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Digital Earths

1. Description of the Activity

The overall objective of this activity is to carry out research activities that support the establishment of integrated interactive 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. We envisage that such systems can exist at both global and regional scales. We also envisage the existence of interim systems as stepping stones towards full Digital Earths systems.

Digital Earths is founded on an optimal blend of models and observations. The activity will push the co-development of ultra-high-resolution Earth-system modeling and the exploitation of billions of observations with digital technologies from the convergence of novel high-performance computing (HPC), big data and Artificial Intelligence (AI) methodologies. Digital Earths will provide open access to data, methodologies and software. It will create innovation in science and technology in support of the World Climate Research Programme (WCRP) Scientific Objectives (WCRP, 2019).

Digital Earths efforts will be developed through national and international consortia, such as the Destination Earth consortium in Europe. The role of the Digital Earths activities within WCRP is to support such initiatives by providing fundamental science and technology developments. There are three major areas of activity in which the WCRP must play a leading role, which are **global coupled ultra-high-resolution modelling, data assimilation for climate, and regional Digital Earths systems.** These will be supported by a fourth activity on **advanced digital technology.**

A detailed description of these activities as well as proposed first initiatives for each of them are provided in Section 4. The fourth activity of digital technologies, which includes HPC, big data and AI, is not an area of core-expertise in WCRP. However, in order to succeed in the implementation of Digital Earths science it is crucial to be well connected to existing expertise in this space.

The preliminary objectives of Digital Earths are to:

- Establish a global research network with expertise in ultra-high-resolution (kilometer-scale or finer) of the global Earth system and its individual components
- Establish an active research community in data assimilation for climate that builds on the existing numerical weather prediction (NWP) and re-analysis efforts and significantly expands them to fulfil the needs of Digital Earths applications

- Support the establishment of both global and regional Digital Earths demonstration projects across the globe and provide a collaborative network for their development
- Enable the above by optimally exploiting extreme-scale computing and data handling resources through inter-operable software infrastructures

The key features of this Lighthouse Activity are shown in Figure 1. Further details on the themes and their interaction, and proposed activities to meet these objectives are described in Section 4.

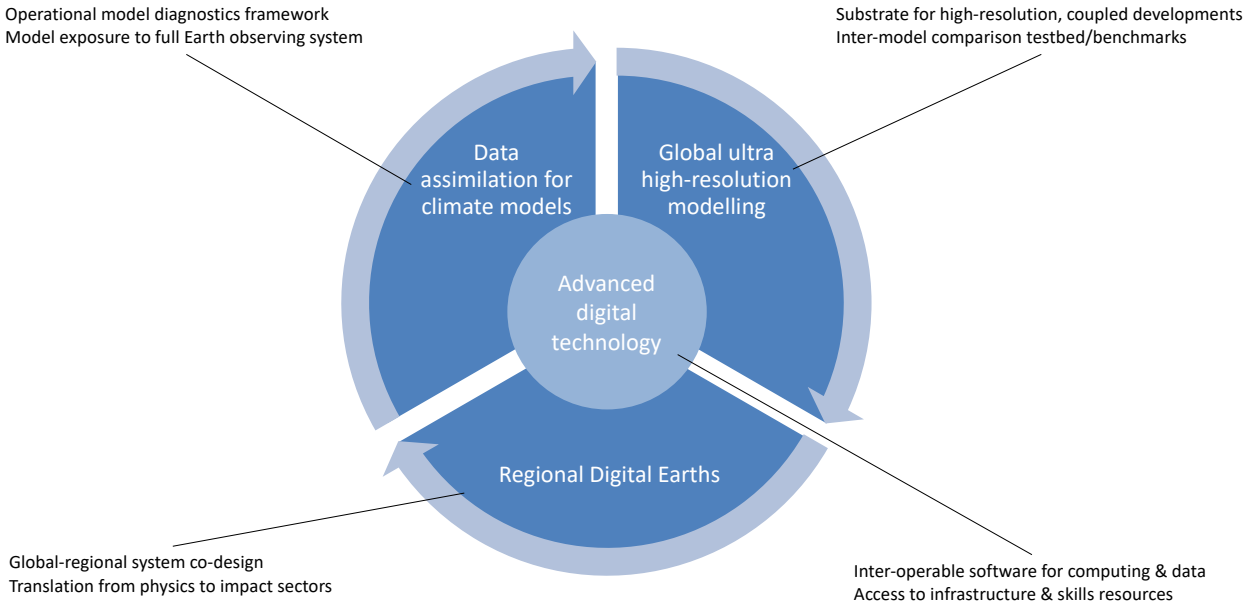

Figure 1: The four themes of the Digital Earths Lighthouse Activity.

2. Relevance to the World Climate Research Programme (WCRP)

Digital Earths addresses the urgent need to provide robust Earth-system simulations and data assimilation systems at the temporal and spatial scales relevant to decision makers, with large ensembles and for many scenarios in a near-continuous fashion. Currently, this need cannot be fulfilled.

There is substantial experience in data assimilation for creating initial conditions in NWP up to seasonal time scales, km-scale modelling in limited area systems, climate monitoring through reanalyses and impact sector activities associated with climate services – most of which are covered by the World Meteorological Organization (WMO) framework through dedicated programmes, working groups and data/information platforms. Digital Earths, however, promises to boost these capabilities all at once, enabled by advanced digital technologies for producing the much-needed upscaling of assimilation and simulation systems and the full integration of societal impact sector components towards a highly interactive system. Through Digital Earths, WCRP can drive the capabilities to develop a new, global storm-resolving model generation, operationalize data assimilation for model diagnostics,

coupling and parametrization optimization, and for societal impact and adaptation/mitigation assessment. Digital Earths will also ensure that digital technologies and electric power resources are invested in an environmentally responsible way, a message that WCRP can easily identify with.

Digital Earths will contribute to all four WCRP Scientific Objectives (WCRP, 2019). The availability of a comprehensive, high-resolution description of the Earth system will provide an unprecedented opportunity for a quantum leap in our understanding of its internal workings (Objective 1). The revolutionary prediction/projection capabilities of Digital Earths will support Objectives 2 and 3 through much advanced prediction systems based on high-resolution ensembles, the integration of climate and Earth-system components in a single modeling (not a single model) framework, a common experimental design, and the enhanced synergy between observations and models. Objective 4 will be supported by the provision and co-production of its results with all relevant sectors of industry and society to enable a step-change in climate-related decision making across the globe.

Digital Earths will deliver a significant upgrade of critical infrastructure elements, namely seamless and unified simulation tools, optimal exploitation of observational information content and characterization of their uncertainties, open access to data, methodologies and software, and extreme-scale computing, big data handling and artificial intelligence methodologies.

3. Partnerships

Given its scale, implementing Digital Earths will require the creation of new multi-national (virtual) institutions as existing partnership bodies will not suffice to deliver the necessary developments at the required pace. WCRP must play a critical role in promoting their establishment. Doing so requires engagement with the following partners:

- The World Weather Research Programme (WWRP) and Global Atmosphere Watch (GAW), national hydro-meteorological services, national climate centres and climate services
- The WCRP sponsors: WMO, the International Science Council (ISC) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.
- The main national funding agencies supporting digital infrastructure development (e.g. European Commission's EuroHPC, US Department of Energy, Japan's MEXT and RIKEN etc.); philanthropic support
- Copernicus in Europe, Earth Cube in the US, International Society on Digital Earth
- HPC and software industry
- Existing weather/climate-computational science efforts (e.g. US Energy Exascale Earth System Model (E3SM), European Centre for Medium-Range Weather Forecasts (ECMWF) Scalability Programme, Centre of Excellence in Simulation of Weather and Climate in Europe (ESiWACE), e-infrastructure of the European Network for Earth System Modeling (IS-ENES))
- Academia (model/data assimilation development, computational science)

- Future Earth

Regarding the opportunities and challenges presented by novel digital technologies, WMO's recently established Research Board has created a temporary international expert team that is presently compiling concept papers on extreme-scale, data handling and the potential of artificial intelligence (here machine learning) for weather and climate prediction. These papers will propose approaches for entering into partnerships with the above communities and to translate technology into benefits for science and services.

Digital Earths sits at the interface between science, technology and services – sectors that have mostly developed independently from one another in the past. The above partnerships need to focus on synergy and coordinated developments at an advanced pace. For example, the optimum benefit of climate data for impact sectors may require assimilation and simulation system/protocol design changes, and digital technology may require a methodological and algorithmic redesign of models and workflows. A more open and interactive software framework needs new approaches for data and software governance throughout prediction systems and with international coordination. WMO (and WCRP in particular) has an opportunity to lead these co-design developments through this partnership approach.

4. Details and Scope of the Activity

Digital Earths has four main themes: global coupled ultra-high-resolution modelling, data assimilation for climate, regional Digital Earths, and advanced digital technologies. Each of these is integral to the success of the Lighthouse Activity and all are interconnected and depend on one another.

a. Global coupled ultra-high-resolution modelling

The overall goal of this part of the activity is to advance global modeling of the Earth system towards 'Digital Earths' that can be used for broad applications of Earth-system science relevant for human communities. Specifically, this will require us to accelerate and advance the development and use of ultra-high-resolution global models (4 → 1 km) for all relevant spheres and to couple them into Earth-system models (ESM) of unprecedented detail. A second important goal of this activity to make Digital Earths the substrate for scientific innovation, thus enabling research activities across all of WCRP and beyond to perform advanced simulations, exploit the full information content of observations, and provide convenient and fast access to massive amounts of diverse data.

A first important step towards achieving these ambitious goals is to establish a community – similar to the CMIP community – dedicated to km-scale global modelling, building on existing efforts in the different spheres and in coupling at km-scale. This requires i) the consultation of all WCRP Core Projects and activities and ii) the establishment of a coordination group. The most logical existing groups within WCRP framework to advance modelling at km-scales are:

- *Atmosphere:* The Global Atmospheric System Studies (GASS) in WCRP's Global Energy and Water Exchanges (GEWEX) Core Project – Early talks have taken place and a plan to integrate the existing DYAMOND[1] efforts into GASS is emerging
- *Land:* The Global Land/Atmosphere System Study (GLASS) in GEWEX – Supported by the GEWEX leadership, working level talks are the next step
- *Ocean:* The Ocean Model Development Panel (OMDP) in WCRP's Climate and Ocean Variability, Predictability and Change (CLIVAR) Core Project – No discussions yet
- *Sea Ice*: WCRP's Climate and Cryosphere (CliC) Core Project – No discussions yet
- *Land Ice:* CLiC – No discussions yet
- *Coupling:* This will require a coordination effort either within the Digital Earths Lighthouse Activity or in the Earth System Modelling and Observations (ESMO) Core Project.

Proposed immediate first steps:

- A global model ultra-high-resolution coupled modelling workshop involving existing efforts (e.g., DYAMOND) with a focus on extending the concept to all spheres and the coupled systems led by the relevant WCRP groups above
- Development of a white paper on feedback from previous work and what is needed for the future.
- Establishment of the km-scale modelling coordination group within the WCRP structure (e.g., a working group on ultra-high-resolution climate models)

Long-term vision:

- A CMIP-scale enterprise in ultra-high-resolution climate modelling supported by a range of projects in the WCRP Core Projects.

b. Data assimilation for climate

Data assimilation methods have been shown to be the optimal approach to exploit the rich and yet incomplete set of observations of the Earth system for a comprehensive and consistent description of the state of the system at any given time. However, almost all data assimilation efforts are targeted at creating initial conditions for prediction with little to no regard given to the fundamental constraints that are critical to climate research, such as energy or water conservation. Furthermore, current data assimilation methodologies have serious limitations (linearity, degrees of freedom, computational costs) that will need to be overcome when including fast processes acting at small scales, when fully interfacing Earth-system components such as atmosphere, oceans, sea ice and land, and when integrating new information beyond the physical system. In short, extending data assimilation to climate prediction/projection in an operational (i.e. regular, with generic methods and operational set of observations) way and approaching the Digital Earths scales at the

[1] DYAMOND - DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains

same time requires nothing less than a paradigm shift in how this methodology is used and how climate models are assessed.

The existing efforts in data assimilation are largely concentrated in NWP centres (global, limited-area) and in some climate modelling centres for initialization of the ocean for seasonal-to-decadal prediction. Apart from the re-analysis community, which with very few exceptions is also represented by NWP centres, there is no discernible community dedicated to data assimilation for climate. Hence, the most important task of the Digital Earths Lighthouse Activity is to create this community by bringing together existing climate, NWP, re-analysis and observational groups to plot a course for this critical, and yet underappreciated, research area.

The groups that need to be involved at an early stage are:

- Climate model development centres
- NWP centres experienced with coupled modelling and model initialization
- WWRP Assimilation and Observing Systems (DAOS)
- The Working Group on Numerical Experimentation (WGNE)
- The Subseasonal-to-Seasonal (S2S) Prediction Project, Seasonal and Decadal prediction groups
- Reanalysis community
- Observations community from all WCRP Core Projects

Proposed Immediate first steps:

- A foundational workshop on Data Assimilation for Climate involving the above communities with the aim to provide a strategy for establishing, growing and institutionalizing this important area of research in WCRP

Long-term vision:

- A high-visibility data-assimilation for climate effort, supported by its own structure and led by WCRP, which integrates across WMO weather and climate activities as well as with the impacts modelling community

c. Regional Digital Earths

While a major focus of the Digital Earths initiative is on supporting the establishment of global ultra-high-resolution systems, there is both a need and opportunity to directly involve and integrate regional efforts. WCRP should aim to establish a global-regional modelling alliance that works closely together in the design and application of Digital Earths systems. There are two separate needs that WCRP activities must address: i) the inclusion of the regions in designing Digital Earths systems and ii) the inclusion of the regions in the application of the results of Digital Earths systems for monitoring and decision making. As they require different approaches and likely include different WCRP communities, they will be described separately acknowledging that there is significant overlap between them.

Regional Digital Earth System development

Regional models and their application for science and simulation have had a long tradition in WCRP (Coordinated Regional Climate Downscaling Experiment (CORDEX), GEWEX Regional Hydroclimate Projects (RHPs), to name but a few examples). Their smaller domains have made them trailblazers for higher resolution. This, combined with the ability to connect to local and regional user communities more easily, puts regional systems in an ideal position to drive some of the development of the science and technology required to build Digital Earths systems. This is a huge opportunity for the WCRP community involved in regional modelling and its application.

As for global climate models, a key challenge, but also opportunity, will be to meaningfully integrate data assimilation into the design of regional Digital Earths systems as well as to extend the system beyond the physical spheres of climate alone. Discussions with the GEWEX community have identified the comprehensive integration of hydrological reservoirs and fluxes (e.g., ground water, streamflow) in a meteorological data assimilation and prediction system at regional scale as an excellent opportunity for a ***Demonstration Project*** that could be organized through GEWEX in collaboration with the wider community.

As with the other activities, an important first step would be to unite the relevant groups and to map out possible pathways, including that for a small number of demonstration projects. Those groups are:

- CORDEX
- GEWEX RHPs
- WCRP Regional Information for Society (RIfS) Core Project
- Other lighthouse activities
- Weather services with regional data assimilation capabilities
- National Climate Services
- Developers and providers of community regional modelling systems (e.g., the Weather Research and Forecasting (WRF) model)
- Existing efforts in assimilation and monitoring beyond the meteorology, such as the United States Geological Survey (USGS) National Water-Quality Assessment (NAWQA) or the current Hydro-terrestrial Earth Systems Testbed (others need to be identified)

Immediate steps:

- Organize and commission one or more demonstration projects to be carried out over the next 2-5 years – GEWEX to lead one on regional water reservoirs and flows
- Organize a workshop dedicated to the **development** of regional Digital Earths systems

Digital Earths Systems application in the regions

A second important engagement with WCRPs regional efforts should occur through projects that aim at applying results of global as well as regional Digital Earths systems to climate decision making. Early discussions have revealed two opportunities: i) the development of a standardized but flexible system for regional climate impact assessment based on Digital Earths and ii) the development of capabilities for **e**nhanced regional climate monitoring with a special focus on developing regions.

Both activities technically require Digital Earths systems to exist first but could conceivably start immediately using existing information from global and regional analyses and re-analyses in their development phase.

Immediate steps:

- Create a WCRP-wide Task Force that identifies opportunities for the application of Digital Earths outputs and propose demonstration projects for their potential utility.

Long-term vision:

- A global-regional modeling alliance as a core activity of the Earth System Modelling and Observations (ESMO) Core Project

A key goal in the early establishment of Digital Earths science in the regions, both in the development and application of systems, is the full integration of the world-wide pool of talent in the scientific, technological and community integration challenges ahead. Of equal importance is the coordination of global and regional modeling activities together in a global-regional model alliance that sets a joint agenda for future development.

d. Advanced Digital Technologies

Digital technologies, mostly related to high-performance computing and big data handling, are increasingly posing serious upper limits on the scale and complexity at which climate model ensembles can be run and model output can be post-processed, disseminated and stored. Present prediction system codes are more than a decade behind the potential that present and emerging processor, memory and network technology offer leading to highly inefficient performance and lack of scope for upgrading model resolution, complexity and flexible use. Apart from a lack of simulation and data throughput this also creates poor acquisition and operation value-for-money ratios for computing infrastructure investments.

While these shortcomings have been recognized and documented for a while in weather and climate science, the complexity of the science – computational science problems and the large diversity of actors/developers/operators has not yet led to generic and sustainable solutions the wider community can contribute to and benefit from. The recent reemergence of machine learning (also known as AI) powered by processor technology developed for commercial applications has raised awareness to

this domain though and stimulated both funding and rethinking of scientific code development paradigms more widely.

The WMO Research Board's scoping papers on extreme-scale computing and data handling and on the use of AI provide the most comprehensive overview of the state of the current thinking and existing activities in this area. The WCRP Digital Earths Lighthouse Activity can be the host of some of the coordination activities proposed by the scoping papers, in particular directed at (i) access to advanced technology HPC infrastructures, (ii) access to highly specialized knowledge and skills at the interface Earth-system – computational science, (iii) access to data resources, storage and analysis tools, (iv) creation of generic AI based tools and training datasets, particularly targeted at impact sectors for which the translation of data to information to insights to decisions is key.

Of utmost importance is the generation of generic software infrastructures that are not model, simulation or application specific, that scale and deliver sufficient computing and data throughput to justify infrastructure investments.

The groups that need to be involved at an early stage are:

- WMO Research Board scoping paper expert teams; WGNE
- HPC vendors and software developers; software governance entities
- Computational science teams in academia (and existing ones in prediction centres)
- Operational NWP and climate centres
- HPC centres providing leading technology
- National/international organizations in charge of federations for computing, data handling

Proposed Immediate first steps:

- A workshop engaging both public and private sectors to:
    - Identify solutions for generic software development
    - Provide a roadmap for complementary, internationally coordinated delivery
    - Enable HPC access and software and data governance mechanisms fulfilling the needs for climate prediction/projection in the future
    - Take along impact sectors and policy making
- A WMO policy action for how to institutionalize this topic through WMO members and the private sector

Long-term vision:

- A WMO-wide digital technology effort in which the WCRP is a key player

5. Timeline

We envisage that the immediate first steps identified for each activity area in Section 4 will be implemented within the first 12-18 months of the Digital Earths program. We plan three workshops in 2022 on global coupled ultra-high-resolution modelling, data assimilation, and regional Digital Earths.

We envisage some of the early activities to lead to the establishment of new projects within and across the existing WCRP Core Projects. Each of these projects will likely take several years to complete.

We envisage the Digital Earths activity to be completed when its components have been fully integrated into the operations of the WCRP Core Projects. Ideally this would happen within 3-5 years.

6. Requirements

A key gap in the current planning has been our inability to connect with the relevant people/organizations due to COVID-19 restrictions on travel. Formal online meetings, while undoubtedly useful, have not been able to replace the ability to interact broadly and deeply. Given very wide and deep reach across many communities within and beyond the WCRP, an early requirement for the success of this Lighthouse Activity is to organize a face-to-face meeting of the key groups identified in this document at the earliest opportunity.

7. Budget for 2022

Workshop costs largely – 3 major workshops (models, data assimilation, regional), 50-80 participants each. Assuming that these will be in person workshops, we allocate CHF 15,000 per workshop for logistics and travel assistance, in addition to support from selected host organizations.

8. Deliverables and outcomes

3 years from now: There will be several global and regional Digital Earths systems under development across the world, all of which are actively participating in WCRP Digital Earths activities.

5 years from now: Research on the science and technology of Digital Earths systems is a major activity of the Earth System Modelling and Observations (ESMO) Core Project within WCRP.

10 years from now: Digital Earths systems developed with the support of WCRP science are delivering open-access actionable climate information for the globe in a fully shared framework.

9. Communication and capacity exchange

There are multiple levels of communication and capacity exchange required for this activity. The delivery of regional and global Digital Earths will require a multi-stakeholder approach, which means that communication and co-design are intrinsic to the development process. Encouraging stakeholders, with different and potentially competing objectives, to work together for the benefit of society will be one of the challenges of the activity.

New and innovative approaches will be needed to develop Digital Earths capabilities. It is important that incentives are available to encourage this development across the world and attract the best talent. Together with the WCRP Academy, Digital Earths will work to ensure that training for climate scientists on how to contribute to and use Digital Earths systems is available.

We propose the establishment of a Digital Earths Forum, which exploits the full spectrum of communication and interaction tools. Initially these would be websites, discussion fora and social media channels built around our major activities.

We envisage that the WCRP Academy Lighthouse Activity can and should play a key role in the important capacity exchange activities.

10. Risks

The main risk for the success of the activity is a lack of buy-in from the community. The Lighthouse Activity, by design, confronts many of our traditional approaches to climate simulation and information systems. Mitigation against this risk requires good communication and opportunities for the whole WCRP family to discuss this (at the dinner table). Virtual meetings are not suitable for such a discussion.

While COVID-19 restrictions limit our ability to meet, we need to lower the bar on speed and depth of the design and implementation of activities. This carries the risk of a loss of enthusiasm by the community. Mitigating this risk requires the clear and realistic setting of goals and their communication.

11. Authors

Name	Organization	Country	Rep*	Email Address
Christian Jakob (Co-chair)	Monash University	Australia		christian.jakob@monash.edu
Peter Bauer (Co-chair)	European Centre for Medium-Range Weather Forecasts	UK		Peter.Bauer@ecmwf.int
Andreas Prein	National Center for Atmospheric Research (NCAR)	USA	GE	prein@ucar.edu
Andrew Gettelman	National Center for Atmospheric Research (NCAR)	USA	MD	andrew@ucar.edu

Aneesh Subramanian	University of Colorado Boulder	India/US	CR	aneeshcs@colorado.edu
Bryan Lawrence	National Centre for Atmospheric Science (NCAS), University of Reading	UK		b.n.lawrence@reading.ac.uk
Camille Lique	Laboratoire d'Océanographie Physique et Spatiale (LOPS)	France	CL	camille.lique@ifremer.fr
Chihiro Kodama	Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Japan	SP	kodamac@jamstec.go.jp
Claas Teichmann	Climate Service Center Germany (GERICS)	Germany	CX	Claas.Teichmann@hzg.de
Dai Yamazaki	University of Tokyo	Japan		yamadai@rainbow.iis.u-tokyo.ac.jp
Daniel Klocke	Max Planck Institute for Meteorology (MPI-M)	Germany	GE	daniel.klocke@mpimet.mpg.de
Helene Seroussi	Jet Propulsion Laboratory (JPL), California Institute of Technology	USA	CL	helene.seroussi@jpl.nasa.gov
Mark Govett	Advanced Technologies Division at the National Oceanic & Atmospheric Administration (NOAA)	USA		mark.w.govett@noaa.gov
Martin Visbeck	GEOMAR Helmholtz Centre for Ocean Research Kiel	Germany	JSC	mvisbeck@geomar.de
Michael Morgan	University of Wisconsin – Madison	USA	WWRP	mcmorgan@wisc.edu
Pascale Braconnot	Laboratory for Climate and Environmental Sciences (LSCE), Institut Pierre-Simon Laplace (IPSL)	France	JSC	Pascale.braconnot@lsce.ipsl.fr
Peter Dueben	European Centre for Medium-Range Weather Forecasts (ECMWF)	UK		peter.dueben@ecmwf.int
Pier Luigi Vidale	University of Reading	UK	MD	p.l.vidale@reading.ac.uk
Svetlana Jevrejeva	Centre for Climate Research Singapore (CCRS)	Singapore	CR	Svetlana.jevrejeva@gmail.com

WCRP Support: wcrp@wmo.int
Narelle van der Wel: nvanderwel@wmo.int
Nico Caltabiano: avazcaltabiano@wmo.int
Wenchao Cao: wcao@wmo.int

* Representative:
CL WCRP Climate and Cryosphere Project (CliC)
CR WCRP Climate and Ocean Variability, Predictability and Change (CLIVAR)
CX WCRP Coordinated Regional Climate Downscaling Experiment (CORDEX) (Regional Climate Information for Societies)
GE WCRP Global Energy and Water Exchanges (GEWEX)
JSC WCRP Joint Scientific Committee

MD Combined WCRP Modelling and Data Core Activities (Earth System Modelling and Observational Capabilities)
SP WCRP Stratosphere-troposphere Processes And their Role in Climate (SPARC)

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