is particularly well-placed to address specific priority topics that would yield rapid results to the modeling community and the broad user community. These include activities focused on model improvements via the reduction of systematic errors, the use of reanalysis and data assimilation, the coordination of observational activities and datasets curated toward the context of modeling, as well as links to external partners such as developers of emerging software and hardware technologies. ESMO will focus on organizing various collaborative activities including working meetings between parties with shared needs and interests but from different activities within WCRP, as well as collaborative overview papers and task teams.

The **Coupled Model Intercomparison Project (CMIP)** is an international climate modeling project, designed to better understand past, present and future changes in the climate.

CMIP (wcrp-cmip.org) is a flagship project of WCRP, under ESMO and its Working Group on Coupled Modeling (WGCM), supporting activities across all core projects and lighthouse activities. Members of the CMIP Core Panel are currently working on developing the design of CMIP phase 7 (CMIP7). Task teams have been created to bring in expertise from across the climate science community, each tackling a different aspect of the design. The CMIP7 overview paper is expected to be published during 2024. The data output for CMIP phase 6 (CMIP6) is available on the Earth System Grid Federation (ESGF), as are the Observations for Model Intercomparisons Project (Obs4MIPs) datasets curated toward evaluating CMIP-class models and their components.

2. Improve monitoring, understanding, and attribution of climate system changes and impacts

Bringing together information from observations and models in coupled systems and ensuring robust uncertainty quantification is critical for capturing and attributing the past evolution of the Earth system. Such knowledge will allow for a better understanding

not only of the characteristics, but also of the impacts of climate change. A key aspect of this objective is a robust signal detection and attribution supported by consistent uncertainty quantifications in observational and reanalysis data sets. A special focus will be given to the physically consistent use of different data sets in coupled systems and to a consistent representation of the different spatial and temporal scales of the Earth system. ESMO will lead efforts on quantifying observational and reanalysis uncertainties by supporting the development of common vocabularies, concepts, computational data types, methodologies and tools, organizing observation inter-comparison projects and implementing meteorology concepts. Global surveys across WCRP are envisioned to quantify observational needs and identify useful data being collected across the community, while establishing libraries of data repositories aims to provide a collaborative communication platform. ESMO will support the homogenization and curation of observational data sets for specific user communities, Such date sets can be used as time varying boundary forcings for reanalyses, training data for emerging technologies such as machine learning, and data storage models ensuring that uncertainty estimates can readily be propagated alongside observations and model variables. In addition, the curation of observation-space data sets of in situ observations as input to data assimilation will be promoted. ESMO also aims at establishing a framework for enhanced intellectual and technical exchanges among reanalysis producers.

3. **Advancing and harnessing emerging technologies.**

Each of the above objectives requires an internationally coordinated, integrated, and consistent framework combining global Earth system observations, data assimilation and modeling. New and emerging technologies - such as machine learning, the latest satellites, and the highest possible resolution models - will impact all methods of operation in climate science including Earth system modeling, data assimilation and interpretation, and observations. Adoption and understanding of these technologies will benefit from ESMO activities and guidance. For instance, machine learning techniques can be exploited across the whole climate science and services cycle, from observational quality control and model development, data assimilation and post-processing to large language model interfaces addressing queries from the community. Other technological advances fitting within this ESMO objective are the use of new computing languages, improved sharing of large datasets online, cloud computing, and interactive queries with bots to efficiently generate tools for analysis. Bots can also be used to scale scientific expertise toward large communities' needs for applications such as citizen science and local climate resilience. There are several opportunities to partner with technology developers, in government labs, academia, or industry. This objective aims at advancing the applications of such new technologies for use by the WCRP community.

One branch of advanced modeling seeks to represent the global Earth system in ever finer detail by targeting cloud-resolving and ocean eddy-resolving kilometer-scale resolutions. Such simulations require advanced computing and software architectures and generate immense amounts of data that must be stored, analyzed, and served to the scientific and climate impacts communities. Emerging technologies such as machine learning and new computing languages for analysis will be used for mining and interpreting this data, and in making simulations and data sharing more efficient.

The challenges of distilling scientific understanding from model outputs will only magnify, so that hierarchies of weather and climate models, including simple low order models and emulators projecting only a few key variables at very low cost, will continue to serve as vital

points of reference. As climate change intensifies, opportunities for access to quantitative information and "what if?" efficient modeling tools will become increasingly valuable to scientists and decision makers. Ensuring that these data and tools are accessible, not just to scientists in affluent countries, but to potential users worldwide and especially across the Global South, can help narrow the gap in climate readiness and resilience. Key activities will focus on ways of strengthening sustainability of technical systems for working with observations and model outputs, harnessing emerging technologies for climate modeling and research, expanding capabilities and understanding to a broader audience of users, and bringing best practices from research and operations closer together.

4. Cross-cutting themes

ESMO has identified three initial example cross-cutting themes (Figure 7) that are central to the WCRP Scientific Objectives. ESMO will continue to develop further cross-cutting themes as the project and working groups evolve. The first cross-cutting target is to quantify changes in the carbon cycle across timescales and in response to natural and forced change including linkages with the water and energy cycles. This cross-cutting theme is part of the wider WCRP (and, in particular, GEWEX) focus on changes in water, energy, and carbon cycles, but also entails a range of scientific issues across the ESMO objectives drawing together many components of the earth system models and observations of the atmosphere, ocean, cryosphere, and land cutting across all of the WCRP Core Projects. In this context, ESMO will coordinate the solicitation of observational requirements for carbon cycle monitoring, promote the need for a fully coupled land-ocean-atmosphere carbon cycle reanalysis, and support the development of near-term prediction systems in support of carbon verification and monitoring activities.

A key connection to the CMIP modeling activities is the need for constraining processes within the carbon cycle in emissions-driven ESM projections. The second cross-cutting theme focuses on meteorological, oceanic, and hydrological extreme events and their improved monitoring and prediction. This second cross-cutting theme will be closely developed with the Global Extremes Platform (GEP) that sits under RIfS. This theme cuts across all ESMO objectives as new data structures and analysis tools are needed to capture extremes, as well as higher-resolution models and observations. A third cross-cutting theme seeks to better understand the needs and approaches for data assimilation and simulation initialization in coupled models. As an example activity within this theme, an ongoing effort between ESMO's Working Group on Numerical Experimentation (WGNE) and CLIVAR's OMDP and other interested parties to understand the initialization of ocean models for coupled forecasts and predictions has been brought within ESMO for support and expansion. Underneath the ESMO SSG, there are a number of Working Groups, Panels, and limited-duration Task Teams, supported by an IPO. Opportunities for short term inter-group collaborations through meetings and joint publications are being developed, and these efforts will often prompt the formation of Task Teams. The ESMO SSG consists of scientists representing modeling, data assimilation and observations across all climate-related disciplines in atmospheric, oceanic, hydrological and cryospheric sciences. It guides the formation of ESMO's scientific planning in consultation with the Working Group co-chairs. The IPO is responsible for the overall ESMO management and co-ordination. It supports all ESMO activities by planning meetings, implementing research goals, and producing a semi-annual newsletter to keep the ESMO community informed.

ESMO Working Groups advance science via various activities and carry out organizational tasks. To ensure consistency in science direction, the co-chairs of ESMO Working Groups are ex-officio members of the SSG. There are three Working Groups and two project panels that contribute to ESMO's science plan and develop the various components of modeling in WCRP:

- WGCM oversees CMIP through the joint governance of the CMIP panel and the WGCM Infrastructure Panel (WIP). CMIP and the WIP are supported by the CMIP IPO.
- The Working Group on Subseasonal to Interdecadal Prediction (WGSIP) oversees the work programme of numerical experimentation for variability and predictability, including the use of observations to initialize and constrain these experiments.
- WGNE oversees the analysis of numerical methods, systematic errors, and intercomparison projects to probe these topics. WGNE is also supported by WMO in addition to WCRP.
- The Subseasonal to Seasonal Prediction Project (S2S), jointly supervised by WCRP and the World Weather Research Programme (WWRP) concluded in December 2023. Discussions with WWRP and the S2S leadership are ongoing to understand how to retain the S2S community within WCRP.
- Obs4MIPs is a project panel on observations that collaborates closely with CMIP and WGCM and contributes to ESMO's science plan.

One example of a crosscutting task team is the Digital Earths and ESMO joint kilometer-scale modeling group. Additional observational and reanalysis Working Groups will be established, to address the needs identified by the ESMO SSG in consultation with the JSC, Core Projects, and Lighthouse Activities.

Ongoing and planned research for the next 5 – 10 years

In agreement with WCRP general objectives and in accord with WCRP's core activities, ESMO is currently in the process of developing its new science directions. Many of the activities listed above are currently being established but reveal the future plans and ambitions which ESMO aims to address over the next few years. Some early projects fitting the ESMO mission are being brought forward from WCRP activities in other Core Projects or ESMO Working Groups to serve as initial trials and exemplars of the developing implementation and science plan of ESMO.

Recognizing the broad and ubiquitous nature of modeling and observational activities within WCRP, ESMO is forming connections and partnerships with all WCRP Core Projects and Lighthouse Activities with the goal to enhance and advance total capability. ESMO aims to act as a modeling and observations focal point for collaborations with external partners such as regional and global research and operational groups, technology developers, and observational coordination bodies. Within WCRP, ESMO will establish or build on strong collaborations and crosscutting activities with the observational and modeling panels and working groups of the Core Projects and Lighthouse Activities. Such collaborations will facilitate efficient communication across WCRP constituencies and communities and remove fragmentation and duplications. The initial crosscutting activities will help to focus initial efforts, develop norms and practices, and advance existing WCRP modeling, data assimilation and observational efforts and connect them within an integrating framework under ESMO.

3.1.5. Global Energy and Water Exchanges (GEWEX)

Science goals and objectives

The Global Energy and Water Exchanges (GEWEX) Core Project is dedicated to understanding Earth's water cycle and energy fluxes at and below the land surface and in the global atmosphere. The International GEWEX Project Office supports these activities by planning meetings, implementing research goals, and producing quarterly newsletters.

With its emphasis on a fundamental understanding of the water and energy system and its close linkages to the satellite and services communities, GEWEX plays a key role in WCRP Scientific Objective 1 (fundamental science) and 4 (science for society). GEWEX also works closely with the modelling community on improving predictions and projections, particularly with regards to the water cycle.

GEWEX coordinates science activities to facilitate research into the global water cycle and interactions between land and the global atmosphere. One of the primary influences on humans and the environments they live in, the global water cycle encompasses the continuous journey of water as it moves between the Earth's surface, the atmosphere, and beneath the Earth's surface. Many GEWEX scientists conduct research on those and other elements to help refine our understanding of them and their impact on the climate. GEWEX also highlights important gaps in knowledge and implements ways to fix those gaps, whether through new studies, reviews of datasets, gatherings of experts, or other opportunities. GEWEX organizes international activities through its four panels, as summarized in Figure 8.

The four GEWEX Panels that oversee, facilitate, and support the international community in the working groups and projects that carry out the GEWEX scientific programme are:

- GASS Panel activities facilitate and support the international community that carries out and uses observations, process studies, and numerical model experiments to advance the understanding and prediction of weather and climate. GASS coordinates scientific

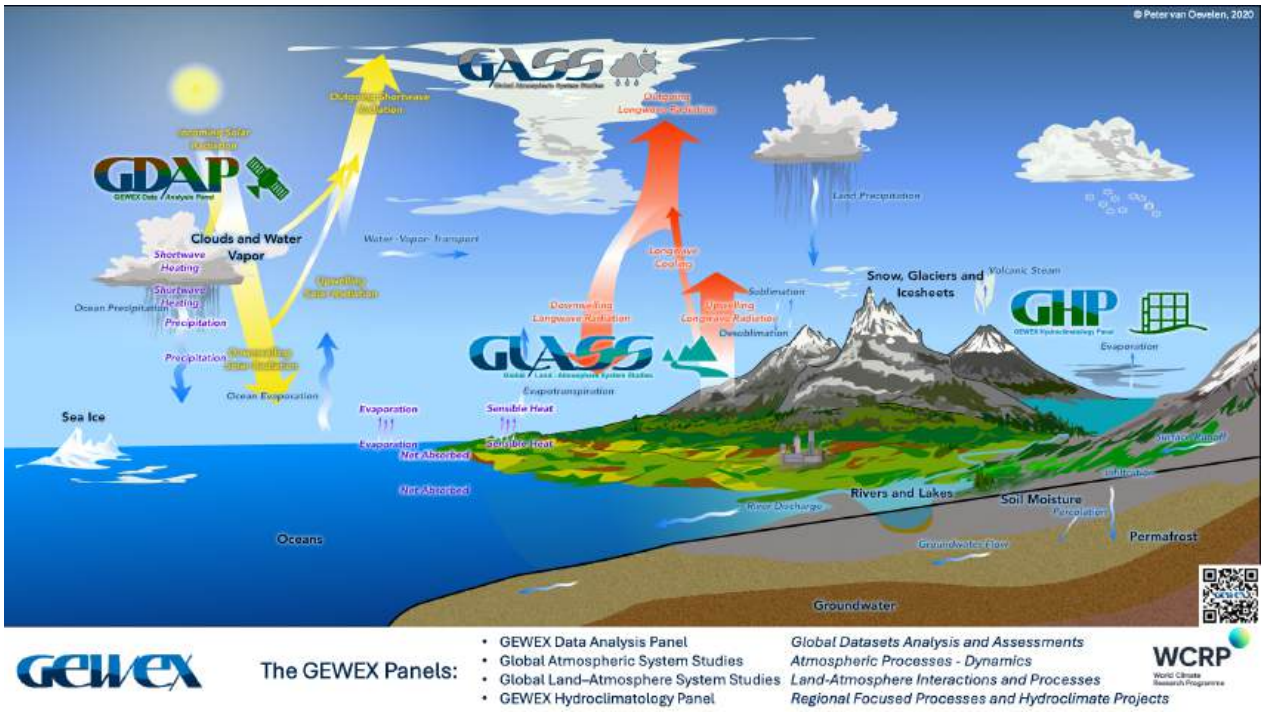

Figure 8: A schematic of the various activities and areas of focus of the GEWEX Panels.

projects to improve the physical understanding of atmospheric processes and their representation in weather and climate models.

- GEWEX Data and Analysis Panel (GDAP) guides the production and evaluation of long term, atmospheric, surface water, and energy budget products mostly derived from remote-sensed observations.
- GEWEX Hydroclimatology Panel (GHP) aims to understand and predict continental to continental-scale hydroclimates for hydrologic applications. It addresses at regional scale multi-disciplinary interactions occurring around the water cycle and in the water resources.
- Global Land/Atmosphere System Study (GLASS) Panel focuses on understanding the role of land surfaces in the Earth system. Its main activity is the development and evaluation of land surface models and encouraging the research community to integrate more natural and anthropogenic processes.

There are several crosscutting GEWEX activities. To simplify the organizational structure, these crosscutting projects report to one or two panels (rather than to the SSG directly). Some GEWEX activities are closely related to other WCRP Core Projects. For instance, GEWEX and CLIVAR work together on monsoon studies (see Figure 6). Both monsoon studies and the GEWEX crosscutting project on Upper Tropospheric Clouds and Convection are closely related to APARC. Precipitation as part of the water cycle is the source for ice sheet mass balance, and GEWEX has emphasized atmospheric boundary layer processes over polar regions through several projects. Both are related to CliC. GHP activities provide a trans-disciplinary vision of regional water cycle related to RIfS. The two panels (GASS and GLASS) focus on modeling activities, working in close collaboration with WGNE and ESMO.

Because Earth's water cycle is both central to and integrative of most WCRP activities, GEWEX science capabilities are core to the cross-cutting Lighthouse Activities: The Digital Earths Lighthouse Activity integrates Earth observations with kilometer-scale modeling, and GEWEX expects a strong collaboration with its model development capabilities and regional expertise (through the GHP). As one of GEWEX's top priorities is the understanding of processes which link the water and energy cycles on Earth, the collaboration with the Explaining and Predicting Earth System Change Lighthouse Activity is expected to be very close. GEWEX expects that this collaboration will help advance an understanding of the processes linked to latent and sensible energy exchanges in the atmospheric and with the surface. GEWEX's knowledge on the recent trends in the energy and water cycle and the coupling of these cycles with the carbon cycle as well as the relevant process understanding will contribute to the SLC Lighthouse Activity (water availability and high-risk themes). GEWEX's efforts in bringing together scientific communities in various regions of the world around trans-disciplinary regional projects will contribute to the MCR Lighthouse Activity. That collaboration is expected to widen the scope of Regional Hydroclimate Projects and integrate other WCRP activities. GEWEX's efforts in developing and organizing trainings, workshops, and summer schools will contribute to the WCRP Academy.

Ongoing and planned research for the next 5 – 10 years

GEWEX just revised its Science Plan for 2023–2032, with an effective and streamlined organizational structure. The above-mentioned panel activities and crosscutting projects (with 25–30 active GEWEX projects), collaborations with WCRP Core Projects, and joint efforts with the Lighthouse Activities will continue. This is true for the shorter term (1–3 years) and the longer term (4–10 years).

The short-term objective for GEWEX is to consolidate the current activities, initiate several new activities and resume the degree of collaboration which existed before the COVID pandemic. All panels have ongoing activities which aim to understand which new knowledge on the water and energy cycle processes is gained by using higher resolution observations and model output. A new vision on the organization of convection and the hydrology of mountain catchments is starting to emerge. Recent field campaigns have focused on highly managed areas of the world to get new insights on how irrigation and water management is changing evaporation, the lower atmosphere and more generally impacting the continental water cycle. It is also hoped that WMO's new strategy on hydrology will bring about a closer integration of hydrological research and forecasting to improve our water resource forecasting tools. The coming years will also be focused in coordinating with the Lighthouse Activities.

In the longer term, GEWEX will support the community's effort to operationalize research using kilometer-scale observations and models of the Earth's water and energy cycles. This is an important step in the vision we build of the coupling of the various processes which drive the water and energy exchanges in the system. The resolution we aim for in climate studies corresponds to what hydrological sciences have been using for the last two decades, simply because water and vegetation are organized at these spatial scales by topography and land use. These continental features also drive atmospheric boundary layer processes and surface energy partitioning contrasts which trigger large scale atmospheric processes. It is expected that this evolution over the next decade of our vision of the Earth system will bring about new knowledge and refined forecasting tools more relevant for society's needs.

For the period from 2023–2032, GEWEX has formulated the following three science goals with specific topics of special interest for each goal.

Goal 1: Determine the extent to which Earth's water cycle can be predicted: This Goal is framed around making quantitative progress on three related areas posed in terms of the following questions:

- Reservoirs: What is the expansion rate and the spatial characteristics of the fast reservoirs (atmosphere and land surfaces), what factors are involved, and are changes predictable?
- Flux exchanges: To what extent are the fluxes of water between Earth's main reservoirs changing and can these changes be predicted and if so on what time/space scale?
- Precipitation extremes: How will local rainfall and its extremes change under climate change across the regions of the world?

Goal 2: Quantify the inter-relationships between Earth's energy, water, and carbon cycles to advance our understanding of the system and our ability to predict it across scales:

- Forcing-feedback understanding: How can we improve the understanding of climate forcings and feedbacks formed by energy, water and carbon exchanges?
- Atmospheric Boundary Layer (ABL) processes representation: To what extent are the properties of the ABL defined by sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere?
- Understanding circulation controls: To what extent are exchanges between water, energy and carbon determined by the large-scale circulations of the atmosphere and oceans?
- Land-atmosphere interactions: How can we improve the understanding of the role of land surface-atmospheric interactions in the water, energy, and carbon budgets?

Goal 3: Quantify anthropogenic influences on the water cycle and our ability to understand and predict changes to Earth's water cycle:

- Anthropogenic forcing of continental scale water availability: To what extent has the changing greenhouse effect modified the water cycle over different regions?
- Water management influences: To what extent do water management practices and land use change (e.g., deforestation) modify the water cycle on regional to global scales?
- Variability and trends of water availability: How do water and land use and climate change affect the variability (including extremes) of the regional and continental water cycle?

For its new direction in the next decade, GEWEX will include the coupling of energy and water cycles with the carbon cycle, with a focus on process understanding to enhance our ability to observe and predict them. Another direction is the inclusion of human activities in the Earth system to understand and predict their impact on the water and energy cycle over continents. These two goals are closely linked, as most of the water management in the world is for the benefit of agriculture and thus also impacts the carbon cycle.

3.1.6. Regional Information for Society (RIfS)

Science goals and objectives

The overarching objective of the Regional Information for Society (RIfS) Core Project is to facilitate and catalyze new targeted research related to the provision of actionable information about climate variability and change in support of adaptation and mitigation, that draws on the best available science. RIfS uses the application context to inform research on aspects of understanding the climate system, the collation and/or generation of relevant data, the construction of context relevant actionable information, and the communication and engagement with policy and decision makers and relevant stakeholders. The term "context" is used in this document to refer to the context in which the climate information is used. This may include the broader aspects of culture, operations, institutions, policy frameworks, governance, etc. A key flagship activity of RIfS is the Coordinated Regional Climate Downscaling Experiment (CORDEX) (see box below).

The Coordinated Regional Climate Downscaling Experiment (CORDEX)

Vision: The CORDEX (https://cordex.org) vision is to advance and coordinate the science and application of regional climate downscaling through global partnerships.

Goals:

- Develop better understanding of relevant regional/local climate phenomena, their variability and changes, through downscaling.
- Evaluate and improve regional climate downscaling models and techniques.
- Produce coordinated sets of regional downscaled projections worldwide.
- Foster communication and knowledge exchange with climate information users.

RIfS is a key element of WCRP's link to society (Objective 4) as is CORDEX, which is also a key part of providing downscaled predictive capabilities. To link climate science and society with context relevant climate information RIfS identifies three overarching science challenges:

1. How to optimally identify, understand, and model the relevant climate processes and their interactions which are most critical to manage the socio-ecological risks at the decision scales within regions.
2. How to optimally integrate multiple lines of evidence from observations, understanding of physical climate processes, and data from dynamical and statistical regional and global models to inform society's climate information needs.
3. How to best undertake engagement between stakeholders and the science community in regional contexts to maximize the information benefit for the stakeholder and ensure that the user context is integrated into the design and execution of relevant climate research.

RIfS seeks to understand, develop, and enhance the effective flow of relevant information among scientists, decision makers and members of the broader society who are developing policy-relevant climate research. It will promote, design, and implement research activities to enhance the beneficial value of climate science for society. It is explicitly recognized that some objectives overlap with other Core Projects. In such cases RIfS will strive to be complementary and not duplicate other efforts.

Through these goals, RIfS seeks to guide the research community towards achieving the following outcomes:

- Improved understanding of the fundamental mechanisms and drivers of regional climate change and regional climate variability.
- Improved understanding of the changes in weather and climate extremes (including compound extremes) and their attribution.
- Improved articulation of the climate relationship between regions and the large-scale climate mechanisms and their interactions across scales.
- Advanced understanding of predictive skills of drivers of regional climate in the context of regional vulnerability.
- Assessment and evaluation of the skill, uncertainty, and limits of tools for developing regional climate prediction and projection information products, including extreme events.
- Improved approaches and methodologies for reconciling and integrating multiple lines of evidence for climate change prediction and projections at the relevant societal scales.
- Improved construction of regional climate information relevant to the decision context and impacts, including a specific focus on extreme events.
- Quantification of the temporal and spatial scales of skillful climate prediction and projection and the associated added value of available statistical and dynamical modeling systems contributing toward actionable climate information.
- Assessment and development of approaches for effective engagement between the research community and society stakeholders and the Climate Services communities.
- Improved research designs that incorporate stakeholder context to advance the

responsible and pragmatic uptake of climate information in a heterogeneous landscape of values and cultural priorities.

- Enhanced methods for co-production with stakeholders on the context-relevant construction, communication, and adoption of actionable information.
- Develop approaches to better integrate and assess the connections across the pathways linking data production, information construction, knowledge development in adaptation.

Mode of operation and organization

RIfS has established its initial SSG, which will be key for implementing the RIfS vision and fully connect with other WCRP Core Projects and Lighthouse Activities. The RIfS IPO has been established in Montreal, Quebec, Canada. The RIfS scope spans a broad range of overlapping and mutually informing research themes, that range from core modeling to the social dimensions of information communication and adoption in society. RIfS groups these activities into four complementary clusters which necessarily overlap with each, drawing on the science and expertise of the others. Notably, the understanding that comes from engagement with society is explicitly threaded through all four clusters.

Ongoing and planned research for the next 5 – 10 years

Work within RIfS is organized within the four RIfS clusters and guided by science themes:

1. Regional climate understanding for climate projections (multi-decadal)
2. Regional climate understanding for predictions (seasonal to decadal)
3. Weather and climate extremes
4. Communication and Societal Engagement

From the perspective of climate information for society, many of the science questions about climate prediction and projection are common across the timescales. Consequently, there is significant overlap in science questions between Clusters 1 and 2, yet also questions unique to each time scale.

Cluster 1 - with links to ESMO, GEWEX, SLC, Digital Earths, Explaining and Predicting Earth System Change (EPESC) and MCR, addresses climate change projections that are forced by external drivers (e.g., varying greenhouse gas concentrations) contingent on human socio-economic activity. Of special note is that the Coordinated Regional Downscaling Experiment (CORDEX) is a key contributor to activities within cluster 1 (as well as 3 and 4).

Cluster 2 - with links to APARC, CLIVAR, GEWEX, ESMO, Digital Earths and EPESC, addresses sub-seasonal to decadal predictability and is largely forced by internal climate processes (e.g., atmospheric ocean, and troposphere-stratosphere coupling). Cluster 2 seeks to advance understanding of the predictability and drivers of regional climate's variability on seasonal to decadal time scales and works in collaboration with leadership in other WCRP Core Projects to accomplish this.

In outlining the science questions for Clusters 1 and 2, RifS recognizes the benefits from collaboration between these communities to learn from and contribute to each other's endeavors. Consequently, for clusters 1 and 2 the key science questions are presented first as those common to both clusters, followed by the science questions that are more specific to the time scales of each cluster.

Research questions for Clusters 1 and 2: What are the knowledge gaps, uncertainties, opportunities for improved regional climate prediction/projection across climate time scales? What model complexity is required to usefully represent regional climates and change? How to reconcile and integrate multiple lines of evidence in providing regional climate information? Research question primarily for Cluster 1: How can the foundations for impact-relevant regional climate projections be enhanced? Research question primarily for Cluster 2: What are the primary sources and drivers of predictability and predictive skill across climate timescales?

Cluster 3 - with links to ESMO, CLIVAR, GEWEX, Digital Earths, EPESC, MCR, and SLC, builds upon and integrates multiple activities on weather and climate extremes across WCRP and contributes to improved understanding of the changes in weather and climate extremes (including compound extremes) and their attribution. GEP is a key contributor to activities within this cluster. It will contribute to improving the ways of delivering science, information, and data concerning extremes in a well-synthesized format and to integrate outputs on extremes across WCRP. Cluster 3 asks: How can we communicate the nature of extreme events that most strongly threaten socio-ecological systems in different regions of the world? How can we deliver timely and useful information regarding the future evolution of these events? How can we develop methods to attribute change in probability of observed extreme events? How can we develop methods for mitigation verification from the perspective of changes in weather and climate extremes?

Cluster 4 – is explicit about bridging with society and emphasizes the partnership with stakeholders. Cluster 4 necessarily draws upon the knowledge in Clusters 1–3, while also informing the activities and knowledge production of clusters 1–3. Questions include: How can we better understand the dynamics and evolving landscape of climate information services, users and usage? How can we enable improved understanding of, and advance the dialogue with stakeholders? This work requires close coordination between natural and social scientists. The WCRP Academy as a fundamental partner in this activity. This component of RIfS is the component that extends most fully beyond the traditional 'boundary' of WCRP. It is thus highly innovative. The WCRP Academy is also envisioned to be closely partnering with the various activities within Clusters 1, 2 and 3.

RIfS is also exploring collaborations with other WCRP activities to develop a framework for including societal elements in co-producing regional science. This interaction is being established with the GEWEX Regional Hydroclimate Project "ANDEX" in South America. Another activity in development involves mapping barriers and challenges to the use of climate information in decision-making.

For a more robust delivery of reliable information for decision-making at the regional scales, CORDEX is envisioning two specific paths: (1) Adding Earth system components to regional climate models (urban, aerosols, ocean, dynamic vegetation, hydrology, groundwater, etc.) to capture additional feedback processes relevant at the regional scale; (2) Producing kilometer-scale simulations for regional domains focusing on specific phenomena, which will also provide benchmarks for convection permitting modeling for global kilometer-scale initiatives.

3.2. Lighthouse Activities

3.2.1. Digital Earths

Science goals and objectives

The Digital Earths Lighthouse Activity facilitates the research required to build quantitative frontier climate information systems and to support the international community engaged in developing and implementing them. The overall objective is to coordinate the design and facilitation of research in support of the establishment of integrated digital information systems that provide information on the past, present, and future of our planet. We define the word "integrated" to mean that the system combines all elements required to describe the coupled Earth system as well as models of human systems, so that the impacts of a changing Earth on such systems can be estimated in the most realistic way. It provides a framework to improve predictions and projections, though also provides an opportunity to explore fundamental science questions.

The success in building interactive climate information systems that enable society to answer critical questions depends on major advances in at least three areas:

- Modeling of the physical climate system that resolves storms in the atmosphere, eddies and boundary currents in the ocean, stream flow in catchments on the land and large glaciers in the cryosphere;
- The fusion of models and observations through data assimilation systems for climate;
- The full integration of quantitative models of human interactions with the changing climate in the information system workflow and infrastructure.

Each area is worked on by an Digital Earths Working Group, overseen by the SSG. In addition, working groups are established to engage in designing and implementing Digital Earths style systems. This design follows the function of the working groups WGNE and WGCM of ESMO, who fulfill this function for major Numerical Weather Prediction (NWP) and climate modeling centers.

Planned research for the next 5 – 10 years

1. **Modeling of the physical climate system at storm, eddy, river, and glacier resolving scales:** Understanding and predicting how a warmer world affects local communities requires significant advances in our ability to realistically model and predict the system at local scales. At those small scales, key processes in the climate system have strong effects on and interact with the behavior of the system at large scales. Organized (and propagating) deep convection affects the planetary circulation of the atmosphere, small-scale ocean eddies set the characteristics of the Gulf Stream, small-scale interactions between the ocean and ice sheets strongly influence the overall amount of sea-level rise. Yet, our current climate models do not resolve these phenomena. With the advent of exascale computing we can build fully coupled global and regional climate models that resolve storms in the atmosphere, eddies and jets in the ocean, lakes, and large rivers on our continents, leads in the sea ice and large glaciers. Digital Earths Lighthouse Activity is the home for the critical and urgent science required to construct such models to better understand and predict the climate system.
2. **Data assimilation for climate:** The advent of ultra high-resolution climate models creates an unprecedented opportunity to better exploit the myriad of existing Earth observations,

from in situ measurements, weather radars to satellite observations, as the resolved model scales become closer to those of the observations. The integration of traditional climate models with those that describe society's interactions with it allows, for the first time, to also integrate observations of those systems to initialize predictions from the present and to improve the systems. Many are "observations of opportunity" from data intended for other uses (energy use, mobility data, personal weather stations). Being able to accurately describe the state of the Earth at any given time in this way would be nothing short of a revolution. Achieving this ambitious goal requires major advances in the techniques weather and climate scientists have used for many decades to optimally combine models and observations to create initial conditions for the predictions they make. Enhancing data assimilation methodologies to exploit the availability of the new modeling tools and observations above and to provide a detailed analysis of the state of the Earth at any given time, including going back into the past to challenge models against observations, is the goal of data assimilation for climate activities.

3. **Modeling beyond the physical Earth System:** While knowing future states of the climate system is a crucial ingredient to mitigation and adaptation decisions, the predictions of climate variables themselves are rarely what determines those decisions. Instead, it is the potential impacts on human systems that decision-makers need to assess. Consequently, a Digital Earths information system must go beyond the traditional generation of climate model simulations and generate information on the impacts of the local changes in weather and climate, as well as the integrated upscale impacts of human activities such as landscape modification. This is further amplified by the need for a paradigm shift in how climate change information is stored and presented that is brought about by the vastly larger data volumes that ultra-high-resolution climate models will produce. This creates both a need and an opportunity for a paradigm shift to move away from treating humans as an external force in climate models to fully integrating dynamic interactions between socio-economic and natural climate change in Digital Earth systems. This shift includes the integration of quantitative climate impact models, from those of the human influence on the water cycle, crop models, models of economic activity, and population dynamics, to name a few, in the Digital Earths information system workflow. Such coupling constitutes a significant challenge as it requires uniting diverse communities. Advancing the science of modeling the Earth inclusive of the human influence on it is the goal of the Digital Earths Lighthouse Activity modeling beyond the traditional Earth System focus area.

Key outcomes and impacts, including approximate timeline

The Digital Earths Lighthouse Activity coordinates a global research network of experts in ultra-high-resolution (kilometer-scale or finer) modelling of the Earth system and its individual components. A working group on kilometer-scale modeling has been created with strong links to ESMO and WGCM. This work started with a foundation workshop in October 2022 in Boulder, USA, where community-wide modeling activities were proposed to rapidly advance our abilities in ultra-high-resolution modeling around the globe. The outcomes of the workshop were documented in a white paper. In collaboration with ESMO, Digital Earths Lighthouse Activity also establishes an active research community in data assimilation for climate that builds on the existing NWP and re-analysis efforts and significantly expands them to fulfill the needs of Digital Earths applications. During a strategic meeting in 2022 (jointly with the EPESC Lighthouse Activity), first steps in advancing data assimilation systems for climate were identified. Connecting climate modeling with the impacts modeling at the system level is perhaps the most challenging aspect of the Digital Earths Lighthouse Activity, which takes place in consultations with a wide range of

communities to identify opportunities for "demonstration projects."

Co-development with the Core Projects

All Digital Earths activities are performed in close interaction with Core Projects. The Lighthouse Activity pioneers the joint Data Assimilation for climate together with the EPESC Lighthouse Activity, ESMO, and the ultra-high-resolution modeling. Many of the model development activities for individual model components reside in different Core Projects, such as the atmosphere and land in APARC and GEWEX, ocean in CLIVAR, and ice in CliC. Active discussions on how to best bring together the subsets of these efforts that deal with very high resolution are part of the effort.

3.2.2. Explaining and Predicting Earth System Change (EPESC)

Science goals and objectives

The goal of the Explaining and Predicting Earth System Change (EPESC) Lighthouse Activity is to develop an integrated capability to understand, attribute, and predict annual to decadal changes in the Earth system, including capabilities for early warning of potential high impact changes and events. The overarching objective of EPESC activity is: to design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning and prediction of Earth system changes on global and regional scales, with a focus on annual to decadal timescales. It is therefore fundamental to WCRP's Scientific Objective 2 in terms of improving predictions of the climate system.

Related work is also concerned with:

- Improving persistent errors in climate models and re-analyses of historical observations.
- Assessing possible improvements to observational networks and modeling systems to capture early indicators and the full evolution of these changes in the climate system.
- Providing quantitative assessments of current and future hazards, underpinned by robust process understanding.
- Maximizing the value of the advances achieved through the development of an international open-access multi-model archive of seasonal-to-decadal hind cast and forecast data, and through case studies employing co-design of decision-relevant products.

Given the breadth of the targeted goals, EPESC has organized its work around three major themes (working groups): (i) monitoring and modeling Earth system change; (ii) integrated attribution, prediction, and projection; and (iii) assessment of current and future hazards. Figure 9 shows the key elements of these activities.

The bottom layer in Figure 9 shows the importance of coordinated observational and modeling efforts serving as key tools and inputs to the integrated attribution, prediction, and projection efforts in the middle layer. Both layers feed into the outputs and societal benefits displayed in the top layer: causal explanations, predictions and early warnings, and hazard assessments. Fundamental physical process understanding concerns all aspects of the Lighthouse Activity.

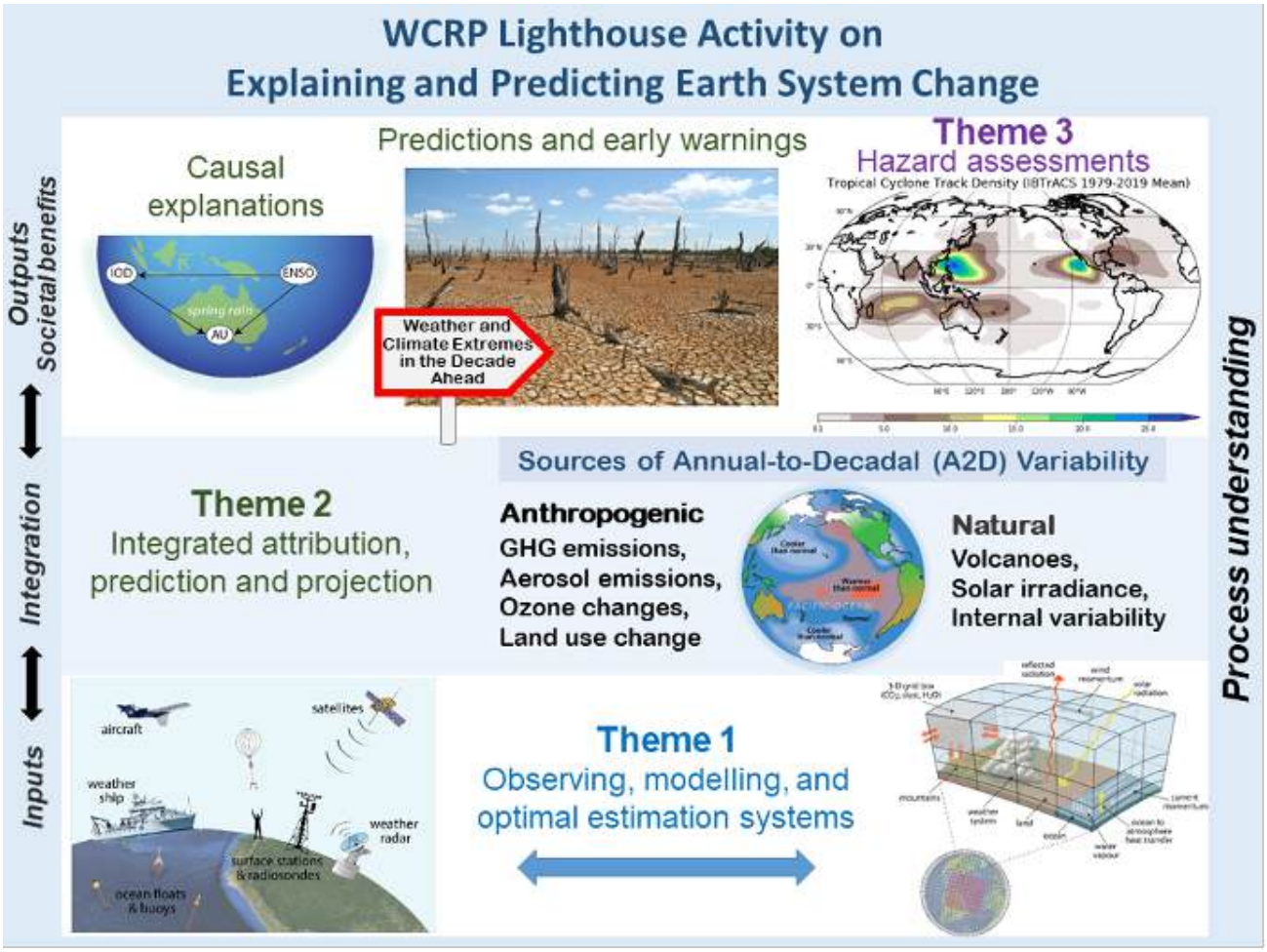

Figure 9: Elements of the Explaining and Predicting Earth System Change Lighthouse Activity.

Research planned for the next 5 – 10 years

Work over the coming years will be organized in three working groups, as listed below.

WG1: Observing and modeling Earth system change:

- Identify observational (in situ and remote sensing) and modeling requirements to measure, explain, and predict changes in the Earth system on Annual to Decadal (A2D) and regional to global scales.
- Develop data assimilation techniques that can be used to most effectively combine observations and models to quantify, explain, and predict changes in the Earth system on A2D and regional to global scales. This includes reanalysis methods for estimating Earth System change.
- Assess and work to remedy persistent biases in model simulations; identify observations which will offer the greatest improvements in predictive and explanatory skill and identify where those enhancements should be targeted.

WG2: Integrated attribution, prediction, and projection

- Develop detection and attribution techniques and apply them to identify and attribute the drivers of changes in the Earth system on global to regional and A2D scales.

- Identify requirements for operational integrated attribution and prediction capability on global to regional and A2D scales to provide early warnings for decision making.
- Use large ensembles to understand circulation changes in the atmosphere and ocean.

WG3: Assessment of current and future hazards

- Identify how internal variability and external forcings influence the characteristics and occurrence of meteorological hazards on annual to decadal scales in different regions (e.g., tropical cyclone landfall, large-scale drought and/or wildfires).
- Use observations, models, and process understanding to deliver robust assessments of current and future hazards for specific regions and hazard classes.
- Investigate hazard predictability and likelihoods.

Key outcomes and impacts, including approximate timeline

Three cross-cutting dimensions connect the work of the three thematic elements. First, the development of a capability to observe, explain, and predict changes in the Earth system requires the tight integration of observations and models, including characterization and quantification of uncertainties. Second, initial steps to develop a capability to observe, explain, and predict Earth system change will focus on a small number of compelling case studies targeting climate "events" that have occurred in recent decades (e.g., the rapid warming of the North Atlantic in the 1990s, changes in phase of the Interdecadal Pacific Oscillation, persistent droughts, etc.). Finally, we envisage that large ensembles of single-forcing experiments will inform the activities at the heart of each of the themes. These are essential to characterize the responses to different forcing factors, thereby informing observing system design (Theme 1), providing quantitative process-based attribution (Theme 2), and improving our understanding of the drivers of changing hazard frequencies and intensities (Theme 3).

Co-development with the Core Projects

Representatives from the Core Projects have been involved since the initial stages of the Lighthouse Activity as part of the Science Implementation Team, thus contributing to the development of the Science Plan. The Working Groups are developing strategic links and activities with WCRP Core Projects and other Lighthouse Activities. One such example is joint activities on Data Assimilation for Climate that are being planned together with the Digital Earths Lighthouse Activity. Collaboration between Theme 1 and the ESMO Core Project will help advance the objectives of both groups. Similarly, Theme 3's objectives present ample opportunity for collaboration with the MCR Lighthouse Activity and the RIfS Core Project. There is also potential for collaboration with SLC Lighthouse Activity in areas such as early warning of possible rapid change (or "tipping points") and the use of observations to constrain long-term projections.

3.2.3. Global Precipitation Experiment (GPEX)

Science goals and objectives

Precipitation is one of the most important weather, climate, and hydrological variables with direct connection to society and the environment. The observation, modeling, and prediction of precipitation over land or over the ocean remains one of the frontiers in climate research, especially hydroclimate extremes (floods, droughts etc.). The urgency to make progress in this

field also becomes increasingly obvious as freshwater availability, with precipitation being its primary source, appears to decline around the world.

The goal of the Global Precipitation Experiment (GPEX) Lighthouse Activity is to provide a unique opportunity to make progress in understanding phenomena and processes critical to precipitation. It will accelerate progress in precipitation prediction by leveraging existing WCRP projects and community capabilities in observation, modeling, research, and conducting new and focused activities, including planning for the "WCRP years of precipitation". The GPEX objective is to accelerate advances in precipitation knowledge and prediction at different temporal and spatial scales, to enhance public access to relevant datasets, and to benefit society, by coordinating national and international activities. Its outputs are relevant to all four of WCRP's core objectives, particularly in terms of improvements in precipitation prediction.

Planned research for the next 5 – 10 years

GPEX will focus initially on the 'WCRP Years of Precipitation' and associated coordinated global field campaigns, gridded data evaluation and analysis, kilometer-scale modeling, process understanding, and prediction of extreme events. This has to be done by drawing on the expertise across all WCRP activities and many other programmes (e.g., WWRP, WMO Hydrological Coordination Panel and Standing Committee on Hydrological Services). GPEX will build on international initiatives already underway within WCRP programmes, including planned observational campaigns, modeling activities, process studies, capacity development activities, and activities on the usage of precipitation information by stakeholders. The work involved will cover:

- Planning and organizing globally coordinated field experiments;
- Evaluating, improving, and developing gridded datasets of precipitation;
- Evaluating, improving, and developing precipitation modeling and prediction; and
- Increasing capacity for precipitation related efforts via provision of open access precipitation datasets and model predictions.

Key outcomes and impacts, including approximate timeline

The primary outcomes of GPEX are expected to use precipitation as the unifying force for cross-WCRP activities, to attract more national and international funding and hence attract more scientists (including those from the Global South) to WCRP activities, and to provide scientific deliverables. The key outcomes will include:

- Identification of the sources and magnitude of uncertainties in quantitative precipitation estimates over global land and ocean, particularly in regions of vulnerable populations and limited observing capabilities, and how can we address them.
- Enhanced understanding of how precipitation is produced by complex moist processes and their interactions with atmospheric dynamics and other components of the Earth system.
- Quantification of the sources of precipitation errors in weather and climate models and an understanding of how we can reduce them to improve predictions and projections of precipitation at different temporal and spatial scales.
- Enhancement of regional and local capacity building for precipitation observations,

process understanding, prediction services (e.g., early warning systems), projection, and applications.

Co-development with the Core Projects

Precipitation is emphasized within numerous activities of WCRP's Core Projects and Lighthouse Activities. For instance, precipitation has been one of the central foci of GEWEX over the past three decades (e.g., on observational data assessment, process studies, and high-resolution modeling). Precipitation over land is affected by remote ocean processes through teleconnections (explored via CLIVAR). Deep convection provides a mechanism for the troposphere-stratosphere interaction (emphasized via APARC), and snowfall is the source for snow/ice over ice sheet and sea ice (studied via CliC). Precipitation affects human and natural systems (emphasized via RIfS), and model intercomparisons have been coordinated via ESMO. Kilometer-scale modeling carried out by several WCRP activities (Digital Earths Lighthouse Activity, GEWEX/GHP, ESMO/CORDEX) will be valuable for precipitation process understanding and model improvement. Furthermore, the science and applications of precipitation have been addressed by other international programmes. For instance, precipitation (particularly extremes) has been a focus of WWRP. The applications of precipitation have been emphasized by the SysTem for Analysis, Research and Training (START) programme. Precipitation as part of hydrology has received substantially increased attention in the WMO Vision and Strategy for Hydrology and its related Plan of Action, reflected also in the WMO Research Strategy for Hydrology. Satellite precipitation measurements have been the focus of space agencies for a long time (e.g., National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Japan Aerospace Exploration Agency (JAXA), the European Space Agency (ESA), and Copernicus Climate Change Service (C3S).

3.2.4. My Climate Risk (MCR)

Science goals and objectives

The My Climate Risk (MCR) Lighthouse Activity aims to develop and mainstream a 'bottom-up' approach to regional climate risk, which starts with the requirements of decision-makers. By 'risk' we mean the combination of hazard, vulnerability, and exposure that is particular to a given regional context. By developing a new framework for assessing and explaining regional climate risk using all the available sources of climate information (observations, reanalyses, model simulations, better understanding, etc.), climate information will be made meaningful at the local scale. Whilst any application of the framework will inevitably be specific and tailored to local concerns, the framework itself will be generic, hence flexible and applicable across several region types (large scale, urban, typical Special Report for Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) region, etc.) and intended to become much-needed support for the development of climate services. At the same time, the activity can identify needs to be addressed by the WCRP Core Projects and other Lighthouse Activities (e.g., implications of model biases). MCR activities cross all WCRP's Scientific Objectives, with a particular emphasis on bridging climate science and society, and it is a key WCRP activity that works closely with social scientists.

To facilitate the desired 'bottom-up' approach, MCR will be implemented in a non-hierarchical way through an informal ecosystem of regional hubs. Together, the regional hubs will support a 'mycorrhizal network' of communities of practice, sharing knowledge and resources. Regional hubs need to be anchored in an existing locally based institution with a commitment to the

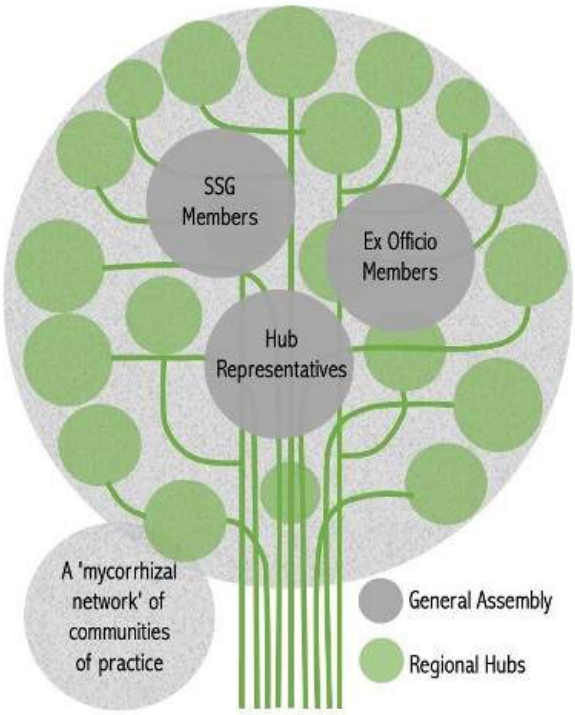

Figure 10: My Climate Risk management structure.

principles of MCR, to ensure long-term continuity and local engagement. Representatives of the hubs, together with a SSG and Ex-Officio members (who are responsible for liaison with international partners, both within and outside WCRP) will together constitute a General Assembly, providing connection points between the hubs and the relevant expertise that exists in the wider climate science community (see Figure 10). In order to ensure equitable participation, the General Assembly will only convene virtually, with in-person meetings held at hub level.

Planned research for the next 5 – 10 years

MCR will primarily use a case-study approach, in the form of labs (communities of practice) that provide dynamic, exploratory, trans-disciplinary environments. These communities of practice could take a variety of forms depending on local needs and interests. A canonical activity will be to discuss current risk in a given situation, with proximate explanations, and then develop storylines of future climate-related risk based on those explanations. In this way, the past can be related to the future within a risk framing. Understand what regional climate information is needed by stakeholders.

- Understand what regional climate information is needed by stakeholders.
- Understand what regional climate information can be provided based on existing observations, models and knowledge.
- Inform the WCRP community about which model and experiment developments may best serve user needs, thus closing the gap between the first two points, and better integrating the use of models and observations.
- Provide a framework for bringing different information (including contradictory climate outcomes) together within a particular risk context in a way that others can work with.
- Understand how climate change can push a low-risk situation into a high-risk situation.
- Help develop prototypes through case studies, in partnership with others.

- Develop 'risk map guidelines' for different hazard types in different regions and contexts.
- Improve the collaboration between WCRP activities.
- Foster capacity building, particularly in the Global South.

Key outcomes and impacts, including approximate timeline

The proposed outcomes of MCR are two-fold: new user-oriented methodologies on how to deliver climate information, and a legacy in the form of the envisaged 'mycorrhizal network' of self-sustaining communities of practice following the spirit of MCR and connected to the breadth of WCRP. The success of the first outcome will be measured by the development and uptake of the new methodologies and by the extent of user engagement. The success of the second outcome will be measured by the extent and health of such a continuing 'mycorrhizal network'. More specifically the outcomes should include:

- A framework for assessing and explaining climate risk using all the available sources of climate information to construct decision-relevant and scale-relevant information. This will include guidelines on available information, data, and their usage ("value-chains of data"), as well as outlining the main purposes/limitations of the data sets/information. It will also follow a two-layered approach, generic vs. context-specific climate data/information.
- Case study/lab examples of the development/application of the risk framework, but leading to scalable and operational activities, i.e., not 'pilot studies.'
- Application of the risk framework in risk assessment/management structures.

As a Lighthouse Activity, an approximate timeline of 5–10 years is envisaged. The first milestone was to get an initial set of regional hubs established, which is now in place. Over the next few years, the priority is on consolidation and maturation of the existing hubs and the development of the envisaged 'mycorrhizal network' between and around them, with continued expansion into parts of the world that are currently under-represented within WCRP. A wider expansion can be envisaged to leave the desired legacy.

Co-development with the Core Projects

All Core Projects are represented in MCR, either through an SSG or Ex-Officio member or by leading one of the MCR regional hubs. Many Core Projects are represented multiple times. It is envisaged that Core Projects will help develop MCR in two main ways: by directly engaging with specific regional hubs, where the interests strongly connect; and by providing a home for more thematic or cross-cutting activities.

3.2.5. Research on Climate Intervention (RCI)

Science goals and objectives

Climate intervention (RCI) refers to deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change and includes both large-scale Carbon Dioxide Removal (CDR) and sequestration technologies as well as Solar Radiation Modification (SRM). This is an emergent and critical research topic that is rapidly gaining increased attention internationally. However, there are still many scientific knowledge gaps and uncertainties around the potential benefits, risks, and sustainable scale potential of both scaled-up CDR and

SRM. In view of this, the JSC has concluded that WCRP will initiate a new Lighthouse Activity on the science of RCI, in part to ensure that research to inform decisions about CDR and SRM will be conducted transparently, with open access to data, results, and the models used to assess such interventions and their impacts. Its aims are focused on fundamental science and providing advice to policy makers. However, the outcomes are expected to feed into future predictions and projections of our climate system.

Planned research for the next 5 – 10 years

RCI research is, in some respects, already taking place across the various Core Projects and the current Lighthouse Activities, but they are not well coordinated across communities. A new WCRP Lighthouse Activity on RCI will significantly enhance internal WCRP coordination and communication, and it will also do so with Future Earth and other international research programmes. Additionally, the new Lighthouse Activity will help WCRP bridge existing gaps between science (physical and social), politics, and governance, as well as facilitate the entrainment of developing nations and early career scientists into RCI research. The JSC concluded that a new Lighthouse Activity will effectively establish WCRP as an honest broker and respected community voice in comprehensively assessing the benefits and risks of proposed CDR and SRM approaches, and in synthesizing results.

3.2.6. Safe Landing Climates (SLC)

Science goals and objectives

The Safe Landing Climates (SLC) Lighthouse Activity is an exploration of the routes to "safe landing" spaces for human and natural systems (See Figure 11). It will explore future pathways that avoid dangerous climate change while at the same time contributing to the United Nations Sustainable Development Goals (SDGs), including those of climate action, zero hunger, clean water and sanitation, good health and well-being, affordable and clean energy, and healthy ecosystems above and below water. The relevant time scale is multi-decadal to millennial and so the lighthouse provides key input to WCRP's Objective focused on the long-term response of the climate system, as well as improving the fundamental science and bridging across to society.

Planned research for the next 5 – 10 years

Planned research is centered around five themes (Figure 11):

Safe landing pathways: what climate trajectories and destinations are safe and unsafe, and for whom? The objectives of this theme are to define safe landing climate pathways and landings, preserve habitability and food security, identify adaptation limits. The theme aims to foster analytic, modeling, and model-data fusion tools that enable representing and estimating large-scale climate risks, including cross-system feedbacks (climate, biosphere, and society).

Understanding high-risk events: what are the risks from low-probability, high-impact events? The objectives of this theme are to enhance our understanding of highly uncertain planetary risks (such as large carbon release, multiplicative compound hazards, large-scale extreme events, severe fire activity, biome collapse, but also ice shelf and ice sheet collapse, circulation regime shifts, high equilibrium climate sensitivity). It will facilitate the incorporation of uncertain risks into future projections, and identify adaptation limits and determine whether risks can be avoided (or caused) by climate mitigation or climate intervention efforts.

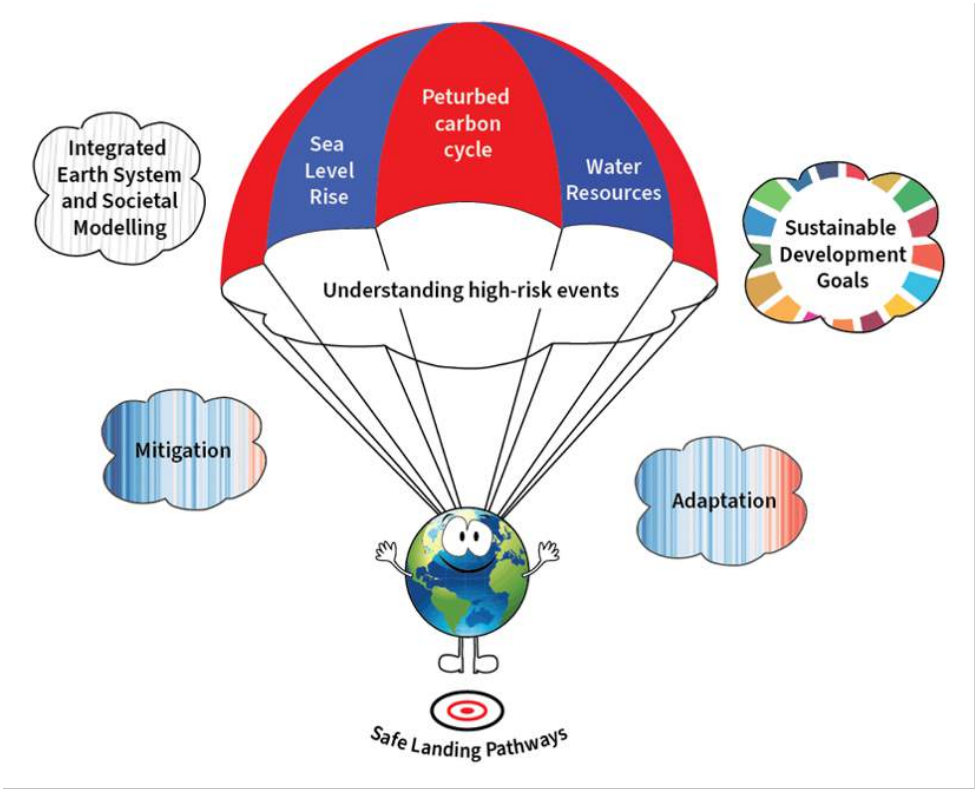

Figure 11: Safe Landing Climates themes.

Perturbed carbon cycle: how will the carbon cycle change in the future? The objectives of this theme are to determine the climate implications of carbon dioxide removal (including bio-energy with carbon capture and storage) while maintaining food and water supply, preserving biodiversity, and limiting ocean acidification. The theme will also assess the possible contribution to mitigation by methane, nitrous oxide, etc., evaluate the risk of surprises or rapid changes in greenhouse gases due to land sources, determine the implications for allowable greenhouse gas emissions under the Paris Agreement, and build an understanding of the coupled carbon-energy-water cycle.

Water resources: how will major reservoirs of water change in the future? The objective is to identify the long-term redistribution of water in land-based natural systems or reservoirs, including glaciers and tropical rain forests, due to climate change and direct human activity. This theme will identify thresholds of tolerance and risk of collapse, and integrate physical climate, social and economic sciences, and local and indigenous knowledge.

Sea level: how will the habitability of our coasts change in the future? The objectives of this theme are to quantify "acceptable" sea level rise and its irreversibly, estimate the impact of storm surges and hurricanes on low elevation land, communities, and ecosystems, and assess the potential for adaptation. The theme will facilitate the interaction of modeling efforts across spatial scales from global to coastal and will foster interaction and co-production between sea-level experts and coastal planners worldwide.

Key outcomes and impacts, including approximate timeline

- Formation of five diverse working groups that are actively interacting on key topics, and subgroups addressing intermediate goals listed above has been completed.
- Online events to consolidate expertise and inform the community about key science goals, including the Tipping Point Discussion Series co-organized with AIMES, the Earth

Commission and Future Earth, are ongoing.

- Targeted activities have been developed. A workshop on transient carbon response to emissions has been conducted with anticipated outcome of a report / review paper in development to feed into IPCC. The lighthouse team has co-developed a Model Intercomparison Project, 'WhatIfMip,' in collaboration with Earth System Modelling community and the Tipping Points MIP (TIPMIP), which will inform the consequences of breaching tipping points (timeline: CMIP7 timeline). The lighthouse team has been involved in a recently submitted review paper on links between extremes and tipping points and hopes to develop the theme of cascading shocks further in an interdisciplinary scientific meeting with outcomes (e.g., a paper) which also explores costs of such events (timeline 2 years). The team also explores gaming and decisions/scenarios to develop future scenarios that are more relevant outside the climate sphere (timeline: next few years). Further activities on impacts of global water variability in future scenarios and signpost approaches for sea level rise are being developed.
- Desired impacts include: An advanced understanding and communication of risks and opportunities arising across the Earth system including those involving interactions with ecosystems and society. Strategic focusing of some IPCC Working Group I science efforts in ways more informative about future climate risks; informed in collaboration with WG2 and WG3 communities. Improved recognition of future risks, pathways and opportunities based on consistent lines of reasoning and scenarios that incorporate relevant knowledge across sectors/communities.

Co-development with the Core Projects

A table of anticipated links can be found in the SLC Science Plan. It is our goal to continue interacting with Core Projects to co-develop activities and draw on their projects and expertise. Specific links that have been explored include: GEWEX GLASS and GASS on tropical rain forest hydrology and precipitation; climate sensitivity; and drought changes relevant to large scale extremes, APARC on the role of short-lived climate forcers, CliC on risks of future ice-sheet losses and sea level rise, CLIVAR on ocean heat and carbon uptake, decadal to centennial variability, tipping points, EPESC on design of climate model simulations and heat/drought from near-term to future, and RIfS on large-scale extreme events.

3.3. The WCRP Academy

Goals and objectives

The WCRP Academy is the research training advisory and coordination arm of WCRP. Its mission is to equip current and future climate scientists with the knowledge, skills and attributes required to tackle the world's most pressing and challenging climate research questions.

The Academy's activities promote and advance lifelong learning opportunities and global equity in climate science training. It will measure its success by the scope and diversity of the global climate research community that engages with the Academy as well as its ability to improve global access to high-quality climate science training and professional development without prohibitive costs to the trainee.

The WCRP Academy is a hub that connects people who need climate science training with people and institutions that can provide that training. Fundamentally, this hub is needed to deliver the

step-change in research training to build the scientific workforce required to deliver WCRP aims and, at the same time, to train the next generation of WCRP leaders (Figure 12).The objective of the Academy is to determine the requirements for climate research education and build enabling mechanisms. The key mechanism for this is an online marketplace for climate science training, which connects training providers and climate scientists who are seeking training. This marketplace is both inward facing, aiming to consolidate and support existing and future training activities within the WCRP, and outward facing, which will bring together an even broader range of training opportunities. The Academy will also identify training gaps and advocate for those needs to be met.

This marketplace was launched at the WCRP Open Science Conference (23–27 October 2023) in Kigali, Rwanda, as an online portal that provides a catalog of various climate training events and opportunities contributed by registered training providers as well as our partners. The catalog is regularly updated, especially as new opportunities become available. Activities external to the WCRP are reviewed by experts within or outside the WCRP community to ensure scientific and pedagogical rigor. If recommended, the activity is added to the catalog, curated, and showcased. To build this marketplace the Academy works with WCRP core activities, including the Lighthouse Activities, and established climate education providers such as universities. Further, the Academy will undertake an annual stocktake to ensure that it continues to meet the needs of the climate science community, and will systematically review the global climate education landscape, to identify gaps in training and development opportunities, as well as provide recommendations for improving climate science training.

The Academy will link WCRP climate scientists with science training and communication experts and providers across the world to deliver innovative and impactful training content within WCRP, to its partners, and to the wider community. The Academy will provide the WCRP research community with an outlet to communicate their expertise in various contexts, from expert seasonal schools to public lectures, and serve as a central repository for webinars, courses and online activities developed by the WCRP Core Projects and Lighthouse Activities.

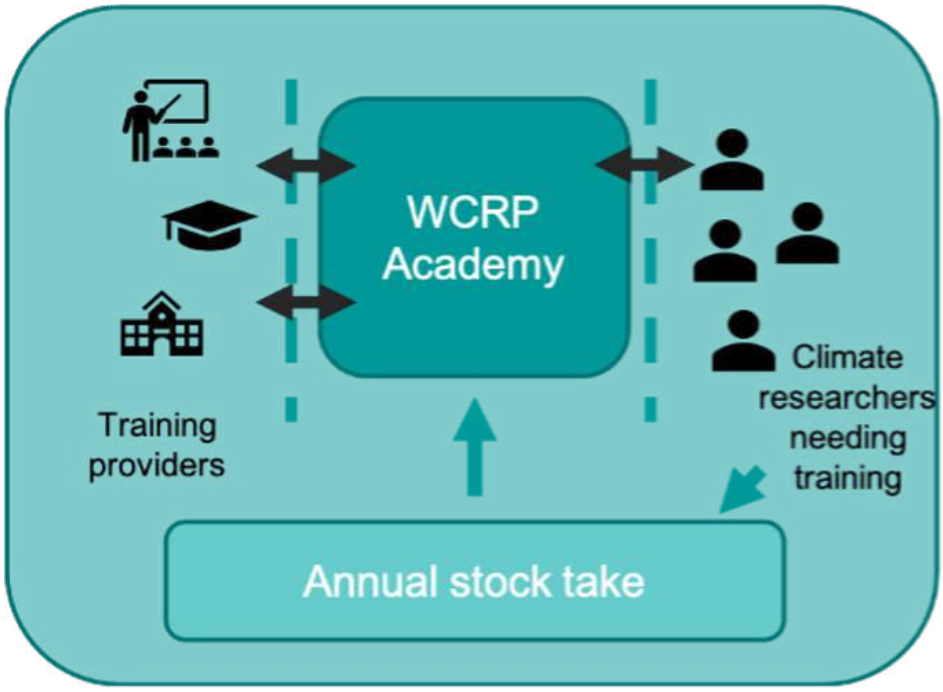

Figure 12: Schematic of the WCRP Academy.

The Academy will initially operate within the climate science community, linking climate scientists who require some form of climate science training with communities who are able to provide relevant training.

Training (in our Academy context) aims to improve climate science literacy (see below) of communities who require climate information in their research, operational or decision-making contexts. At the end of the training, the skills will exist for:

- Understand and explain the essential principles of Earth's climate system.
- Analyze and use available tools and methods.
- Critically assess scientific information about climate.
- Communicate about climate change and thus enable new applications of climate science.
- Make informed and responsible decisions with regards to actions that may affect the climate.
- Provide expert advice to users of climate information.

Partnerships

An analogue for the WCRP Academy is the WMO Global Campus and a liaison has been established to ensure that co-benefits between the Academy and Campus are realized. The success of the WCRP Academy will also critically depend on partnerships with training providers around the world, e.g., the International Universities Climate Alliance, a new and large global collaboration of leading universities worldwide. Plans to engage with other major international academic training providers (e.g., University Corporation for Atmospheric Research (UCAR), International Centre for Theoretical Physics (ICTP), universities and national professional bodies are being developed in the establishment phase of the Academy.

A key part of planning activities will be to ensure that there is a viable and enduring model for training providers to participate in the Academy. A regional hub approach will enable those partnerships to be meaningfully driven at the regional level. As training is part of many national and international research programmes, a close collaboration of the WCRP Academy with the activities of our major sponsors (WMO, IOC-UNESCO, and ISC) and partners (e.g., Future Earth) will be vital and must be facilitated at both the central and regional level.

Moving from a Lighthouse Activity to a permanent part of the WCRP structure

In 2023, the Academy departed from its Lighthouse concept in favor of a new structure, with a Support Unit and an Advisory Board (Figure 13). This was in response to the realization that the Academy represents an inherently overarching activity that touches all aspects of WCRP. The duties of the Advisory Board are to provide feedback about the Academy´s scope and future direction; establish guidelines and processes for approving applications of training providers; take the lead in building partnerships to raise the visibility of the Academy and aid in fundraising. The Advisory Board will be composed of representatives from stakeholder communities (e.g., providers and users of the Academy services such as trainers and trainees), funding agencies, and Early Career Researchers. The Advisory Board will also liaise with WCRP Lighthouse Activities and Core Projects through ex-officio members and reports to the WCRP JSC.

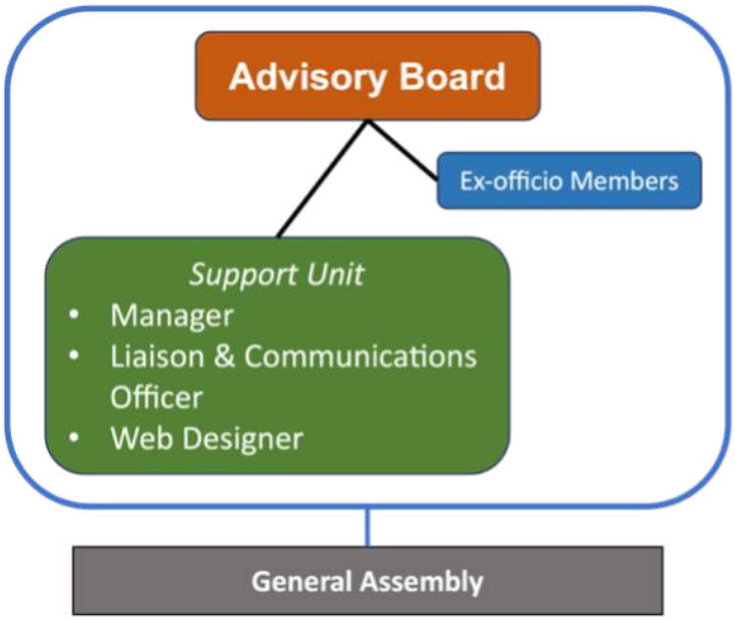

Figure 13: Academy Organization

The Academy Support Unit will support the running of the Academy and oversee the curation and development of the catalog of training opportunities and training providers and liaising with the science community within and outside WCRP.

Key outcomes and impacts, including approximate timeline

- A curated web hub as a focal point for advertising and sharing training opportunities was launched at the WCRP Open Science Conference. In the early days of the Academy, this is focused on collecting and sharing details of training developed and offered by the WCRP community and resources to support that training. In the long term, this should develop into a one-stop shop for training opportunities for climate scientists. Training providers, including those in WCRP core projects and lighthouse activities, now have the opportunity to register via the Academy website and upload their training activities for easy access by the broader climate science community.
- An annual stock-take of research training requirements. Results from the stock-take are shared widely and openly with the climate science community, including being recently presented at the WCRP Open Science Conference. The stock-takes identify both where there are gaps in training provision and where sustainable markets for training delivery exist. The Academy website and associated catalog will also help to lower the barrier to entry for new training providers by:
- Simplifying access to training consumers and providing some simple administrative functions which will interface with those of the training providers.
- Including an equal or greater number of external training opportunities in the catalog.
- Establishing a publishing mechanism for annual stock-take surveys.

Co-development with the WCRP core activities

The Academy will work together with all activities across WCRP Core Projects and Lighthouse Activities, to ensure that an integrated approach is taken to the delivery of climate science training. For this, the Steering Group and ex-officio members will ensure regular liaisons with Core Projects and Lighthouse Activities.

The WCRP Academy is a direct contribution to WCRP's mission "to develop, share, and apply the climate knowledge that contributes to societal well-being," as the sharing of knowledge requires the training of and by those who we wish to share it with. The Academy aims to be the flagship programme that supports this vision. The Academy directly contributes to all four WCRP objectives:

Objectives 1–3 require a thriving and well-educated climate science community that is truly global and freely shares knowledge and experiences. The Academy's specialist training and capacity exchange programmes will be vital to build that community.

Objective 4 aims to connect our science to society. This will require climate scientists who have the skills and confidence to interact with a diverse range of stakeholders with varying prior experiences of climate science and the scientific process. The Academy aims to give climate scientists, at all career stages, these skills and confidence. The Academy will work together with all activities across WCRP, including the Core Projects and Lighthouse Activities, to ensure that an integrated approach is taken to the delivery of climate science training.

4. Partnerships

WCRP's activities are approved and overseen by its three co-sponsoring organizations: WMO, ISC, and IOC-UNESCO. Working closely with the co-sponsors ensures that WCRP collaborates closely with all subsidiary activities sponsored individually by one of WCRP's parent organizations, and those that are co-sponsored. In addition, WCRP works closely with other UN agencies such as UNEP to ensure close collaboration.

In this landscape of activities, WCRP's proven strength resides in physical climate and Earth system sciences. But while pursuing its research, WCRP relies heavily on collaboration with other programmes, be it with respect of observations (Global Climate Observing System (GCOS) or GOOS), aspects of the Earth system not covered by WCRP (e.g., the carbon cycle, biology or chemistry), or climate service-related aspects (GFCS), including health aspects. Specifically, if it comes to bridging climate science and society and improving climate information these aspects are of utmost importance, taking advantage also of other climate science disciplines that are more represented in programmes like Future Earth.

WCRP regularly informs the United Nations Framework Convention on Climate Change (UNFCCC) and its Subsidiary Body for Scientific and Technological Advice (SBSTA). In particular, WCRP produces climate and change knowledge and information that forms the basis for the assessment work of the IPCC: WCRP produces the knowledge that subsequently gets assessed by IPCC. One specific activity that needs to be highlighted in this context is WCRP's CMIP effort that on a regular basis produces the knowledge required by each IPCC assessment cycle to flourish. On top of this, CMIP output is widely used by many governments in support of their decision making, as are the results from WCRP's CORDEX effort. In addition, WCRP supports the Stratospheric Ozone Depletion Scientific Assessments carried out by WMO and UNEP. It also provides significant input to a variety of other policy fora on climate issues, such as the UN Convention on the Law of the Sea, the Sendai Framework for Disaster Risk Reduction, and multilateral environmental conventions.

All the above are stakeholders of WCRP. But the stakeholder community is continuously growing stimulated through the new science priorities of WCRP described above and involves also increasingly the private sector.

In the following we will give more specific regarding the individual collaborations and provide suggestions where they can be further improved under the new WCRP described in this Science and Implementation Plan.

4.1. Collaborations with subsidiary co-sponsor activities

WCRP works with activities across WMO's Science and Innovation department, with a focus on advancing fundamental science, enhancing the science for services value cycle, and advancing policy relevant science. With WWRP it cooperates on a number of activities including monsoon activities, and both programmes are involving each other in their new activities and groups (e.g., WCRP's Digital Earths and WWRP's SAGE (S2S Applications for aGriculture and Environment). With the Global Atmosphere Watch (GAW) of WMO, WCRP works on e.g., the Ozone Assessments as well as foci such as urban climates. The knowledge gained and information facilitated through WCRP essentially benefits climate services and the cooperation with the Global Framework for Climate Services (GFCS).

With respect to IOC-UNESCO, WCRP actively cooperates with various climate-ocean cross-cutting research activities, including the United Nations Decade of Ocean Science for Sustainable Development (2021–2030). Specifically, the CLIVAR Core Project has been contributing to the scientific design and implementation of the regional and global ocean observing systems as well as the synthesis/reanalysis of global ocean, atmosphere and coupled climate information that are all relevant to IOC-UNESCO's objectives. Several other WCRP activities also have ocean components that are all relevant to IOC-UNESCO.

WCRP works with several ISC activities. In particular, ISC provides the linkages to the national Academies or research funding bodies. This holds true especially for the co-sponsored programmes of Future Earth and its activities. Future Earth is a global network of scientists collaborating for a more sustainable planet. WCRP cooperates with many of Future Earth's Global Research Projects, Knowledge Action Networks, and other Future Earth activities to address climate problems together in an interdisciplinary way.

A high-level cooperation agreement was signed in 2021 (see www.wcrp-climate.org/news/wcrp-news/1636–fe-wcrp-joint-statement) and both organizations are working together on several activities. However, there is room for better interactions and collaborations that could be stimulated through the planning of joint activities. Interactions could also be increased through occasional joint planning and steering meetings bringing the high-level oversight bodies together from both programmes.

4.2. Collaborations with co-sponsored international programmes

WCRP works with international and national partner organizations that also have a focus on climate – these might be allied research programmes, national agencies, and stakeholders who use WCRP's research outputs. These partners may contribute services, information, solutions and/or funds into WCRP activities. The overarching objectives of this partner network are to improve understanding of the climate system, climate change and the interactions between climate, society, and the environment.

For example, WCRP collaborates with Past Global Changes (PAGES), Analysis, Integration, and Modeling of the Earth System (AIMES), Surface Ocean – Lower Atmosphere Study (SOLAS), Integrated Marine Biosphere Research (IMBeR), iLEAPS, International Global Atmospheric Chemistry (IGAC) and the Global Carbon Project (GCP) and is involved in both the Risk and Ocean Knowledge Action Networks. CLIVAR works closely with several other existing projects, in particular PAGES, IMBeR, SOLAS, and North Pacific Marine Science Organization (PICES). WCRP also interacts with the International Union of Geodesy and Geophysics (IUGG) and three of their associations: the International Association of Hydrological Sciences (IAHS), the International Association of Meteorology and Atmospheric Sciences (IAMAS) and the International Association for the Physical Sciences of the Oceans (IAPSO). Moreover, the Special Committee on Oceanic Research (SCOR) and SCAR support joint activities with CLIVAR and CliC in particular (Section 3).

Individual WCRP Core Projects and Lighthouse Activities have wide-ranging partner networks. As an example, APARC collaborates with the international research community around atmospheric composition comprising a complex network of bodies and panels, including IGAC, GAW, Aerosol Comparisons between Observations and Models (AeroCom), Aerosols and Chemistry MIP (AerChemMIP). APARC has made connections with some of these groups, for example, through the joint APARC/IGAC Chemistry Climate Model Initiative (CCMI).

CliC works with a host of different partners, including SCAR and IASC, with which it has several joint activities, e.g., Ice Sheet Mass Balance and Sea Level (ISMASS) expert group and the Southern Ocean Regional Panel (with CLIVAR). CliC also provides independent scientific advice not only to UNFCCC, but also to polar governance structures, in particular to the Antarctic Treaty System and to the Working Groups of the Arctic Council.

CLIVAR works closely with GCOS and GOOS, to implement and coordinate observations in support of climate research. CLIVAR representatives are ex-officio members of the GCOS/GOOS/WCRP Ocean Observation Panel for Climate (OOPC) that oversees the implementation of the ocean observing system in support of the Framework for Ocean Observing (FOO), led by IOC-UNESCO. CLIVAR contributes to initiatives of IOC-UNESCO, mainly through the UN Decade of Ocean Sciences for Sustainable Development (2021–2030), as well as the activities on Integrated Ocean Carbon Research (IOC-R) and Eastern Boundary Upwelling System (EBUS), etc. CLIVAR also provides input to a variety of policy fora and documents, such as the UNFCCC process, and the United Nations Convention on the Law of the Sea.

External partners of ESMO include, but are not limited to, GCOS, GOOS, the Committee on Earth Observation Satellites (CEOS)-Coordination Group for Meteorological Satellites (CGMS) Working Group Climate, WWRP, GAW, Future Earth, and GCP.

ESMO also connects to broader stakeholders including the UNFCCC, the IPCC, the Global Framework for Climate Services (GFCS) and implementing initiatives such as C3S and WMO operational entities.

GEWEX has a strong partnership with satellite agencies, in particular NASA and works with others such as WMO Hydrology, the High Mountain Partnership. RIfS partnerships tend to be on a local level via its Hubs and via CORDEX but are developing quickly.

As for partnerships external to WCRP, the following groups and activities have been identified: Climate service providers (Climate Service Center Germany (GERICS), Regional Integrated Sciences and Assessments (RISA) Program (USA), Ouranos, GFCS, etc.), Vulnerability, Impacts, Aadaption (VIA), risk/resilience research community (including commercial services), Future Earth (e.g. Risk Knowledge Action Network (Risk-KAN)), WWRP's Working Group on Societal and Economic Research Applications (SERA) and High Impact Weather (HiWEATHER) Project, START, the Inter-American Institute for Global Change Research (IAI), the European Climate Research Alliance (ECRA), ClimatEurope, C3S, and ICNet.

4.3. Partnerships with global climate observations programmes

Research observations are essential for monitoring and understanding climate variability, for documenting trends, and for initializing models for climate prediction. WCRP's key partnerships with respect to climate observations involves GCOS and GOOS who advocate the implementation of a sustained climate observing system, including support for quality-assured observations. WCRP and GCOS collaborate on a number of activities such as co-sponsorship of OOPC and other panels as well as new activities spinning up such as looking at cycles and budgets of energy, water and carbon. A collaboration with CEOS is concerned with climate observations from space, involving international space agencies, e.g. NASA and ESA.

Specifically, ESMO works closely with the GCOS Steering Group and panels to support GCOS in its role of assessing the status of global climate observations and producing guidance for its improvement. By establishing strong and strategic links, ESMO will help to ensure that WCRP's

observational needs are integrated into GCOS periodic releases and help to sustain provision of observations inclusive of access systems and analysis tools. Links to CEOS-CGMS Working Group Climate will allow ESMO to provide input to the space agencies on all issues related to climate monitoring from space.

4.4. Regional and national partnerships

WCRP cooperates with National Agencies and National Academies from around the world. As an example, WCRP has a long-standing partnership with the United States Global Change Research Program (USGCRP) where WCRP activities contribute directly to achieving several of their identified research goals. Working directly with funders and funding agencies is critical to jointly ensure the coordinated funding of key science. The Belmont Forum is a partnership of funding organizations, international science councils, and regional consortia committed to the advancement of trans-disciplinary science. It focuses on international trans-disciplinary research providing knowledge for understanding, mitigating, and adapting to global environmental change. Many other funding groups focus on regions such as IAI.

RIfS is recently supporting a key activity in the development of an African Alliance. CORDEX has already set up teams in central, south, east and west Africa. With the organization of a workshop in Pretoria, South Africa, the aim is to identify strategic focus areas and priority actions that may be built from the bottom-up and support the organic growth of a collaborative research community in Africa. The foci will target the most critical research needs and span the spectrum of issues of physical climate science, vulnerability, impacts and adaptation, climate services, and social issues. In this context, the workshop contributed to new efforts to build collaborative research in Africa, with outcomes focused on developing draft concept proposals for collaborative research actions serving the information needs of Africa to manage regional climate change risks. Similar efforts are going on in Latin America, and Asia.

5. WCRP governance

Governance can be thought of as the framework of authority and accountability that defines and controls the outcomes and benefits from WCRP. Such a framework includes the way and a clear description of how WCRP's organizational elements are structured, and the roles, responsibilities and membership of these organizational elements. Governance also includes those systems, processes and policies that enable WCRP to adapt to the dynamic nature of climate science and to work effectively across WCRP's community of researchers, partners and stakeholders.

Section 5.1 describes WCRP's structure along with the relevant information about organization, membership, roles and responsibilities. Section 5.2 summarizes key underlying governance principles, systems and processes - including approaches to ensure diversity, inclusion, representation and transparency. Aspects of communication and engagement, which are also key to effective governance, are covered in Section 6.

5.1. WCRP's organization

The following describes how WCRP and its elements are organized, including their governance and operation. This information, along with the sub-structures (working groups, teams, panels) and additional relevant information, is summarized in Table 3. The Guidelines on Membership and Responsibilities of WCRP High-level Steering Committees outlines the governance of WCRP core activities (see https://www.wcrp-climate.org/about/Guidelines-on-Membership-and-Responsibilities-of-WCRP-Bodies-27-Sept-2022.pdf).

1. Joint Scientific Committee (JSC)

Scientific guidance for WCRP is provided by the WCRP JSC, which meets annually and consists of up to 18 scientists selected by mutual agreement between the three sponsoring organizations (WMO, IOC-UNESCO, ISC). The main annual JSC Session includes representatives from all WCRP activities as well as from co-sponsors, partners, and funding agencies. The public part of each meeting is typically accompanied by a closed session, where the JSC make decisions on financial and confidential matters. The annual JSC Session is supplemented by additional meetings organized as required.

JSC members are selected and appointed following an open self-nomination process overseen by the JSC and WCRP Secretariat with final approval by WCRP's three co-sponsors organizations. Membership includes scientists from a wide range of disciplines, from the natural and social sciences, and strives for regional, age, career stage and disciplinary diversity. Each member serves an initial term of four years that can be renewed by additional terms each two years long upon approval from WCRP's co-sponsors.

JSC Members elect, from within the Committee, a Chair, Vice Chair and three Officers. The tenure for each of these positions (Chair, Vice-Chair and Officers) is two years and can be renewed through re-election. The JSC, through its Chair, is accountable to the co-sponsors for all WCRP actions.

2. Core Projects

Core Projects are governed by their SSG (or equivalent), led by two or more co-chairs. The SSG of each Core Project is accountable to the JSC and therefore is required to report at their annual meetings. The SSG and its co-chairs are supported by an IPO. Each Core Project develops a

Table 3: Organizational elements presented in Figure 3 and described in Section 5.1.

Organizational Element	Leadership	Purpose (including Terms of Reference (ToRs) if relevant)	Sub-structures (Working Groups, Teams or Panels)	Additional relevant Information
Joint Scientific Committee (JSC)	Chair Supported by Vice Chair and three Officers	Leading and steering all aspects of the WCRP science direction. Representing WCRP to Co-Sponsors. ToRs specified in Co-Sponsors Agreement.	JSC Liaisons are appointed for each Core Project. Fixed term Working Groups and Task Teams can be created as needed, with ToRs, and report to JSC.	a) Up to 18 members for a 4-year term with a 2-year term extension possible, and further extensions by exception. b) JSC Chair, Vice Chair and Officers voted in by JSC members; approved by co-sponsors.
WCRP Secretariat (formerly Joint Planning Staff (JPS)) Remunerated, i.e. paid positions	Head of WCRP Secretariat	Provides Secretariat support to the JSC and WCRP, and other organizational elements, and liaises with the IPOs. Core role in coordination across WCRP.	N/A	a) Centralized Secretariat hosted within WMO; staff are WMO employees. b) Staff outside Geneva managed by host institutions.
Core Projects	Co-Chairs (Scientific Steering Group, SSG)	Facilitates and coordinates science in accordance with strategic goals and science plans of the Core Project developed by the SSG. ToRs are the approved science plans and projects.	Working Groups and Panels are created by the SSG, who approve and appoint the leads, members, and science plans - refer to each Core Project for details.	a) SSG Membership approved and appointed by JSC. b) RIfS includes CORDEX, and the Extremes Platform. c) ESMO includes the Working Group on Coupled Modeling, which oversees CMIP.
Lighthouse Activities	Co-Chairs (Scientific Steering Group, SSG)	Focus on new and major projects where progress is urgently needed. They integrate and draw upon capabilities from across WCRP.	Working Groups and other sub-structures are created by the SSG, who approve and appoint the leads, members, and science plans	a) Co-Chairs are appointed from across WCRP family, considering gender, geography, expertise. b) Science Plan Team members were nominated from, and so represent, the Core Projects.
International Project Offices (IPOs) Remunerated, i.e. paid, positions	Executive Director	Under the Executive Director, provide an effective "executive/operational arm" to the SSG and associated sub-structures of the Core Projects	N/A	a) IPO Directors formally report to host institution; activity reporting to SSG Co-Chairs and funders. b) IPOs support "horizontal" coordination across WCRP, in liaison with WCRP Secretariat. c) CORDEX, CMIP and S2S are also supported by an IPO.
Ongoing Activities and Fora	Defined and established by the JSC as needed	To fulfill a clearly defined goal, as described in ToRs. Fixed term and sponsored by the JSC and/or Core Projects and/or Lighthouse Activities.	N/A	These are sponsored by one or more organizational elements of WCRP; they report to the relevant sponsoring element(s) and thence to the JSC.

Note: a) Unless otherwise indicated all committee members undertake these roles voluntarily i.e., they are not paid roles. b) See Table 4 for accountability and reporting lines.

strategy for its science directions and research plans – this is the primary responsibility of the SSG. These plans can also include the organization of observing system components, model infrastructure or other infrastructure aspects.

Underneath the SSG, the organizational structure of each core project is an organizational structure consisting of panels that advance science and carry out organizational tasks according to the science strategy. These panels meet regularly to review scientific progress, address research priorities, coordinate activities, develop best practices, guidelines, and recommendations for the community as a whole and promote scientific capacity development.

The SSG is also responsible for organizing interactions with other Core Projects, Lighthouse Activities, the WCRP Academy, partner organizations, and stakeholders. Each Core Project is supported by an IPO, which is hosted and funded from contributions by nations or research agencies. Core Projects have no sunset date.

The WCRP JSC approves the membership of the Core Project's SSGs on the advice and recommendation from the Core Project co-chairs following a public call for nominations. The JSC also approves the science plans of the Core Projects.

3. Lighthouse Activities

The Lighthouse Activities are governed by a SSG (or equivalent), which is led by two or more co-chairs. The Lighthouse Activities work closely with the Core Projects to co-develop and co-deliver

Table 4: Reporting and accountabilities

Organizational Element	Accountability	Reporting
Joint Scientific Committee (JSC)	JSC Chair: Co-Sponsors	JSC Chair and Vice Chair: Co-Sponsors; JSC; WCRP activities; Partners and Funding Agencies
WCRP Secretariat	• JSC • Host Institution • Activities can be under the leadership of a JSC member.	• Head is supervised by the WMO Director of Science and Innovation in consultation with the JSC Chair. • Secretariat staff report to Head formally.
Core Projects	• Co-Chairs: JSC. • Core Project activities: SSG and Co-Chairs • JSC approve SSG membership, Science Plans.	• Core Projects report to JSC via the SSG Co-Chairs. • SSG Members (and sub-committee leads) report to SSG Co-Chairs. • JSC to be notified outputs, discoveries and advances.
Lighthouse Activities	• Co-Chairs: JSC. • Projects and tasks: Lighthouse Activity Co-Chairs • JSC approve Co-Chairs, Science / Business Plans.	• Lighthouse Activities report to JSC, via the Co-Chairs. • JSC to be notified of key outputs, discoveries and advances. • Teams / groups within Lighthouse Activity report to Co-Chairs.
International Project Offices [IPOs]	• Host Institution and funding agency. • Work closely with SSG Co-Chairs and WCRP Secretariat.	• Directors formally report to their host institution. • Work closely with the respective SSG Co-Chairs and WCRP Secretariat.
Ongoing Activities and Fora	Defined in Terms of Reference for activity.	These are sponsored by one of the organizational elements; report to sponsoring element(s) and the JSC.

outputs that address critical and urgent climate research that requires a specific focus, new technologies, infrastructure and governance. For this reason, Lighthouse Activities are expected to have a limited lifetime (from a few years up to a decade). Each Lighthouse Activity is required to develop a strategy for its science directions and research plans. This is the responsibility of the SSG (or equivalent), who is also responsible for organizing interactions with other elements of WCRP along with external partner organizations and stakeholders. Below their respective Steering Groups, Lighthouse Activities can have several sub-elements such as working groups, research foci or other short-term activities. They are supported directly by the WCRP Secretariat or secondments.

The JSC approves the science plans of the Lighthouse Activities, appoints their co-chairs, and approves and appoints the membership of their respective Steering Groups (or equivalent) following a public call for self-nominations. The Lighthouse Activities are accountable to the JSC, and report to them via their respective co-chairs at the annual JSC meeting.

4. Supporting structures and organization

WCRP's support structure comprises a central WCRP Secretariat located at WMO Headquarters in Geneva augmented by the IPOs, secondments and WCRP Support Units located around the world. The purpose of the WCRP Secretariat is to work with and support the JSC in developing and implementing the WCRP programme. This includes coordination and communication across all organizational elements and liaising with the IPOs. IPOs are supported by individual nations or research organizations on a voluntary, time limited basis.

All support structures facilitate communication, collaborations, and engagements, internal and external to WCRP – including webpages, news, and announcements; provide scientific and logistical support of events (meetings, workshops, webinars, etc.) and to the production of publications and reports; and operational support (including administration, mailing and membership lists, financial budgets etc.). They proactively support coordination and integration "horizontally" between the WCRP elements.

5.2. Governance principles and systems

WCRP is committed to four principles across all aspects of its operation and decision-making:

i. Transparency, consultation and effective communication, especially in sharing information and decision-making;

ii. The need for inclusion, diversity and equity (across career stage, gender, culture, discipline and geography) in its activities and leadership groups;

iii. Promoting and supporting cooperation, coordination and collaboration with partners, allied disciplines and stakeholders; and

iv. Clarity – i.e., that purpose, structure, roles and responsibilities, etc. are all publicly available and clearly explained (i.e., accessible).

These principles have guided the transition to the new WCRP and led to revisions of WCRP's governance. They imply that directions and guidance from the JSC involve consultation, and decisions are then clearly and openly communicated. The following systems, processes and policies implement these principles across all aspects of WCRP's operation, leadership and decision-making.

Transparency, consultation and effective communication

- WCRP's Communication Action Plan (Section 6) identifies goals, approaches, and priority actions to ensure timely and effective sharing of information and WCRP decisions, both internally and externally. This Plan includes guidelines and expectations governing meetings (reporting and frequency); communication modalities; code of conduct, and induction of new WCRP community members.
- All formal WCRP meetings are publicly advertised, including whether attendance is open or by invitation only. All such meetings provide a meeting report that includes a summary of the discussions, decisions made, and actions required (with a timeline). This includes the annual meeting of the WCRP JSC, where decisions on budgets, membership, and other strategic aspects are made.
- Consultation, within the WCRP community and externally with partners and stakeholders, is a commitment that WCRP has made and sustained throughout the drafting and implementation of WCRP's Strategic Plan. This commitment is manifested through regular formal meetings, effective communication and, where appropriate, informal meetings with the Chairs of the JSC and core WCRP activities.
- A clearly defined purpose, roles and responsibilities of the formal organizational elements which include guidelines and expectations about how membership and leadership decisions are made along with meeting frequency and modalities. All membership and leadership appointments are advised to WCRP's community via email, newsletters and relevant meeting reports (as per the Communication Plan).
- Establish and support WCRP Secretariat and IPOs to provide internal coordination and communication between the organizational elements of WCRP. Importantly, they support workshops and activities that span groups and disciplines across WCRP, and externally.
- Appoint Liaisons between WCRP's overarching JSC and each of the Core Projects. These are referred to as "JSC Liaisons" (see Table 3 below), who provide neutral advice and guidance and communicate as needed between the JSC and Core Projects, without being engaged with the core project activities themselves.

Inclusion, diversity and equity

WCRP is very cognizant of the importance of being inclusive and building diversity across career stage, gender, culture, discipline and geography in its activities as well as its scientific and strategic leadership. The WCRP JSC are implementing several new initiatives within this Science and Implementation Plan to address this, including:

- Setting expectations and targets to strengthen diversity. This includes directly nominating or appointing individuals where needed. Additional initiatives, such as mentoring and shadowing arrangements, are under consideration to strengthen diversity – especially in those places where WCRP has long struggled to meet these diversity goals – and strengthen our succession planning for both subject matter experts and leadership roles.
- Encouraging membership term extensions by exception only, so that more members of WCRP's community are given the opportunity to lead and participate in the organization of the Programme and to ensure a renewal of ideas and expertise.
- Leveraging WCRP's initiatives to build stronger engagement across the WCRP community

– for example, capacity development through the WCRP Academy; engagement with a more diverse group of researchers through WCRP regional activities (e.g. RIfS, MCR, CORDEX) and co-sponsors regional associations and other means; and strong affirmative actions across all WCRP's core activities.

- The WCRP Secretariat continually monitors diversity information for WCRP's activities, membership and leadership groups.
- WCRP has a Code of Conduct (www.wcrp-climate.org/community-resources/WCRP-Code-of-Conduct.pdf) recognizing that we embrace diversity, demand equality, and wish to build capacity for the future. To achieve this, we all should be able to work in a professional, respectful, and harassment-free environment.

Cooperation, coordination and collaboration

It is fundamental to WCRP's mission, to "coordinate and facilitate international climate research to develop, share, and apply the climate knowledge that contributes to societal well-being". A key element of WCRP's Strategic Plan is to strengthen its connection with partners, allied disciplines and stakeholders, to achieve the four Scientific Objectives (Figure 1) - including bridging climate science and society. It requires WCRP's climate research to be well coordinated and, where needed, jointly undertaken between the core activities described in Section 3. An informal WCRP Leadership Team has been formed to facilitate this coordination, communication, and collaboration across WCRP and to enhance integration and synergies (see Table 3 for a complete description and Table 4 for accountability and reporting lines).

In this Science and Implementation Plan, WCRP is also prioritizing its connection with our key partners who are described in Section 4. As described there, this includes developing informal and formal cooperation agreements with other research agencies and programmes and agreeing to work jointly on critical issues.

6. Communication, engagement, capacity building

Communication, coordination, and engagement are key to how members of the WCRP community work together, and how WCRP collaborates and co-designs science with co-sponsoring organizations and partners. They are needed to build the connections and facilitate collaboration between people and projects. They are important factors that support WCRP's role as the authoritative voice of climate science to broader society. Further communication strategies will be developed over the next 1–2 years.

6.1. Communication

Effective communication is the basis for the flow and exchange of information; engagement with and transparency to our community; collaboration, co-design and co-production; and an understanding and awareness of WCRP's science. Effective internal communication is needed both "horizontally" across WCRP's organizational elements and "vertically" between the hierarchy of committees and working groups. WCRP also needs to effectively communicate externally with its sponsors and funders, and with partner programs.

WCRP's key communication strategy is:

- Create communication products that are clear, concise, well-targeted, and, where possible, that contain a single message or ask.
- Build a foundational "infrastructure" of tools and platforms that are widely used.
- Continually assess and review tools and products to ensure they meet ongoing needs and adopt current technologies and best practice approaches.
- Take a community approach, with a commitment to open access (i.e., publicly available to all), transparency, consistency, and inclusive and accessible language.

The strategy is being enabled by the governance structures, processes, systems and policies and a Communication Strategy. The WCRP Secretariat provides the support and oversight for all aspects of WCRP's communication.

6.2. Engagement

Engagement with the WCRP community of researchers and practitioners, allied partner programs, and sponsors and funders, is an important part of WCRP's mission. Engagement occurs through WCRP's core scientific activities and is coordinated by the WCRP Secretariat, IPOs, and Support Units. It is manifested as conferences, workshops, panels, and discussion groups as well as projects and other scientific activities.

WCRP engages with early to mid-career researchers through several early career networks, including the Young Earth System Scientists (YESS) community, which itself has over 2000 members. YESS strives "to help shape the future of Earth system science, by fostering international and trans-disciplinary leaders of tomorrow who pioneer the development and delivery of research and knowledge, which provide solutions to benefit society, towards a more equitable and sustainable future", with a focus on ECRs working in the interdisciplinary field of Earth system sciences, including social and natural scientists. By collaborating with early career networks, WCRP leadership and core activities ensure that ECRs are entrained in WCRP activities

and have a say in WCRP's strategic planning.

In 2019, WCRP initiated a series of regionally based online Forums, called Climate Research Forums (CRFs), in response to feedback that WCRP's broader scientific community were not that familiar with the new strategy and initiatives being developed as part of the Science and Implementation Plan. Further regional consultations using this CRF format may be undertaken based on a regular assessment of WCRP's needs for tailored engagement in the regions.

6.3. Capacity building

WCRP fosters increased scientific capacity around the world to address challenges and opportunities resulting from climate variability and change at the regional and global levels. WCRP tries to ensure that capacity building is integrated into all activities, including in leadership positions (either directly or by some kind of mentorship). To this end, WCRP collaborates with START, a programme to make the knowledge and the tools of climate predictions available to scientists from developing countries.

WCRP has a commitment to make sure its expertise, its data and publications are shared as widely as possible. This includes using hybrid meetings and making recording of key activities available. A major step in this direction is undertaken by the WCRP Academy, which is a key activity going forward, with its overarching objective to determine the requirements for climate research education and build enabling mechanisms. These might be for Early Career Scientists focused on regions of the world (in particular the Global South) and are usually on a specific topic. Each individual core activity also contributes to capacity building, with a few examples given below.

In developing its capacity-building activities further, WCRP's CLIVAR Core Project pursues various approaches:

- Contributing to the education of the next generation of climate scientists with a particular focus on interdisciplinary studies and scientists from developing countries. CLIVAR offers a regular Series of Summer Courses in collaboration with the First Institute of Oceanography (China), and the International Centre for Theoretical Physics (Italy).
- Providing global and regional fora for the exchange of ideas and knowledge amongst climate researchers and students. Support will be sought to bring early career scientists and those from the Global South to CLIVAR meetings and conferences.
- Encouraging making research outputs useful and easily accessible to the broader scientific community and to end-users such as adaptation planners, policy makers and decision-makers in climate-sensitive sectors such as adaptation, mitigation, resilience, agriculture, energy and construction.

The APARC Core Project community includes a large body of ECRs. These researchers are engaged, proactive, and bring new perspectives to APARC. APARC encourages involvement of ECRs in Activity leadership. Moreover, APARC's support for ECRs is currently met through travel support to attend meetings/workshops and through delivery of training, e.g., APARC-sponsored Summer Schools. As part of APARC's new strategy, we would like to build from this example to support other ECR initiatives. For instance, the growth in Artificial Intelligence (AI) and Machine Learning (ML) in atmospheric science, and the fact that ECRs are rapidly becoming the new generation of experts in the application of AI/ML techniques. APARC plans to consult with the APARC ECR community on the appetite for an AI/ML Researcher Forum that could comprise presentations, discussion sessions and an online base for sharing code/tools.

The CliC Core Project works closely with both the Association of Polar Early Career Researchers and Polar Educators International, to ensure the next generation of researchers are included in their activities.

CORDEX pursues capacity building activities over different regions of the world around topics that are regionally relevant. These activities are usually co-organized with regional institutions and are often focused on downscaling techniques and applications and on bridging the gap between climate information and societal needs. CORDEX has built up regional teams in several of the CORDEX domains and they collaborate within and across the groups. Workshops and trainings are regularly held, especially in developing regions, and at some of them young scientists have also been trained in writing scientific publications. This has, for instance, resulted in many publications being included in the IPCC reports. These activities are also delivered for more senior scientists although mainly focusing on ECRs and most of them are organized in the Global South. CORDEX has also organized trainings for non-scientists in regions with very low capacity, for instance to train meteorologists in climate issues.

7. Financial support and investment

All three co-sponsors support WCRP's science coordination, intellectually as well as in different ways, financially. The intellectual sponsorship implies that WCRP's Strategic Plan and research priorities are consistent with, and embedded in, the plans of all co-sponsors. Their sponsorship also implies that WCRP's goals and work aligns with the programs and communities supporting all three co-sponsors. WCRP's coordination work is also supported financially both directly and through voluntary contributions from individual nations (mainly through ISC Member Countries). WCRP also receives significant financial support in the form of national support for IPOs. Understanding WCRP's support structure thus requires considering all support streams, including direct and indirect support.

It must be recognized that funding for all WCRP science activities is ultimately provided through national funding streams, i.e., national funding agencies and national academies. This financial support is guided by WCRP's science directions and generated in response to national calls for research often launched in consultation with the WCRP leadership. This national science support provides the foundation for the climate research coordinated and carries WCRP's research priorities forward. Given that WCRP coordinates climate science that is too large for any single institute or nation to take on, it will be desirable for the future to better interact and coordinate with funding agencies around the word to target specific topics that require international involvement. This idea is pursued by the Belmont Forum. It needs to be expanded for climate science at large.

Beyond a purely monetary consideration, WCRP's expenditure and coordination work also includes significant "non-cash" contributions resulting from the involvement and service across the scientific community. This amounts to well over 5000 scientists involved in WCRP's many activities.

In the following we summarize WCRP's present income streams and explain the different categories of ongoing expenditures. This will be done in terms of:

i. WCRP Secretariat located in Geneva

ii. IPOs distributed around the world

iii. WCRP's science coordination effort

7.1. WCRP Secretariat and International Project Offices (IPOs)

The financial support for running the WCRP Secretariat at WMO in Geneva is provided primarily by WMO, covering a significant portion of staff salaries as well as most of the operational costs. Presently four personnel are located in Geneva. Additional personnel are seconded to the WCRP Secretariat by national institutions and are located elsewhere, e.g., by the Centre National de la Recherche Scientifique (CNRS)/ Institut Pierre Simon Laplace (IPSL) in Paris.

In terms of the WCRP structure, IPOs and other WCRP Support Units are "satellites" of the WCRP Secretariat (Figure 14). WCRP relies heavily on these IPOs. These IPOs support WCRP's Core Projects and other core activities such as WCRP's service-oriented "flagship" projects--CORDEX, and, since 2022, the joint (with WWRP) International Monsoons Project Office, from 2023 the Global Extremes Platform. In total, the financial support for the IPOs is around 4 million CHF per year. Funding to support the IPOs is sourced from voluntary contributions from individual nations, primarily via research institutions or national academies (ISC members). These funds are used to cover salary costs, IPO operations (including printing, computing etc.), and travel of IPO staff members.

Figure 14: Current WCRP International Project Offices and Support Units

7.2. International coordination

Annual income

Funds received to support WCRP's international coordination efforts flow primarily through the Joint Climate Research Fund (JCRF), an independent trust fund managed by WMO on behalf of the three co-sponsors of WCRP. Support for international coordination activities, and some operational costs for the WCRP Secretariat, is provided to this fund. This involves financial contributions by WMO and, directly or indirectly, the other two co-sponsors. However, the largest proportion of these contributions for science activities come from the National Academies of Sciences, i.e., ISC Members. Over the past decades, WCRP has received significant financial support via this route on an annual basis to enable scientific activities and developments. Under present circumstances, the projected core income (i.e., not including funds raised for specific activities such as the WCRP Open Science Conference) for WCRP until 2025 is shown in Table 5.

Annual budgeting and spending process

In the past, most voluntary national funds were used to support travel, to bring together WCRP scientists engaged in various core activities. In 2020, COVID-19 hit, interrupting all in-person operations, and forcing WCRP (as every other organization) to move its operations online. As we move ahead with the implementation of the new WCRP, we anticipate a substantial impact on WCRP's operations post COVID-19 in that many meetings and workshops will be held virtually thereby saving on travel and logistics support. This aligns with WCRP's goal to reduce its carbon footprint; it will free up voluntary financial contributions required for the new WCRP efforts such as ESMO, RIfS and the Lighthouse Activities, and to pursue new avenues of WCRP's international coordination by setting new goals.

The resulting reduction in travel costs will free up funds and enable WCRP to consider new strategic investments into those areas requiring urgent and focused effort and are aligned to WCRP's new goals. However, to some extent the reduced travel will have an offset as making successful virtual meetings will come at some cost for better IT, infrastructure, interpreters (for some meetings) etc. This includes proactive and meaningful ways to entrain the Global South community into all WCRP activities, considering language barriers, time zones etc. We also need financial support for appropriate communications, coordination, and research infrastructure. WCRP should also provide more support to initiatives that allow high level syntheses, coordinated fast track studies on key science aspects or directions.

Table 5: Summary of WCRP core* annual income from 2022 - 2025 (thousand Swiss francs)

	WMO	ISC/Country	USGCRP	IOC-UNESCO	Total
2022	325	135	222	24	706
2023	359	134	327	13	833
2024	350	135	343	22	850
2025	371	135	415	23	944

* This table includes funds from WMO, ISC (including national contributions from ISC Member countries), IOC-UNESCO, and USGCRP grants. It does not include contributions from countries hosting IPOs, Support Units, or events.

From 2024, WCRP is implementing a new annual budgeting process in which resources for coordination operations are being divided into five different budget items, which align to WCRP's Strategic Plan:

1. Baseline funding of core activities, considering activity size.
2. Strategic funds to sponsor special activities (e.g., workshops, conferences etc.), which can sit either within core activities, or which will be initiated by the JSC.
3. Funds to support capacity building, including the Global South Fellowships.
4. Funds to support JSC activities, overarching operational activities, such as communication and outreach efforts.
5. Funds to support WCRP's Lighthouse Activities and the WCRP Academy, where needed.

Each of these budget lines are described in more detail below. Here it suffices to note that baseline funding is typically concerned with ongoing needs (subject to the approved science plans), whereas the other items are typically time-limited and more strategic in nature (e.g., one-time conference support, time-limited research activity or a short-term fellowship) and/or associated with a specific output (e.g., a scientific assessment paper).

The annual budgeting process has the following elements. A task force of the JSC is in charge of the steps below working out the annual budget for all WCRP activities.

1. **Baseline funding:** core activities provide a budget request required to cover their regular activities. Baseline funding will vary between Core Projects and Lighthouse Activities; it can also vary between Core Projects. The baseline funding does not need to be revised on an annual basis as it reflects the work plans as published in core activities S&I plans.
2. **Strategic funds:** core activities will be asked annually to provide a budget request for specific activities that require financial support above the baseline support. The JSC also gets a chance to initiate additional efforts annually pending inside or outside demands, such as the production of a special report or a new assessment paper.
3. **Annual budget process:** based on the proposals from the core activities and strategic activities planned by the JSC, the JSC allocates the available resources. Based on the actual income, the required baseline funding, the remaining budget will be identified and distributed to cover other needs, including strategic resource, funds for global fellowships, capacity building; funds to support overarching operations activities, and funds for Support Units for the Lighthouse Activities and the Academy, where needed.

7.3. Detailed budget line description

7.3.1. Baseline funding

Baseline funding concerns regular operations and projects by core activities as defined and documented in the respective science plans. A baseline funding will be identified during the process of writing or revising a science plan. Allocation will depend on availability of funds.

7.3.2. Strategic funds

Strategic funds are allocated at the discretion of the JSC and will be distributed on an annual basis. They relate to proposals submitted by core activities for specific expenses, such as conferences or workshops. Strategic funds will also be used to fund strategic projects identified by the JSC. Such projects can be performed in collaboration with or within specific core activities. They can, likewise, be undertaken as new short-term projects outside of the core activities and with outside partners. The following categories describe the range of potential strategic projects.

Advancing science and technology

a. Support for rapid updates, syntheses, assessments, and gap analyses. Assessments can be used to provide answers to critical questions. This includes coordination support as well as entraining leading scientists from around the world and across all relevant disciplines.

b. Initiating new approaches for science support, e.g., new pilot studies, field campaigns/ experiments and modeling (improvement) studies. This can include working together with space agencies to develop new instrumentation; conducting targeted observational campaigns; developing new modeling capabilities and supporting the generation of new data and information (could also include reference datasets for benchmarking).

c. Guidance for, and/or development of, new technologies and infrastructure.

Closing urgent knowledge gaps: Knowledge gaps include regionally relevant information down to the urban scale, compound extremes and event attribution, overshoots, tipping points, and air quality benefits of mitigation. Changing patterns of extreme weather (such as storms and heat waves) and climate-related events (such as droughts) can affect public health, national security, the economy, infrastructure, and other essential systems. Extreme events can interact and build on each other, creating multiple stressors that make it difficult to plan and improve preparedness. Tipping points occur when Earth system changes become irreversible, leading to large-scale shifts in the Earth system that can have significant impacts on society. Understanding tipping points is critical to informing risk management strategies. It is expected that concerted efforts into advancing process understanding, and capturing this into our model systems across the components of the Earth system will bring benefits in overcoming systematic errors in climate models.

Developing climate information for decision-making: Funds are required to establish regional work in the Americas and in the African continent, as well as in the Pacific islands, Southeast Asia, Southern and Central Asia, to co-develop and co-deliver climate information in these locations. From a WCRP perspective, research to deliver robust climate information for decision-making is required. This is not climate services but a key component of being able to deliver robust climate services. This would also cover capacity development and training of the next generation of climate scientists. Here, the new WCRP Academy will be a central element to be developed in cooperation with START, Future Earth and the Belmont Forum.

7.3.3. Capacity building, fellowships, and inclusion

- Global South Fellowships: Can be full-time equivalent over a year; or split in shorter periods. A process to decide, distribute and oversee these needs to be developed. Global South Fellowships could target the needs of early career scientists in the Global

South; for example, to support the initiating of activities in their own countries.

- Summer schools, conferences, training workshops etc.
- Leadership development, and succession planning activities.
- Specific events focused on/in the Global South.
- Overarching operational activities

The following may also have links to activities described in the other four categories.

1. JSC operations, including strategic workshops and other events

Logistical needs associated with virtual and hybrid conferences (virtual conferences are not without costs). Funding can be used for information sharing, for example, the publication costs of scientific papers so that they can be open access, costs associated with use of repositories for sharing data, etc. Internships and scientist exchange visits, e.g. scientists from the Global South can visit institutions in the Global North (and vice versa) to have direct interactions.

2. Science partnerships, coordination and collaboration

- Annual planning meetings and workshops to identify and prioritize new frontiers of climate science. This activity includes interactions with national funding agencies.
- Support to build linkages between Lighthouse Activities and Core Projects, including developing effective infrastructure platforms to support collaboration and communication.

3. Communication, engagement and outreach

- Developing and providing information to WCRP stakeholders and the public, e.g., production of educational and informative videos and documentary series.
- Regular community events and conferences, partly in cooperation with existing organizations around the world, highlighting WCRP's science and new frontiers.

4. Advancing international coordination

- Undertake mini assessments, the needs of which are identified from discussions with collaborators, partners, and stakeholders, e.g., on tipping points or RCI.
- Pursue a joint workshop with IPCC Working Groups to identify the gaps and build them into WCRP's work programme via extending the scope of existing, or establishing new, working groups.
- Convene study group on best practices for assessments: Identify new ways of doing climate assessments, and science areas where new assessments are needed.
- Foster collaborations with GCOS and CEOS; Future Earth, START and IAI: establish new collaborations to pursue collaborative research actions.

7.3.4. Support Units for WCRP Lighthouse Activities and WCRP Academy

Currently the Lighthouse Activities and WCRP Academy are supported through WCRP's Geneva-based Secretariat. It is obvious that both the Lighthouse Activities and the Academy need additional dedicated personnel to move forward. Until additional funds are found, e.g., from an external agency, to sustain these Support Units, some of the WCRP income and resources must be used for this support.

8. Timelines and measures of success

8.1. Timelines and milestones

Timelines:

- Review of WCRP and its Strategic Plan every decade
- Update of the Science and Implementation Plan every 2–4 years
- Review of Core Project Science Plans every five years
- Review of work during annual JSC meetings
  - Regular assessment of the adequacy of the science questions, new challenges and organizational aspects
  - Review of new important activities by Core Projects and Lighthouse Activities addressing urgent topics
- Produce WCRP "products" with strategic funding

Milestones:

- First deliverables from each Lighthouse Activity
- CMIP and CORDEX deliverables
- Launch of working groups around assessment papers
- Improved EMCR leadership and visibility
- Launch of WCRP fellowships, annually
- Full implementation of the Academy
- Implementation of published WCRP assessment paper series
- Regular publication of reports from Core Project workshops
- Implementation of new communication tools
- New WCRP public appearance and adoption of new website

8.2. Measures of success

- Publication of peer reviewed WCRP related/initiated papers
- Improved near-term projection and prediction skills
- Improved climate observing system and improved climate modeling
- Delivery and uptake of critically needed WCRP high-level assessment
- Establish regular reporting of WCRP-led and/or funded workshops

- Full-scale engagement of Core Projects in the Lighthouse Activities
- All WCRP Panels membership reflecting global diversity and gender balance
- Advancement in capacity development activities
- Generation of resources to bolster the Academy's endeavors
- Establish additional funding streams to enable more science activities
- Strengthen interaction between WCRP scientific endeavors and their societal impacts
- Growing participation in WCRP sponsored workshops and events, specifically by ECRs
- Generate greater visibility of the WCRP amongst climate scientists and other stakeholders
- Increased active engagement of early career researchers at high levels within Core Projects/Lighthouse Activities, including the development of associated Key Performance Indicators (KPIs)
- Implementation of the WCRP Global Fellowship scheme, including developing topics that benefit WCRP activities, especially the Lighthouse Activities and Core Projects and seeking and selecting high quality applicants
- Continuation of the WCRP Fellowship scheme to ensure its ongoing benefit (to WCRP and recipient) and integrity
- Reduction of carbon footprint through enhanced virtual interactions and reduced travel
- Effective engagement with funding agencies in generating calls for proposals

Appendix 1: List of acronyms

Acronym	Name
COP21	21st Conference of the Parties, UNFCCC
ABL	Atmospheric Boundary Layer
AeroCom	Aerosol Comparisons between Observations and Models
AIMES	Analysis, Integration, and Modeling of the Earth System, Future Earth
APARC	Atmosphere Processes and their Role in Climate, WCRP
APECS	Association of Polar Early Scientists
C3S	Copernicus Climate Change Service
CCMI	Chemistry Climate Model Initiative
CDR	Carbon Dioxide Removal
CEOS	Committee on Earth Observations and Satellites
CGMS	Coordination Group for Meteorological Satellites
CliC	Climate and Cryosphere, WCRP
CLIVAR	Climate and Ocean Variability, Predictability and Change, WCRP
CMIP	Coupled Model Intercomparison Project , WCRP
CMIP6	CMIP Phase 6
CMIP7	CMIP Phase 7
CNRS	Centre National de la Recherche Scientifique
COP	Conference of Parties, UNFCCC
CORDEX	Coordinated Regional Climate Downscaling Experiment, WCRP
CORE	Coordinated Ocean-ice Reference Experiments
CRF	Climate Research Forum
EBUS	Eastern Boundary Upwelling System
ECR	Early Career Researcher
ECRA	European Climate Research Alliance
EMCR	Early and Mid-Career Researchers
ENSO	El Niño–Southern Oscillation
EPESC	Explaining and Predicting Earth System Change , WCRP
ESA	European Space Agency
ESM	Earth System Model
ESMO	Earth System Modeling and Observations, WCRP
ESGF	Earth System Grid Federation
ESSP	Earth System Science Partnership
FOO	Framework for Ocean Observing
GASS	Global Atmospheric System Studies, GEWEX
GAW	Global Atmosphere Watch, WMO
GCOS	Global Climate Observing System, WMO
GCP	Global Carbon Project

Acronym	Name
GCW	Global Cryosphere Watch , WMO
GDAP	GEWEX Data and Analysis Panel, GEWEX
GEP	Global Extremes Platform, WCRP
GERICS	Climate Service Center Germany
GEWEX	Global Energy and Water Exchanges, WCRP
GFCS	Global Framework for Climate Services, WMO
GHP	GEWEX Hydroclimatology Panel, GEWEX
GOOS	Global Ocean Observing System, WMO
GPEX	Global Precipitation Experiment, WCRP
HiWEATHER	High Impact Weather, WWRP
IACS	International Association of Cryospheric Sciences
IAHS	International Association of Hydrological Sciences
IAI	Inter-American Institute for Global Change Research
IAMAS	International Association of Meteorology and Atmospheric Sciences
IAPSO	International Association for the Physical Sciences of the Oceans
IASC	International Arctic Science Committee
ICPO	International CLIVAR Project Office
ICTP	International Centre for Theoretical Physics
IGAC	International Global Atmospheric Chemistry, Future Earth
IMBeR	Integrated Marine Biosphere Research, Future Earth
IndOOS	Indian Ocean Observing System
INSTANT	INStabilities and Thresholds in ANTarctica, SCAR
IOC-UNESCO	Intergovernmental Oceanographic Commission of UNESCO
IOC-R	Integrated Ocean Carbon Research
IPCC	Intergovernmental Panel on Climate Change
IPO	International Project Office
IPSL	Institut Pierre Simon Laplace
IQuOD	International Quality Controlled Ocean Database
ISC	International Science Council
ISMASS	Ice Sheet Mass Balance and Sea Level, CliC/SCAR/IASC
ISMIP	Ice Sheet Model Intercomparison Project, CliC
IUGG	International Union of Geodesy and Geophysics
JAXA	Japan Aerospace Exploration Agency
JCRF	Joint Climate Research Fund
JPS	Joint Planning Staff
JSC	Joint Scientific Committee, WCRP
KPI	Key Performance Indicator
LTCF	Limited-Term Cross-activity Focused projects, APARC
MCR	My Climate Risk , WCRP

Acronym	Name
MIP	Model Intercomparison Project
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
Obs4MIPs	Observations for Model Intercomparisons Project
OMDP	Ocean Model Development Panel CLIVAR
OMIP	Ocean Model Intercomparison Project
OOPC	Ocean Observation Panel for Climate, GCOS/GOOS/WCRP
ORA-IP	Ocean Reanalysis Intercomparison Project
PAGES	Past Global Changes, Future Earth
PICES	North Pacific Marine Science Organization
RCI	Research on Climate Intervention, WCRP
RIfS	Regional Information for Society, WCRP
RISA	Regional Integrated Sciences and Assessments (RISA)
Risk-KAN	Risk Knowledge Action Network, Future Earth
S2S	Sub-seasonal to Seasonal Prediction Project , WCRP/WWRP
SBSTA	Subsidiary Body for Scientific and Technological Advice, UNFCCC
SCAR	Scientific Committee on Antarctic Research
SCOR	Special Committee on Oceanic Research
SDGs	Sustainable Development Goals
SERA	Societal and Economic Research Applications, WWRP
SLC	Safe Landing Climates, WCRP
SOLAS	Surface Ocean – Lower Atmosphere Study, Future Earth
SPARC	Stratosphere – troposphere Processes and their Role in Climate (previous name of APARC)
SREX	Special Report for Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, IPCC
SRM	Solar Radiation Modification
SSG	Scientific Steering Group
START	System for Analysis, Research and Training
TAOS	Tropical Atlantic Observing System
TIPMIP	Tipping Points Model Intercomparison Project
TOGA	Tropical Ocean - Global Atmosphere Project
ToR	Terms of Reference
TPOS	Tropical Pacific Observing System
UCAR	University Corporation for Atmospheric Research
UNEP	United Nations Environment Programme
UNESCO	United National Educational, Scientific, and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	United States Global Change Research Program

Acronym	Name
VIA	Vulnerability, Impacts, Aadaption
WCC	World Climate Conference
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modeling, ESMO
WGNE	Working Group on Numerical Experimentation, ESMO/WMO Research Board
WGSIP	Working Group on Subseasonal to Interdecadal Prediction, ESMO
WIP	WGCM Infrastructure Panel, ESMO
WMO	World Meteorological Organization xz
WOCE	World Ocean Circulation Experiment
WWRP	World Weather Research Programme, WMO
YESS	Young Earth System Scientists

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