WCRP High-level Science Questions and Flagship Workshop

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This report was authored by participants of the WCRP High-level Science Questions and Flagship Workshop: Detlef Stammer, Helen Cleugh, Lisa Alexander, Magdelena Balmaseda, Peter Bauer, Jason Box, Pascale Braconnot, Guy Brasseur, Greg Carmichael, Jens Hesselbjerg Christensen, Francisco Doblas-Reyes, Pierre Friedlingstein, Neil Harris, Gabi Hegerl, Daniela Jacob, Christian Jakob, Masahide Kimoto, Mojib Latif, Jochem Marotzke, Michael Morgan, Jan Polcher, Ted Shepherd, Doug Smith, Michael Sparrow, Bjorn Stevens, Rowan Sutton, Susann Tegtmeier, Martin Visbeck, Frederic Vitart, Nils Wedi, and Narelle van der Wel. It reflects discussions during and outcomes of the workshop.

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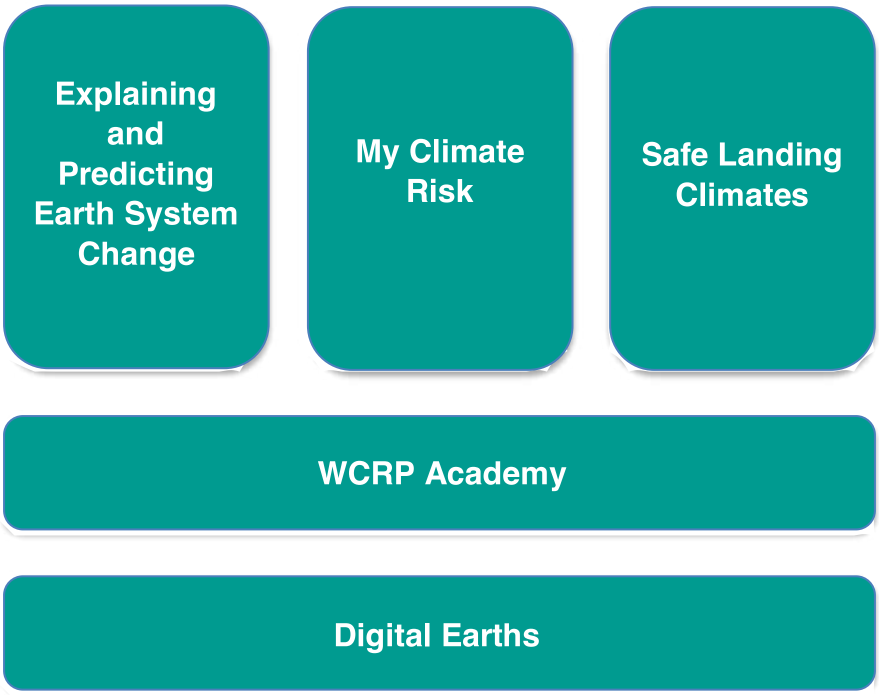
Participants of the WCRP High-level Science Questions and Flagship Workshop. *(First row from left) Pascale Braconnot, Magdelena Balmaseda, Masahide Kimoto, Gabi Hegerl, Lisa Alexander, Helen Cleugh, Detlef Stammer, Mojib Latif, (second row from left) Narelle van der Wel, Susann Tegtmeier, Christian Jakob, Jason Box, Daniela Jacob, Jan Polcher, Jens Hesselbjerg Christensen, Guy Brasseur, (third row from left) Mike Sparrow, Jochem Marotzke, Pierre Friedlingstein, Ted Shepherd, Nils Wedi, (last row from left) Greg Carmichael, Frederic Vitart, Neil Harris, Doug Smith, Rowan Sutton, Michael Morgan, Bjorn Stevens, Peter Bauer. Not present at the time the photo was taken: Francisco Doblas-Reyes and Martin Visbeck.*

Executive Summary

The World Climate Research Programme (WCRP) convened the WCRP High-level Science Questions and Flagship Workshop in Hamburg, Germany, from 24 – 26 February 2020.

The workshop follows the path forward that was developed and agreed on by the WCRP community at the Implementation and Transition Planning Workshop held in Geneva in May 2019. This path included prioritizing the WCRP science that will enable rapid progress towards providing actionable and relevant climate information. Specifically, a task of the Hamburg Workshop was to identify pan-WCRP "Lighthouse Activities" that need to be pursued to make critical near-term progress towards meeting WCRP's Vision, Mission and four Scientific Objectives, outlined in the WCRP Strategic Plan 2019 – 2028. In this respect, the workshop built on previous community brainstorming and consultation activities (e.g. the WCRP Town Halls held at the American Geophysical Union (AGU) Fall Meeting 2019 as well as discussions led within WCRP).

An outcome of the workshop was five proposed Lighthouse Activities (below) that go beyond the capacity of an individual agency or nation and, thus, require the international coordination of climate science that WCRP is uniquely positioned to facilitate.



It is expected that the five proposed Lighthouse Activities outlined in this report will provide high-level guidance to the implementation of the WCRP Strategy, especially to prioritize and focus the very broad Scientific Objectives in the WCRP Strategic Plan and identify the key scientific achievements and outcomes that are required by WCRP to ensure climate science is meeting societal needs.

The next steps in this process involve further consultation with the community to discuss and refine these proposed activities; and to formulate the key programme elements and structures needed to carry them out and, thus, successfully achieve WCRP's strategic objectives.

Pursuing those Lighthouse Activities will empower WCRP, over the next decade and beyond, to provide scientific outcomes that are critical to support emergent societal needs for robust and actionable regional to local climate information. Delivery of robust and consistent regional climate information to stakeholders is needed to inform, for example, the implementation of the Sustainable Development Goals, disaster risk reduction, and climate adaptation, mitigation and intervention strategies. In recognition of this need, WCRP identifies the following Implementation Priorities:

1. ***Foster and deliver the scientific advances and future technologies required to:***

    - *Advance understanding of the multi-scale dynamics of Earth's climate system*
    - *Quantify climate risks and opportunities*

2. ***Develop new institutional and scientific approaches required to:***

    - *Co-produce cross-disciplinary regional to local climate information for decision support and adaptation*
    - *Inform and evaluate mitigation strategies*

Contents

1. Introduction

The World Climate Research Programme (WCRP) is undertaking a series of workshops in 2020 and 2021 to engage the community in guiding the implementation of the WCRP Strategic Plan 2019 – 2028 (WCRP JSC, 2019).

The first of these, the WCRP High-level Science Questions and Flagship Workshop, was held in Hamburg, Germany, from 24 – 26 February 2020. It was hosted and sponsored by the Excellence Cluster of Climate, Climatic Change and Society (CLICCS), Universität Hamburg, and its partners. The workshop was organized to determine the major steps that need to be taken by WCRP to make progress towards reaching the Mission and Scientific Objectives outlined in the WCRP Strategic Plan and to think about what internationally coordinated activities and/or experiments would be required to reach them. The workshop builds on previous community brainstorming and consultation activities (e.g. the WCRP Town Halls held at the American Geophysical Union (AGU) Fall Meeting 2019 as well as discussions led within WCRP).

The workshop was attended by 31 scientific participants, including representatives of the WCRP community, key partners and two members of the WCRP Joint Planning Staff (JPS). The full agenda, participant list and input provided by the community in advance of the workshop are given in the annexes of this report.

This report provides a summary and synthesis of the outcomes achieved during the three-day workshop. These outcomes will feed into further community consultation and an Elements and Structure Workshop, charged with determining the future elements and structure of WCRP.[1]

2. Background

Society faces challenges that require climate scientists to develop new scientific knowledge and partnerships in developing climate and climate risk information, to exploit emerging observational and computational technologies, to expand scientific capacities and collaborations across the globe, and to improve the cost-effectiveness of future investments in support of resilience, and mitigation of and adaptation to a changing climate (including climate variability and climate intervention or geoengineering).

To meet these challenges and opportunities, and in response to a 2017 WCRP Review on behalf of its sponsors, WCRP developed a new strategy to provide the framework to guide and organize this effort. The WCRP Strategic Plan 2019–2028 was approved in 2019 and the WCRP Joint Scientific Committee (JSC) then commenced the process of implementing it. The implementation planning began with an WCRP Implementation and Transition Meeting and dedicated discussions at the 40th Session of the WCRP JSC, both in May 2019. It was decided as part of these discussions that the implementation of the Strategic Plan would have two phases. Phase I, lasting from May 2019 until April 2020, would address the scientific basis for the future WCRP, including science priorities and the infrastructure, elements and structure needed to deliver the Mission and Scientific Objectives of the Strategic Plan. Phase II, from April 2020 to April 2021, would develop the governance and financial model of the new WCRP and put the science basis into action.

[1] The Elements and Structure Workshop was scheduled to be held in March 2020 in Washington, D.C., but due to the Coronavirus Disease (COVID-19) that became a pandemic in early 2020 this workshop was cancelled and will be shifted to a later, but at the time of writing unspecified, date.

To begin Phase I, task teams were formed to make recommendations to the implementation planning in the areas of regional climate activities and information, data, and modeling. In December 2019, there was extensive consultation and discussions on the future of WCRP at the WCRP Climate Science Week, held in conjunction with the AGU Fall Meeting and marking WCRP's 40th anniversary.

3. Workshop Opening and Purpose

The workshop opened with a welcome from Detlef Stammer, Chair of the WCRP JSC and also Chair of the Excellence Cluster CLICCS of Universität Hamburg and its partners. Detlef gave an overview of CLICCS and discussed the concept of the Hamburg Climate Futures Outlook.

Detlef then provided participants with the background to and context of the workshop. Specifically, he outlined the general goal of the workshop as being to identify:

- Flagship Objectives
- Lighthouse Activities

Detlef explained in more detail what was meant by "Flagship Objectives", which were described as high-level WCRP implementation priorities required by the end of the next decade. These would have the same significance as the two past overarching objectives of WCRP that essentially guided all past WCRP research efforts: "to determine the predictability of climate"; and "to determine the effect of human activities on climate".

After the workshop, the JSC Chairs and Officers refined this thinking and definition of Flagship Objectives further. As a result, these are now defined and referred to as "Implementation Priorities," rather than Flagship Objectives, and are outlined in Section 6.

WCRP "Lighthouse Activities," on the other hand, were defined as the major activities that need to be pursued by the international community to make critical near-term progress towards meeting WCRP's Vision, Mission and four Scientific Objectives, as outlined in the WCRP Strategic Plan. Lighthouse Activities are major experiments, high-visibility projects or infrastructure building blocks that extend beyond the capacity of an individual agency or nation and that require international coordination to be achieved. These Lighthouse Activities would be supported directly or indirectly by all WCRP projects and efforts.

Detlef outlined the progress made on implementation planning during and since the WCRP Implementation and Transition Meeting and the 40th Session of the JSC in May 2019. He stressed that the outcomes of the discussions at this workshop will feed into further consultation and WCRP Strategic Plan implementation planning.

Finally, Detlef provided input from two commentaries: *Climate research must sharpen its view* (Marotzke et al., 2017) and *Science Directions in a Post COP21 World of Transient Climate Change: Enabling Regional to Local Predictions in Support of Reliable Climate Information* (Stammer et al., 2018), which set the scene for discussions.

Helen Cleugh, Vice-Chair of the WCRP JSC, set out the specific goals of the workshop, which were to discuss:

- What are the one to three major research objectives (Flagship Objectives) that need to be undertaken by WCRP to fundamentally advance climate science?
- What central WCRP Lighthouse Activities/Experiments need to be organized to make progress toward reaching the new WCRP objectives in support of society?

Helen explained that we need to identify WCRP developments/activities that can revolutionize our insight into the climate system and provide the underpinning scientific advances that contribute to solving the many societal challenges ahead of us. This might be an experiment that needs to be performed jointly by the international community and that otherwise could not be achieved by individual nations, or a large infrastructure project that could transform scientific progress.

Helen referred to the Conceptual Framework (Figure 1; WCRP, 2019) developed at the WCRP Implementation and Transition Meeting in May 2019 to give participants an idea of where the Lighthouse Activities would sit conceptually. She also gave an overview of the outcomes of the WCRP Town Halls and the Union Session that were part of the WCRP Climate Science Week at the AGU Fall Meeting 2019.

It was noted that developing countries were not represented at the workshop. Broader representation and input will be a priority for the wider consultation process moving forward. Helen stated that "being here today is a great responsibility and a privilege. We need you to bring the rest of the community, including countries not represented here, into the thinking."

4. High-level Science Questions

The workshop started by identifying high-level science questions for WCRP. The aim was for participants to discuss the societally relevant questions now facing WCRP and identify what new and novel research is required to address those needs. Knowledge gaps and limitations to advancing climate science were also discussed. Some of the general points raised in relation to the future WCRP science direction were that the key science questions should:

- Be engaging and be able to be communicated to a wide audience
- Reflect the sense of urgency society faces
- Prioritize addressing and communicating key science gaps and uncertainty
- Not simply repackage what the WCRP science community has been doing in the past but make a break with the past with a bold proposal for something new
- Be of benefit to developing countries
- Be driven by societal needs, but not forget the importance of fundamental science and potential surprises in the climate system

Proceedings began with presentations by participants on science questions and knowledge gaps.

These ideas presented, and the ensuing discussions, provided the scientific input into the formulation of the Lighthouse Activity proposals, and proposed Implementation Priorities.

4.1. Science Questions and Knowledge Gaps

1. WCRP: Questions for the next ten years, Guy Brasseur

Guy Brasseur began by explaining that we are living in a time where our societal and political contexts are changing. Climate change is having earlier than expected impacts, especially in weather extremes, and the decision of reducing emissions is no longer rooted in a lack of knowledge, but actually in the political process. The Paris Agreement would not have happened without essential input from climate science, showing the clear role of WCRP in providing scientific knowledge. But scientific knowledge is only one input among many to the decision-making process across many sectors, including the economic sector. Many questions are posed by these sectors that require climate knowledge and information, including improving seasonal to decadal prediction of weather and the hydrological cycle and providing more information at the regional scale.

Now, after COP21, several scientific questions remain open: feedbacks between biogeochemical and climate systems; feedbacks between the hydrological and climate systems; future storage of carbon by the ocean and the continental biosphere; and the irreversibility of climate change.

Guy proposed the following questions to support the ongoing political process:

1. How sensitive is climate to greenhouse gas emissions, and which emissions are compatible with the Paris Agreement targets?
2. How can we better manage the effects of climate variability and short-term changes?
3. What will be the consequences of a (plausible) warming larger than the Paris Agreement targets (3, 5 or 7°C)?

In terms of the WCRP Strategic Plan this would mean (1) enabling an integrated and fundamental understanding of the multi-scale physical and biogeochemical processes that determine the evolution of climate and hence of the socioeconomic system; (2) pushing the frontiers of predictions for sub-seasonal to decadal timescales across the different components of the climate/Earth system at the global and regional scales; and (3) facilitating the development of a new generation of coupled Earth system models that explicitly represent global storms, deep convection, ocean eddies and land-atmosphere interactions (1 km scale) and that provides information with reliable regional precision.

Guy asked whether WCRP will support the development of solutions to the climate crisis, by providing integrated information at the regional and even local scale, by engaging with different communities towards integrated solutions, by linking with other research programs, and by sharing decision-relevant information and knowledge in a two-way dialogue. He stressed that we should show how climate science is an intellectually fascinating topic, rather than just a solution-based science. The coming decade will see an evolution towards open- and citizen-science in most disciplines. WCRP must respond to this evolution, which will allow citizens to become actors in implementing solutions to the climate crisis.

Finally, Guy proposed 2028 as an International Earth System Year, with intensive observational and modeling activities to investigate the complexity of planetary dynamics.

Discussion:
Ted Shepherd began the discussion by stating that there is little funding for fundamental science that does not have societal relevance, and that fascinating science and socially relevant science are not mutually exclusive - some topics can be both. Gabi Hegerl noted that in the future there will be regions that will be uninhabitable and that this is important – both intellectually and socially.

Bjorn Stevens brought in the need for a technological vision, as new technology such as artificial intelligence, autonomous sensing and high-performance computing are coming, and this will bring new allies. Christian Jakob liked the idea of a 2028 Earth System Year. He would push that to be able to describe the Earth system at any point in time. Jan Polcher extended that further to include humans, such as how forest management affects wildfires. This would require a jump in our understanding and in our models. Daniela Jacob supported this with a second example of food production, explaining that we currently miss the feedback links of human decisions. Jason Box highlighted that we need to also consider non-anthropogenic life in the discussion.

Detlef asked whether WCRP could develop a multi-scale information system that could deliver a real-time model of the Earth? Helen liked the idea but wondered how to frame it to receive financial support. Guy reiterated his point about bringing back fascination, in the same way that centers like CERN are driven by fascination. Jochem Marotzke was skeptical that an Earth System Year would have sufficient impact, as, since the International Geophysical Year, no other year has had the same galvanizing impact. There was also concern that developing a digital twin of the Earth by 2028 does not deal with the urgency of the climate situation that we face now. Christian emphasized the need to communicate what we do not know, as CERN does. Daniela also supported the need to be driven by urgency, not by just selling WCRP's vision in a different way.

2. How much confidence can we have in our climate models, Mojib Latif

Mojib Latif recalled that current global climate model bias errors are unacceptable. Referring to the previous discussion of building a digital twin, he warned that we should not go ahead if these biases remain. He outlined several ways that we can correct model biases, including enhanced resolution (we are making some progress but better data are needed, especially in the ocean), multi-decadal to centennial variability and a better understanding of Earth system dynamics (such as why CO_2 changes in the atmosphere - we can't understand the signals of the past well enough). He recommends that we entrain new communities, ensure that we have links with the paleoclimate community and that we include deep ocean observations.

Discussion:
Pascale Braconnot pointed out that we tend to think of impacts and suggested that a better focus could be on the coupled system. Jens Hesselbjerg Christensen asked how we can better communicate biases and asked what this means for our science. Magdelena Balmaseda pointed out that while we need to reduce biases, the problem is that we do not know which ones to reduce. Artificial intelligence can help, but we have to work on the methodology of how to provide good information. We need diverse scenarios, including human activities. We can provide information that is actionable and useful, but at the same time improve models.

3. Thoughts on prioritizing future science in WCRP, Neil Harris

Neil Harris presented his thoughts that were influenced by discussions held during the last Stratosphere-troposphere Processes And their Role in Climate (SPARC) Core Project Scientific Steering Group (SSG) meeting. He framed WCRP's priorities as nurturing and encouraging scientists interested in fundamental climate science for its own sake on one side, but also an urgent societal need for information on how to mitigate and adapt to climate change on the other – asking whether these two points are compatible.

He presented three potential goals or objectives:

1. Improved understanding of the factors affecting climate forcers to provide a firm basis for decision-making on the mitigation of climate change;

2. Improved predictions on subseasonal to decadal time scales to provide longer advance warnings and relevant climate science input for decision-making on adaptation; and
3. Better understanding of the response of the climate system to climate change to provide robust advice on adapting to climate change in the longer term.

For each of these, he proposed a number of areas of climate research WCRP could undertake. At the last SPARC SSG there was "support for a major interpretative initiative to trawl though existing datasets from models and observations," as this could produce the quickest results and could build a global community of data users in all countries, developing tools using latest techniques. His concluding message was to go for what the technology pushes us towards rather than what we are currently capable of.

Discussion:
Pierre Friedlingstein raised the issue that getting to zero emissions is about technology, not science. Neil explained that there are science inputs into these questions. He preferred Guy's formulation of the question, as climate intervention has to be included because it changes the forcing. It was agreed that the climate intervention question is important - not advocating for it, but to understand the impacts.

4. Knowledge gaps in regional climate change information, Ted Shepherd

Ted Shepherd discussed the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) narrative, where reliability is sometimes achieved at the price of informativeness. He highlighted how language is used to express likelihood in a way that can differ from common usage, such as "unlikely" being used to dismiss possibility. He explained how climate science emphasizes avoidance of type 1 errors - where something is measured as true but is in reality false. There is no such thing as value-free climate science.

Ted looked at outputs of the Coupled Model Intercomparison Project (CMIP) and asked why so many resources are put into the project when there have been no substantial changes to the output between the third and fifth phases. He pointed out that there are knowledge gaps in our understanding of the drivers of regional change, regional atmospheric circulation and local climate. He gave the example of the urban heat island effect as a local climate effect that is not well studied. He asked how we bring meaning back into knowledge. Can we talk about the implications of human decisions? We need to consider "soft values" in addition to "hard facts."

Discussion:
Daniela noted that there is a whole community looking at the urban heat island effect. Christian expressed his opinion that it is a question of priorities: climate circulation has a higher research priority than the urban heat island effect. Jens pointed out that they looked at regional information related to circulation for Working Group I (WG I) of the AR5, but the literature was just not there. Magdalena questioned why we have so many type 1 errors and how we can rectify this.

5. Scientific gaps and topics to be considered by WCRP in preparation of IPCC assessment, Pascale Braconnot

Pascale presented a number of key points discussed with Valerie Masson-Delmotte (Co-chair, IPCC WG I).

The next IPCC special report in the Seventh Assessment Report (AR7) will be on cities and climate change. Of direct relevance to WCRP is a need for an international and open-access observational framework for collecting key climate and socio-economic metrics at the city scale.

Also of relevance is improving modeling capabilities, which is key to producing higher resolution data, predicting near term climate futures, and producing models that are customizable to specific cities. It is important that we "humanize" climate models, improve the representation of human activities and land surface processes (cities, irrigation, crop types) in models and take a systems approach to explore relevant and fit for purpose solutions for climate change mitigation and adaptation strategies.

A number of needs for future assessment emerged, reflecting that we are currently limited in our ability to fully assess key scientific questions in an integrative way that accounts for the interactions between different factors and/or spatio-temporal time scales. This included (1) better constraining the interplay between energy, water and carbon fluxes at the land surface; (2) climate and biodiversity; (3) climate information for risk managers and co-design to help the use of climate information by risk managers. Specifically for WG I, there is a need to know more about the Austral ocean (slow variability modes and the coupling between sea-ice, ice sheets, ocean and atmosphere) and the linkages between global and regional climate modeling (model biases and uncertainty/confidence of projections; improved consistency of approaches/questions; methodologies; and improved coordination). There are currently limitations in observations, modeling, forcing and the role of variability. The presentation concluded with a call for an Earth system view, including the human effect, and a call for improved global/regional/local and natural/anthropogenic interactions. Pascale ended by stating that there are three challenges to solve (1) process understanding of the Earth system; (2) predictability and prediction; and (3) integration.

Discussion:
There was a general discussion as to how many of these questions are not new and that, in some areas, we are asking the same questions as we were asking 20 years ago. Jochem pointed out that many of the knowledge gap sections in the upcoming IPCC assessment are not yet mature and are still under construction. Daniela noted that for AR5 Working Group II (WG II) there was a knowledge gap section, and there was a discussion within the European Commission about whether to use it to think about funding. We need to think about how these topics have advanced in the last 20 years. If they have not, then why not. Guy gave the example of climate sensitivity – after 40 years it is not solved. How would WCRP address the problem?

It was noted that addressing hard to solve problems was the purpose of the WCRP Grand Challenges. Addressing climate sensitivity was discussed in relation to CMIP modeling. Bjorn pointed out that models are a tool to be used alongside other tools. We should use many types of assessment and then look at them alongside each other. There was a general discussion about climate sensitivity and single versus multiple lines of evidence.

5. Lighthouse Activities

Participants then made presentations that provided examples of Lighthouse Activities, before breaking into breakout groups to discuss potential WCRP Lighthouse Activities.

5.1. Examples of WCRP Lighthouse Activities

1. Extreme Earth, Bjorn Stevens

Bjorn began his presentation using the example of the collapse of the Amazon ecosystem and the role played by fire and land management. The hydrological cycle is also very important, but this is not simulated well by the current generation of global climate models. If we go to a 2.5 km resolution model, it allows us to model some features much better, such as the hydrological cycle and storms.

Bjorn then presented the idea of Extreme Earth (Figure 1), a project that co-designs science (extreme weather, Earth system trajectories, surprises) with technology (extreme computing, extreme data, extreme information systems) and is linked to society (critical infrastructure, hydrology and water, energy, food and agriculture, health, disaster management). This would fuse observational information with models and open up the models as information systems that people can play around with (also application communities). This is also known as a digital twin or digital replica and is currently being discussed as part of the European Commission's strategy for shaping Europe's digital future ('Destination Earth', starting 2021).

In terms of WCRP, this could be a handful of multinational (continental scale) centers designed to co-develop digital twins of the Earth system capable of and applied to a quantification of Earth system trajectories. Focusing efforts in such centers will be necessary for them to benefit from and stimulate technological developments (in computing, information systems, sensing and assimilation), and it will allow them to advance and expand links to applications and concentrate the critical mass necessary to address questions related to the fate of the Earth system. Different centers would share common elements (concept of a digital twin), but emphasize specific knowledge gaps, using the narrative of surprises and their regional context, e.g.: collapse of tropical-terrestrial eco-systems (South/Central America); land ice, including permafrost and links to carbon cycle (Europe); marine eco-systems (Asia/Pacific); and aridity and links to human habitability (Asia/Africa).

Discussion:
Martin Visbeck began by asking how WCRP, as a climate programme, would contribute to this effort, which is typically seen as an observing enterprise that would include citizen science. Bjorn responded that data coherence requires a model and that there is a narrative of surprises – what are the big risks and what is the probability of these risks happening?

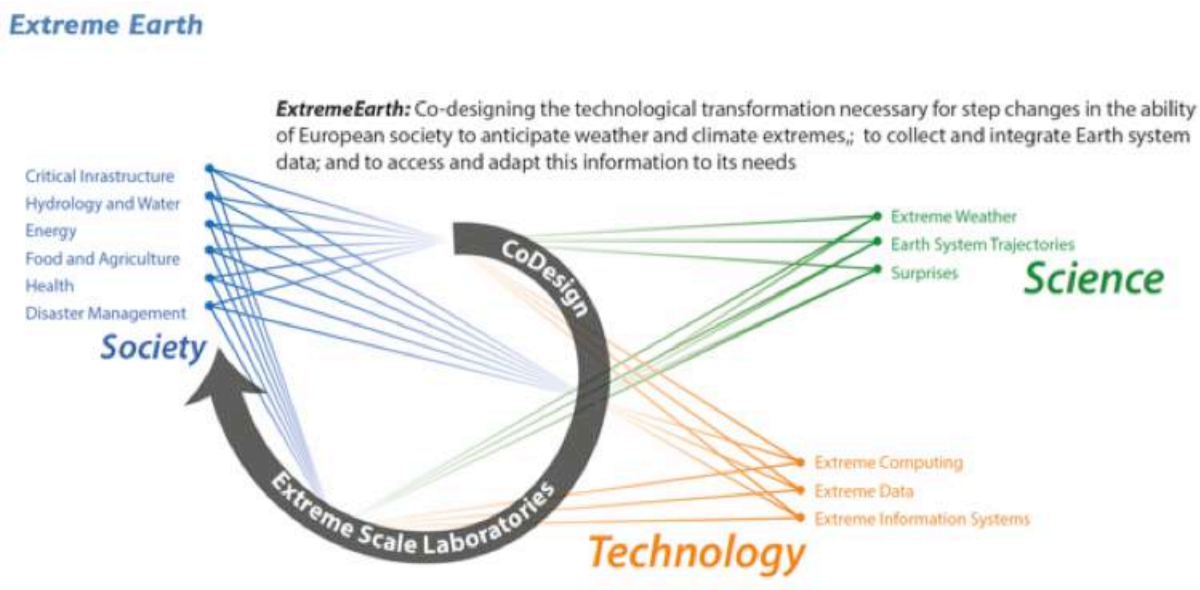


Figure 1: Extreme Earth (B. Stevens and P. Bauer)

Jan pointed out that it is either difficult or impossible to include some things in a digital twin, such as human and political aspects. Ted suggested that we could rather think about adding scenarios, or storylines. Pierre asked how we would add human behaviors and at what point would we stop, as we cannot predict every single behavior. Bjorn responded that it would be a framework for exploring interactions. People could program applications, if we were to open the model infrastructure to the public. Rowan Sutton found the idea attractive, with the missing detail being the interface with decision-makers. Jason Box was also supportive, saying that it gives us the opportunity to think about how we think about climate. Martin asked what it would need for implementation – there is a modeling challenge and also an informatics challenge. We would need to figure out a way for our data to be interoperable. Bjorn explained how using a higher resolution would provide better output.

Francisco (Paco) Doblas-Reyes noted that this project would go beyond WCRP and there was a discussion about what that would mean in terms of driving the project forward. Nils Wedi was fully supportive, pointing out that weather and climate are intertwined with supercomputing. There is a need to rewrite current models in any case. We could combine them with other elements like machine learning. Daniela noted that this is a toolbox idea and that it may help us to decide why we are not making progress in some areas and where we can make progress. Magdalena confirmed that we are ready to do this and that perhaps the evolution is in the institutional arrangement. She also asked how we will know if a digital twin is in fact a twin. We do not have long data simulations for climate.

Neil noted that digital twins that he knows of are data rather than model driven. How will we parameterize points where we do not have data? Bjorn responded that it would be a tool that can be used on a multi-decadal scale. Paco stated that the data-driven digital twin approach will happen anyway. The question is how much we want to take advantage of this. Peter Bauer clarified that there are different flavors of digital twins. Traditionally they are data-driven – as close as it gets is a continuous data simulation problem. When you get into projections you lose this, but you get a much better idea of model uncertainties. It is a much fitter framework, but it needs enabling technologies. Bjorn noted that as we move to the kilometer scale it allows communities to speak the same language.

Martin noted that he is a big fan of the digital twin environment. People could access our information. People would build cool games around this. We can imagine what our cities would look like under certain scenarios. The benefit would be enormous. It is a discovery environment that enables other communities to take part. Peter and Rowan both noted that the old questions would not go away and that people could put their own spins on this. There would need to be a strategy for prioritization. Gabi liked the idea but noted that she is not sure how it would work in terms of sharing language. Bjorn stated that there could be a shared language with different leads. The software could be developed internationally. Paco noted that this will only work if technology developers have an interest and can use this to make exascale computing a success. Helen noted that there needs to be a forward-looking element to this if it is to be successful and if it is to benefit the whole world – not just the “developed” world. Christian stated that he likes this, but that he does not think that it should be the only thing that WCRP does. It was generally agreed that there would be other WCRP activities.

2. To bring meaning to climate change at the local scale, Ted Shepherd

Ted began his presentation by looking at decision making under uncertainty. Climate models (and theory) can disagree on the nature of the circulation response to climate change, which has direct implications for precipitation and for weather-related extremes such as droughts and heat waves. The average of such different projections has no meaning. Epistemic (systematic) uncertainties are different from aleatoric (statistical or random) uncertainties and cannot be treated in the same way. Epistemic uncertainties are intrinsically subjective, which raises issues of trust and intelligibility.

One approach to address this is via storylines: physically-based unfolding of past climate or weather events, or of plausible future events or pathways (causal accounts). Climate attribution of ecosystem extreme events generally takes a forensic rather than a probabilistic approach, focused on building causal accounts. It is important to keep the focus local and contextual; start from the present, and from the observed record; construct plausible storylines for the observed behavior; propagate those storylines into present-day risk as well as near-term (potentially also longer-term) projections; and connect with the subseasonal-to-seasonal perspective. The argument for this is both practical (in terms of stakeholder interest) and scientific (in terms of connecting process understanding; e.g. prediction is the cornerstone of causality).

Ted concluded that WCRP should avoid the creation of 'clubs' that maintain the status quo and suppress creativity; do things that are not being done rather than marking territory in things that are already being done; not self-declare its expert judgment or trustworthiness; be aware of the competitiveness of climate science; highlight the risk associated with climate variability; and empower regional "communities of practice" to which we bring our climate knowledge.

Discussion:
Martin began the discussion by asking Ted what a "World" Climate Research Programme can do to support this. Should we communicate best practice, rather than trying to do it? Ted responded that we should empower it. Detlef asked what recommendations Ted has for us moving forward. Ted responded that WCRP should raise the profile of this type of science.

3. Presentation, Christian Jakob (without a slide presentation)

Christian gave a presentation that started by asking, "What would I be embarrassed about if we did not make progress on it in the next 10 years?" He pointed out that our goal should be to provide actionable information, where actionable does not imply certainty. However, we need to quantify the uncertainties to make information actionable. He argued for seamless information, pointing out that this implies "seamless" as being about what comes out of the box, rather than what is in the box. Once we know our goals, we can state what research is needed to provide this information. We need to come back to the key question – what don't we know? We must not be afraid of asking this question in fear of climate skepticism. He highlighted the need for understanding circulations and their potential changes if we are to provide better regional information. He pointed out that the information we need resides in both observations and models and that blending them optimally, for example through data assimilation, has been proven most powerful.

This resonates with the digital twin idea. However, he also stated: "I would be happy to have 1-3 digital twins, but it won’t be enough. They will not a priori be good climate models. Also, if we push too hard on very high resolution as the only solution, we will alienate 80% of the community. We need to bring the community along." He outlined that his “dream world of climate models” ten years from now would contain 1-3 large international centers pursuing very high-resolution (km scale) digital twin setups. Those would be augmented by a dozen or so national and regional modeling centers that would operate climate models on 10s of kilometer scales. This number reflects the truly independent number we keep finding in CMIP multi-model ensembles. So why not support fewer centers more strongly than having lots of subcritical efforts. In any case, we need to become much more serious about model development. Models do not improve from looking at them. Someone needs to rewrite the code. The percentage of people doing that is very small. We need to educate people who can do this and bring the excitement back. World-class, well-coordinated and well-funded efforts will do this.

Discussion:
Neil began the discussion by stating that we need to harness the community and the brightness of young people, e.g. in computer science. We should also bridge existing knowledge, e.g. in CMIP, for the development of early digital twins. Christian agreed that it is crucial to push the boundaries of what we can do with our models. There was a discussion about what climate centers are currently capable of and how to bring them along and not alienate the community.

Martin questioned the jump in understanding in terms of science, as well as technology. Christian explained that the connection between weather and climate is important – how do modes affect weather and how does weather affect things that we care about as climate scientists? Rowan noted that he liked the suggestion of (a) a digital twin and (b) climate models at some minimal resolution. He suggested that ensembles are a key activity that is needed. Ted agreed that ensembles and model uncertainty are critical. Paco noted that we need more support from computer sciences. Climate models are difficult to modify. We need to code in a different way. Pascale wondered if we were missing long term variability in the discussion. How do we deal with this in WCRP? Detlef brought the discussion back to thinking about how this could contribute to implementing the WCRP Strategy, asking whether a possible focus could be on actionable climate information on regional to local scales. Christian agreed that it would be to "enable" actionable climate information on regional to local scales and noted that we do not know the state of the climate system at any given time. Helen asked if we can combine the discussions around 2028, digital twin and enabling climate information.

4. Presentation, Daniela Jacob (without a slide presentation)

Daniela gave a brief presentation on EURO-CORDEX and on discussion points raised by the WCRP Task Team on Regional Activities. In terms of EURO-CORDEX, it was noted that the community are pushing to the kilometer scale. Important questions include embedded phenomena and regional drivers of those phenomena, and regional predictability and our inability to explain regional trends. The scientific challenges that were identified are a fully regional Earth system approach, with the human dimension included, km-scale / convection permitting Regional Climate Model (RCM) simulations, realistic representation of extremes and related processes, an ability to inform the local scale, trends simulation, regional predictability, and probability, robustness and distillation (see Annex 4 for the EURO-CORDEX submission).

The WCRP Task Team on Regional Activities submission was prepared by Clare Goodess and Bruce Hewitson, who co-chair the WCRP Working Group on Regional Climate. They submitted six questions that seek to improve the provision and sharing of decision- and scale-relevant climate information from across WCRP and other data sources (see Annex 4 for the Task Team on Regional Activities submission). This includes assessing, understanding and reconciling data and the possible co-designing of decision-relevant information on appropriate time and spatial scales.

5. Gross underestimation of decadal atmospheric circulation signals, Doug Smith

Doug Smith began his presentation by explaining that there is a gross underestimation of decadal atmospheric circulation signals in climate models. Model output shows signals as per the real world, but ten times too small. If this means that projections are ten times too small, then we are in for some surprises. If we look at CMIP Phase 5 and CMIP Phase 6 decadal predictions, there is huge uncertainty if the models are taken at face value. However, we can test this. The forecast signal is much too weak. The magnitude of ensemble mean variability is inconsistent with correlation. Doug went on to discuss the signal to noise paradox. The paradox is that models predict the real world better than themselves despite perfectly representing themselves. Members are not alternate realizations of observations and so you need a very large ensemble to extract the predictable signal. This undermines the basis of ensemble prediction. While climate models have the right amount of variability, the proportion of variability that is predictable is too small. The fact that the signal is 10 times too small means that we need 100 times the number of ensemble members to extract it. We need to resolve this paradox to allow reduced ensemble size, to increase prediction skill, and to fully understand the drivers of past climate change and accurately predict the future.

Discussion:
Detlef began the discussion by asking what conclusions we should draw from this. Doug concluded that we should (1) not take simulations at face value; (2) calibrate simulations; and (3) fix any problems – higher resolutions may be needed. Pascale suggested that investigating the signal could be interesting for WCRP, including the sharing of methodologies. Christian put forward the idea that we could initiate an activity around improving models. For example, we could set ourselves quantitative targets such as improving the predictability of rainfall by 50%. Detlef reiterated that if we have not made progress on this in the last 40 years then we need to understand why not. Gabi stated that it is not just about models. Observations are important to understand atmospheric circulation and other processes.

Bjorn suggested that the digital twin idea could drive this. We have not structurally changed models in 20 years. The scope has not changed. We have only added detail. The academic way of doing model development doesn't work. We need to hire professionals to get good models. Regional climate modeling centers have a number of problems that can be addressed. Mojib stated that we do not have the computing power to do many of these things. How can we get more confidence in our decadal predictions in the next five years? Bjorn countered that he believes that we can do it and that we need to challenge the paradigm. Magdalena brought the importance of a seamless approach into the discussion. By having a seamless approach, you can see where the errors appear and then tackle them. It is important to understand the processes to ensure that you are making the right decisions. Christian noted that high resolution does not replace everything. Modeling centers should try and produce models of the same quality at 20 km resolution. Bjorn's project will push the science forward. Whether it is successful or not is almost secondary.

Nils continued the discussion by noting that we don't make enough use of cross-platforms to bring the community and centers together, thus pooling existing yet diverse expertise. Guy reminded participants that models are not the only aspect. We need to bring observations, including from space agencies, into the game. Daniela highlighted the fact that we need to pay attention to vertical layers, such as in the atmosphere. Models and long observation capacities together, in vertical and horizontal scales, would come closer to answering variability questions. Peter stated that we have a number of tools and decades of experience with them. We can convince the space agencies to invest in models and other methods to obtain the information. Destination Earth is the same proposal. We should bring together the successes that we have already had. We should not shy away from computing limitations. We can improve the computing capabilities.

Paco raised the question of needing large ensembles, which Doug pointed out would not need to be so large if we can fix the signal/noise issues. Paco went on to point out that we use large computers for many things and that there is a very big gap between prediction and projection. Christian confirmed that what we need is a paradigm shift. That will mean that we need more observations, not less. Likewise, Jochem stated that we need bold proposals for the future. It is not useful to make excuses for why we cannot do this. Guy pointed out that Figure 2 in the WCRP Strategic Plan 2019-2028 depicts interactions of the Earth system. We are much beyond that today. Can we as a group come up with a new ionic concept, with connections between data, models, etc.?

6. Priorities for climate science in the post-Paris world, Rowan Sutton

Rowan began his presentation reminding participants that climate change is an urgent problem where there are urgent societal needs. The traditional view of "science for discovery" is not appropriate in the context of the urgent issues of today. He proposed a new overarching objective of: "To meet urgent societal needs for robust climate information to support decision making and solutions." He went on to explain that to meet societal needs and the role of research we need to: (1) understand user needs thoroughly; (2) identify all the requirements to meet those needs (including identifying knowledge and innovation gaps); (3) focus research on the most critical decision-relevant knowledge gaps sharply, consistently and persistently; and (4) build collaborations to address knowledge and innovation gaps. This process is a reverse of the traditional model of doing science first and thinking about applications later.

Rowan went on to explain that the key question for prioritization of research activities is, "What is the added value for real-world decision-making of specific new investments in climate science?" From the perspective of decision makers, climate change is not a prediction problem; it is a problem in risk assessment and risk management. For example, the Met Office Hadley Centre Government questions are: present weather and climate risks; future weather and climate risks under different emission scenarios; mitigation strategies and the case for early action; and impacts and opportunities of mitigation and adaptation. What are the consequences of this for priorities in research in physical climate science, climate modeling and climate assessments (see Sutton, 2019)?

Rowan went on to note that the information requirements for risk assessments are:

1. What events are possible?
2. How likely are they? and
3. What could the impacts and consequences be? (Risk = likelihood x impact, impact = f(hazard, vulnerability, exposure)).

Plausible worst-case scenarios and impacts must be quantified but there is no single best measure of impact/risk. In the IPCC process, WG I is required to assess likelihood and the physical hazard component of impact, i.e. to assess risk in terms of physical climate variables. Assessment of likelihood requires a mixture of quantitative and qualitative (scenario) methods.

Key decision-relevant knowledge gaps include: (1) present weather and climate risks, including plausible worst-case scenarios; (2) future weather and climate risks, including plausible worst-case scenarios; and (3) detection and attribution of recent climate and Earth system change, which is essential to both of the above. This means paying systematic attention to quantifying the impacts of climate change in terms of physical climate variables, quantifying current weather and climate risks, quantifying future climate risks and collaborating with other scientists and decision-makers to provide fully integrated risk assessments. As a result, we need to assess very carefully where investments in climate modeling can add most value to risk assessments and decision-making on resilience, adaptation and mitigation. There are opportunity hot spots associated with pushing the frontiers of capability towards (i) the highest possible resolutions (for which only short simulations are possible) and (ii) lower resolution simulations with long duration

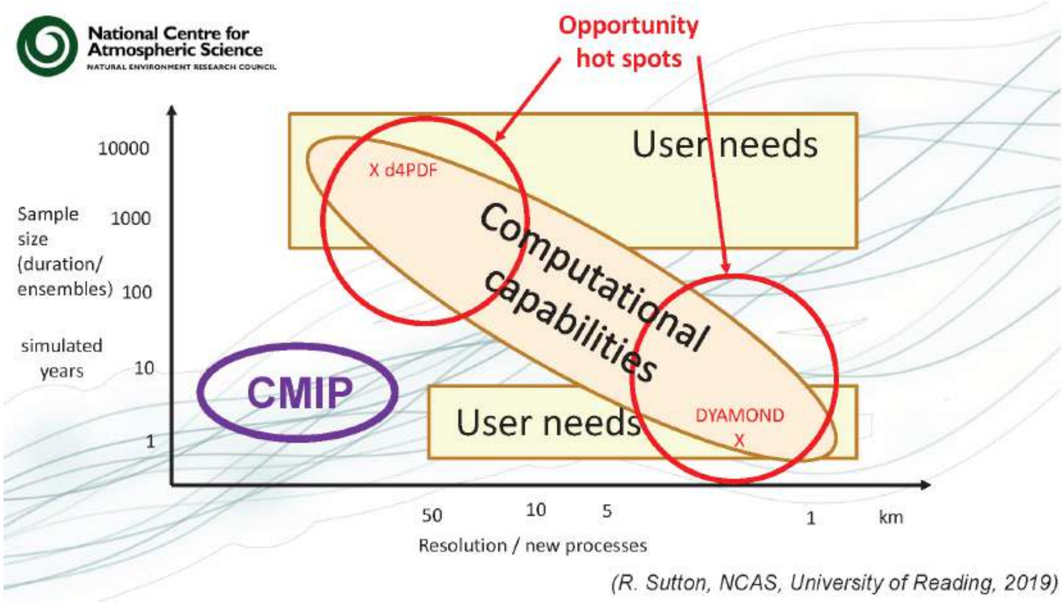


Figure 2: Priorities in climate modeling to meet user needs for risk assessments (Rowan Sutton)

and large ensemble size to adequately sample variability, which is necessary to quantify risks (Figure 2).

In terms of the WCRP Lighthouse Activities, Rowan proposed two concepts: (1) Build an integrated global capability for monitoring, attribution, early warning and prediction of Earth System Change; and (2) RISK-MIP: Internationally coordinated simulations for quantification of regional climate change risks.

The first proposed Lighthouse Activity is based on the detection and attribution of observed changes, as this is fundamental for quantifying current and future risks. At the global scale, this capability is required to enable quantitative assessment and prediction of the global energy, carbon and water budgets, in support of mitigation policy, the Global Stocktake etc. At a regional scale this capability is required to enable quantitative assessment of current and future risks to inform adaptation policies. Components would include: (1) a system for quantitative monitoring of Earth system change; (2) a system for attribution of Earth system change based on very large ensembles of high resolution historical simulations; (3) a system for prediction and projection of Earth system change, conditioned on the latest observations and attribution results; and (4) a research programme to address process-based attribution of specific Earth system changes and quantification of current and future risks, including the potential for early warnings, conditional on the latest observations.

The second Lighthouse Activity would be related, as it would quantify the current and future likelihood of high impact weather and climate events.

Discussion:
Ted opened the discussion noting that this presentation taps into emerging trends. We need to find intelligent ways to sparsely sample the space of model simulations. How do we combine information? Michael Morgan asked if Rowan would see sub-seasonal to seasonal timescales as a good test zone for this to demonstrate capabilities. You could then go to funders with this in relation to climate change. Rowan said that it depends on what you are looking at. Some things

on long time scales you cannot see on short time scales. Climate change science is a more complex problem than numerical weather prediction. We need to think about what we do not understand and what the possibilities are, e.g. traceability of climate change, lack of verification, different drivers of long-term effects. To quantify current risk, you need to understand the full spectrum of variability – not just on a short timescale.

Jan liked that Rowan put risk assessment at the forefront. We want to help people to be able to discuss how they are exposed to climate risk. It is our responsibility. Pierre also liked this. How do we know how much is attributable to climate change? What is the new business as usual? We should be looking at scenarios for climate response that are actionable. Then one can say that this is a high impact scenario. We are not talking about event attribution. We are interested in the attribution of multi-year events and trends.

Magdalena stated that she sees this as an operationalization of the activity. Rowan agreed that points (1) and (2) would be operationalized, but that there is also a science component. Christian noted that CMIP has been successful in many ways, but now needs redesigning. Rowan stated that the data sharing of CMIP is excellent. Daniela noted that for this to work the entire system would need to change. This would require a societal transformation that would take 10–20 years. Bjorn countered that perhaps we don't know what society really wants? Society will need to build an institutional response to this. Daniela confirmed that institutions are being built, but that these are closer to societal interaction than WCRP is currently (e.g. on adaptation). Bjorn and others agreed that WCRP should advocate for addressing these problems. Jens made it clear that we need to clearly identify our borders/partners. Pierre questioned what is meant by the statement that we need institutions first. Christian and Bjorn explained that it is somewhat like weather forecasting: we don’t do weather forecasting in universities, we do it in institutions. But we do research to improve weather forecasting in universities; this would hold also for climate.

7. WCRP Flagship Objectives: Input from CLIVAR, Magdalena Balmaseda

Magdalena presented the workshop input from the Climate and Ocean Variability, Predictability and Change (CLIVAR) Core Project. The overarching developments that can revolutionize our insight into the climate system and solve many societal challenges ahead of us include: (1) reliable seamless prediction and projections; (2) better exploitation of observations for initialization, modeling and calibration; (3) improved and reliable Earth system models: resolution and complexity; and (4) capacity building, support interface organizations. CLIVAR concluded that it would be risky to focus on a single experiment or model in the future, but rather that it is essential to bring together interdisciplinary aspects (e.g. ocean biochemistry). In order to make progress the following infrastructure projects could be considered: databases for sharing experimentation and observations; modeling infrastructure to exchange/share model modules (efficient exchange of ideas); and observation handling infrastructure to confront (and combine) model output with observations. In the case of the ocean, enhanced coordination with the Global Ocean Observing System (GOOS) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO is recommended to boost the ocean observing system.

In terms of societally relevant questions/needs, CLIVAR identified a need to support adaptation and mitigation actions, predict climate emergencies and risks, and better understand the ocean climate for ecosystems and humans – securing our shores. To achieve this, we need research into current knowledge gaps, including regional impacts of climate change and to determine whether there are limits to adaptation (e.g. tipping points). Limits to the assessment which are relevant for research directions are model errors and large uncertainties, the fact that CMIP cycles are too frequent to learn lessons, a need to better use models and observations together, and the fact that research is done in silos with not enough multidisciplinary aspects nor society engagement. According to CLIVAR, the role of WCRP in the program landscape is to maintain databases (such as the Earth System Grid Federation (ESGF)) in order to make model results and observations available to the community, to promote other experiments in addition to CMIP, and to build capacity.

To establish a scientific basis for adaptation and mitigation action for a climate resilient society there are two actions needed: (1) understanding and predicting climate variability and its response to human activities (WCRP experimental campaign); and (2) enabling the generation of actionable climate information on global to local scales (WCRP Climate University and Open Lab) (Figure 3). The aim of the experimental campaign would be to complement the existing CMIP protocol with initialized ensemble seamless predictions. This would require (1) a true Earth system model operating at all time scales, leveraging efforts among modeling centers; (2) Earth system reanalysis back in time (data rescue and data assimilation methods); and (3) an innovative machine learning solution for modeling complex components to enhance the information content of model output (downscaling, calibration, filtering, conditional probability), and to identify signals and errors, causality, and attribution.

The WCRP Climate University (or Academy) and Open Lab would be primarily online and would be multidisciplinary two-way training between climate scientists and climate stakeholders (Governments – Corporate – Non-governmental Organizations). For the University, core projects would provide the faculty in the "hard" sciences of our research areas. It would offer rigorous and credible certificates (even degrees?) in elements of climate science, risks, adaptation, etc., providing credentials that would give the recipients credibility within their organizations. The Open Lab would provide a space for bringing together communities of practice addressing problems shared in widely separated regions across the globe (e.g., salinization of agricultural lands due to sea level rise, health impacts of extreme heat, flooding from intense rains in extratropical storms, etc.). Philanthropic funds could be sought to enhance bandwidth.

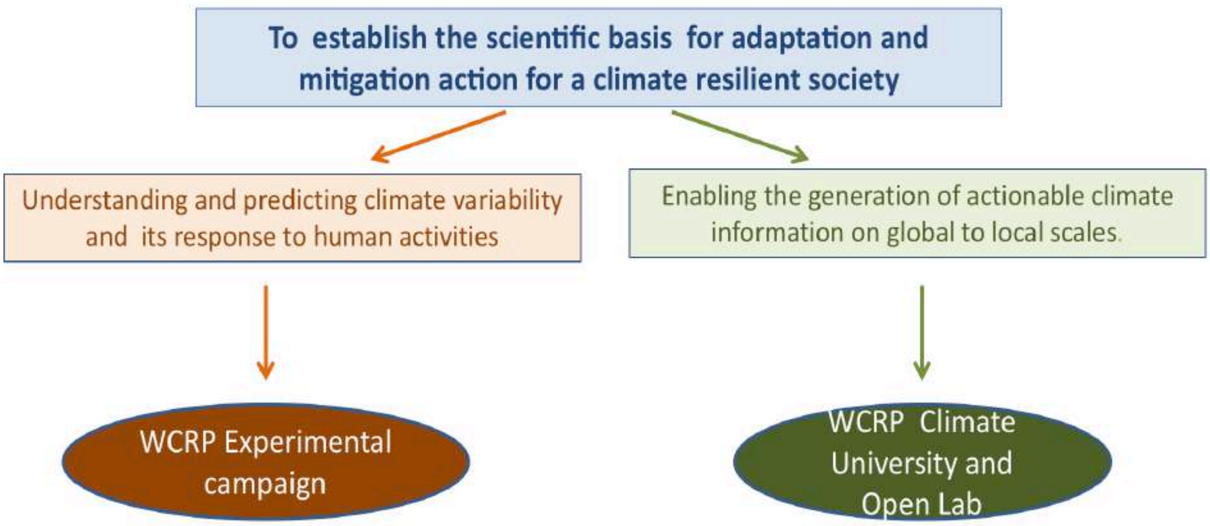


Figure 3: WCRP Flagship Objectives and associated projects: input from CLIVAR.

Discussion:
Rowan began the discussion noting that reliability has a specific meaning and that we cannot demonstrate that climate change predictions are reliable. In addition, to have an Earth system model operating on all timescales will lead to tough decisions in terms of resources. We need to think about priorities and Earth system reanalysis may be a higher priority. Magdalena explained that projections are not enough. Ted suggested that there could be an argument for this in relation to the Global Stocktake. Paco noted that climate services are missing in the discussion and that we are not in the driver's seat.

Christian turned the discussion towards the Open University idea, saying that we should consider supporting it quite seriously as a capacity building opportunity. Detlef stated that we can advocate for it. Mike Sparrow made people aware of the International Antarctic Institute, which is a possible role model.

5.2. Proposed Lighthouse Activities

Workshop participants were divided into three breakout groups and asked to suggest Lighthouse Activities, including a name, purpose, what would be achieved, and other details, such as infrastructure and partnerships required. The following WCRP Lighthouse Activities were proposed as high-visibility projects or experiments that are either led or co-led by WCRP and that will make progress toward reaching WCRP's Scientific Objectives in support of society. The main outcomes (name of Lighthouse Activity and purpose) are summarized in Table 1.

Table 1: Proposed WCRP Lighthouse Activities

Breakout Group 1	Breakout Group 2	Breakout Group 3
What on Earth is going on? A capability for quantifying, observing and explaining Earth system change	**A Global Framework for Regional Assessments** To structure innovative approaches providing a framework for distillation of climate information on specific regional topics	**Attribution and Early Warning** To build and integrated global capability for monitoring, attribution, risk assessment, and risk management
Regional Risk Labs To bring meaning to climate change at the regional and local level	**Towards Digital Twins** Driving a Step Change in Modeling and Observational Approaches	**WCRP Climate Academy** An ‘open lab’ set of online courses for climate knowledge, an online toolbox, run/host hackathons, and entrain people
Digital Earths To create a digital facsimile of the Earth system for the past, present and future	**Climate Risks** Robust Assessment of Present and Future Climate Related Risks	**Digital Earth (Digital Twins)** A revolutionary, digital explorable image of past, present and future Earths
International Climate University To build capacity for climate science in developing countries		**Safe Landing Lighthouse** Mapping potential safe landing spaces for Earth's climate

After an extensive discussion over the proposed Lighthouse Activities it was agreed that they could be combined into five key activities (Figure 4). Breakout groups for four of the Lighthouse Activities were formed to provide a brief description of each proposed activity. After the workshop, these groups went away and produced detailed summaries of each Lighthouse Activity. These are provided in the following pages. Further details of the fifth Lighthouse Activity, the WCRP Academy, will be produced at a later stage.

These Lighthouse Activities should not be considered final, but as suggested activities that will then be taken to the WCRP community for discussion and consolidation.

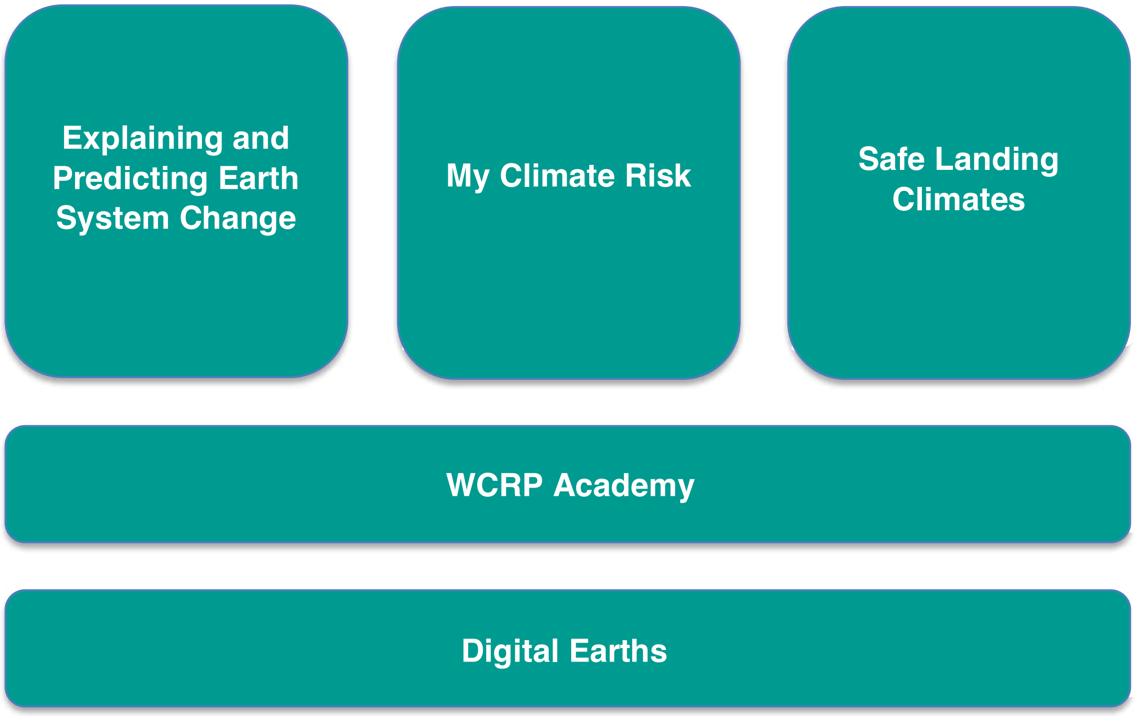


Figure 4: The five proposed WCRP Lighthouse Activities

Author(s): R. Sutton, J. Marotzke, G. Hegerl, D. Smith, M. Kimoto, F. Vitart, …

Description of the activity

The formulation of robust policies for mitigation of, and adaptation to, climate change requires quantitative understanding of how and why specific changes are unfolding in the Earth system, and what might happen in the future. Quantitative explanation of observed changes – through robust process-based detection and attribution – is also fundamental to confidence specification in climate assessments, predictions and projections. However, the capacity to deliver these capabilities is very immature (evidenced, for example, in the recent debates around the "hiatus" in global warming of surface temperature). The proposed WCRP Lighthouse on Explaining and Predicting Earth System Change is intended to address this gap.

The overarching objective is:

- ***To design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning and prediction of Earth System Change on global and regional scales, with a focus on multi-annual to decadal timescales.***

Form of activity

The core activity is a *research programme* to:

1. Design, improve and evaluate individual components of the capability and the integrated capability itself.
2. Advance fundamental understanding of Earth System Change on global and regional scales.

A headline output would be a major enhancement to, for example, the WMO State of the Climate Reports and the WMO Annual to Decadal Climate Updates (currently in pilot phase, with a focus mainly on predictions) as well as the Global Carbon Project and Future Earth activities such as the 10 Insights report. The enhanced annual reports would integrate predictions with the latest assessment and quantitative explanation of changes in the Earth system over recent years and decades, on global and regional scales. This initiative would achieve some of the purposes of the IPCC Assessment Reports (e.g. AR6 Chapters 2-4), but in a more nimble and timely (albeit less comprehensive) manner.

What will it deliver and/or achieve?

The design, and steps toward delivery, of ***an integrated capability for quantitative observation, explanation, early warning and prediction of Earth System Change on global and regional scales, with a focus on multi-annual to decadal timescales***. This capability involves the following components:

1. A more complete and integrated capability for observing Earth system change (climate and composition) on global and regional scales. This component to be led by other partners but with WCRP contributions to the design. An "Earth Year", possibly culminating in an Earth Observation Decade, could provide a focal point for developing an enhanced observing system.

2. Earth system reanalyses and advances in the methods to deliver such reanalyses, supported by enhanced efforts in data rescue.
3. New capabilities for process-based explanation (detection and attribution) of Earth System changes on global and regional scales and multi-annual to decadal timescales, including quantified uncertainties. This component differs from "traditional" detection and attribution, which focuses on multi-decadal to centennial timescales, and also from "Event Attribution," which focuses on individual seasonal or shorter-timescale extreme events rather than system changes. A strong focus on understanding full causal chains at a process level is also essential.
4. Improved predictions of climate and Earth system change on multi-annual to decadal timescales, including new capabilities for early warning and improved confidence in predictions supported by quantitative understanding of recent changes. Regular outlooks for the next decade: these would initially focus on climate variables, but in time could expand to include, e.g., regional risks to food or water security. Longer-term outlooks could include early warning of potentially irreversible changes or tipping points in the Earth system.
5. Improved capabilities for quantitative assessment and prediction of the global energy, carbon and water budgets, supporting mitigation policies. (This component would build on and expand the work of, e.g., the Global Carbon Project).
6. Improved capabilities to quantify current and future weather and climate risks (building on, e.g., the Japanese d4PDF programme), informed by quantitative understanding of recent changes on global and regional scales, supporting adaptation policies.

Relation to the World Climate Research Program Strategy, including as appropriate any aspect that is new or novel.
This activity will contribute to addressing all four of the WCRP Scientific Objectives. It will provide a focused set of priorities and will ensure that advances in fundamental understanding of Earth System Change are targeted to meet the needs of decision-makers faced by climate related risks and opportunities.

Science requirement; including new science and how this draws upon the core research expertise of the WCRP community.
A research programme to address:

1. Enhancing capabilities for observing Earth System Change and for Earth system reanalysis, including advances in data assimilation for Earth System variables.
2. Process-based attribution of specific changes in the Earth System on global and regional scales (climate and composition) including development of attribution methodologies, e.g. using very large ensembles of high resolution historical and initialised simulations sampling internal variability, forcing uncertainties (e.g. emissions, land-use, volcanic eruptions) and process uncertainties affecting forcing and/or response.
3. Improving the fidelity with which climate models simulate internal variability, particularly on multi-annual to decadal timescales, and the response to natural and anthropogenic forcings. Exploring the benefits of higher resolution, large ensembles and improved representation of Earth System Feedbacks.
4. Understanding regional changes in atmospheric circulation, including the “signal-to-noise” problem.

5. Quantification of current and future weather and climate risks, including improved capabilities for near-term outlooks/decadal predictions and early warning of Earth System Change, conditional on the latest observations.
6. Variability and predictability of: Earth's energy budget; carbon and biogeochemical cycles.

Partnerships needed to do this Activity; including if WCRP will be the lead or if it will be a jointly-lead Activity (and if so, who are the key Partners).

- WMO
- Global Climate Observing System (GCOS), Global Atmosphere Watch (GAW), European Space Agency (ESA), National Aeronautics and Space Administration (NASA), Copernicus, etc.
- The World Weather Research Programme (WWRP)
- Future Earth
- Climate services. Users of information especially quantification of risks for multiple sectors – e.g. transport, energy, agriculture, food and water, insurance etc.
- Other WCRP Lighthouse Activities, e.g. Digital Earths, Regional risks

My Climate Risk

Author(s): T. Shepherd, D. Jacob, J. H. Christensen, L. Alexander, S. Tegtmeier, F. Doblas-Reyes

Description of the activity

The objective is to develop 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.) in order to construct decision-relevant and scale-relevant information – in other words, climate information that is *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 a number of region types (large scale, urban, typical SREX[2], etc.) and intended to become a much-needed support for the development of climate services.

Form of activity

It will involve *several case studies, in the form of labs*; where labs are understood to be dynamic, exploratory, transdisciplinary environments, and not physical infrastructure. One such lab could be an evaluation of different national or regional climate risk assessments, to compare methodologies. Another could target specific regions whose risks have not been properly assessed, by bringing together relevant stakeholders to distil the existing information. It is important not to underestimate the effort required by the labs as they can only work with the sustained involvement of experts on different aspects of climate research such as observational uncertainty, detection and attribution, climate prediction and projection, process understanding, etc. The outcomes of the case studies could be published in collections of journal papers.

What will it deliver and/or achieve?

This Lighthouse Activity will help develop a new way of practice to synthesize climate information from different, sometimes contradictory, lines of evidence. Chapter 10 of the IPCC WG I AR6 report is already assessing what the literature offers to undertake this objective for the physical climate system, whereby different methodologies like storylines (explanations) of observed trends and events as well as traditional probabilistic descriptions are constructed, reconciled with information from various sources, and their implications for future risk articulated.

This is a notable departure from the traditional detection/attribution/projection framework, in which the different steps are performed separately – in particular, the observational analysis is largely divorced from the modeling – and where the aim is to construct singular, definitive scientific findings.

The activity would mainstream the new approach and extend it into the production of consolidated regional (in the widest sense possible) climate information based on different lines of evidence for the decision space. The ambition is that the regional case studies would develop into ongoing regional 'communities of practice' (definition: a group of people who share a concern or a passion for something they do, and learn how to do it better as they interact regularly), which would continue to drive research methodologies that can be taken up by the climate service community to be transposed to a wide number of cases requiring regional climate information for risk management. Involvement of scientists from both the Global North and the Global South in the

[2] Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

regional case studies will lead to capacity exchange, and best practice can be shared between the different groups and assessed in meta-analyses.

The labs will be linked via a coordination mechanism set by WCRP. Full traceability of the way the different lines of evidence are consolidated into climate information will be required. A repository of the outcome of the labs will be created to enable the meta-analysis that will lead to the development of a methodology for the generalization of the creation of regional climate information.

Relation to the World Climate Research Program Strategy, including as appropriate any aspect that is new or novel.
Understanding climate change at the regional scale and connecting it to societal needs is a core part of the WCRP Strategy. WCRP has been attempting to deal with the regional climate risk landscape for many years, with limited success. A new approach is urgently needed. The development of new research paradigms in recent years (see 'what will it deliver' above) offers an opportunity.

The present paradigm for regional climate risk assessment is “predict then act”, with contextualization of climate information performed mainly as a post-processing step. This new activity will be a paradigm shift, by bringing together regional actors with all available sources of climate data (observations, reanalyses, regional and global models, and many other sources of both data and knowledge) and with the specific scientific expertise on the best way to use each of these sources of information to distil plausible explanations of past behavior and implications for the future, within a specific risk-based or decision-oriented context. The scientific expertise required lies squarely within the scope of WCRP, which is the only international research community with expertise in all the data sources mentioned above, as well as with knowledge on their merits and limitations.

Science requirement; including new science and how this draws upon the core research expertise of the WCRP community.
It is widely recognized that there is a knowledge gap between global aspects of climate change and the impacts on human and natural systems (see Figure 5), which occur at regional spatial scales. Bridging this gap requires connecting drivers of regional change through regional atmospheric circulation to local climate, which is all core WCRP expertise. There is a lot of research in this space, but it is not bridging the knowledge gap, because the traditional approach has been from the left to the right, which results in a ‘cascade of uncertainty’ and very weak statements of knowledge (Shepherd, 2019). In this activity, we will also work ‘upstream’, from the right to the left, to identify the most relevant pathways, or storylines, within a decision context, i.e. to adopt a risk-based approach, implicitly challenging the ‘cascade of uncertainty’ thinking.

This will draw on the following science (emphasizing mainly the WCRP components):

- Local observations, data rescue, traditional knowledge
- Remote sensing, reanalyses, and inter-comparison of all observation sources
- Observational uncertainty estimates and their use in model validation in the broadest sense
- Fully Earth System approach (human dimension included)
- km-scale / convection-permitting simulations
- CMIP and CORDEX and the full connection to cover all possible sources of uncertainty, including the generalized use of large ensembles
- Sub-seasonal, seasonal and decadal prediction, their potential use to constrain climate projections and methods to reduce the impact of initial shock and drift

- Understanding of extremes and related processes (e.g., land-atmosphere, aerosols, sea ice and snow, water cycle, ocean-atmosphere)
  - Process-based in addition to statistical approaches
  - Storyline approach, physically-based future changes
  - Compound events
  - Connection to observational knowledge & meso-gamma modeling
- Modeling and observations at the landscape scale (e.g., coastal, cities, etc.)
- Identification and attribution of long-term changes
- Regional predictability and its potential sources
- Broader characterization of uncertainty, i.e. beyond the concept of an error bar
- Bringing the concept of values and context into climate science
- Process-based model evaluation at the regional scale
- Better use of observations, because they can be treated in a conditional rather than an aggregated manner
- Establishing/Ensuring FAIR guiding principles for all data sources
- Connecting physical science and social science
- Construction of climate information on the basis of different lines of evidence
- Dedicated experiments, some of them particularly challenging (high resolution, full Earth System Model, large ensembles, etc.) will be needed depending on the labs

Partnerships needed to do this Activity; including if WCRP will be the Lead or if it will be a jointly-lead Activity (and if so, who are the key Partners).
WCRP would facilitate, but, especially for the regional case studies, engagement outside WCRP with the relevant stakeholders would be essential. Many scientists within the WCRP community are already engaged in regional or local risk assessments, so there will already be many partnerships to build on. However, the paradigm shift here is that the stakeholders' values would be the starting point, not the end point; the climate scientists would start by listening but become very active as soon as the challenge is identified, bringing together the different relevant components of WCRP.

Links to IPCC (WG I and II), Future Earth, WMO, World Adaptation Science Programme (WASP) and climate services could be particularly useful, as well as to engineering communities, practitioners and consultants.

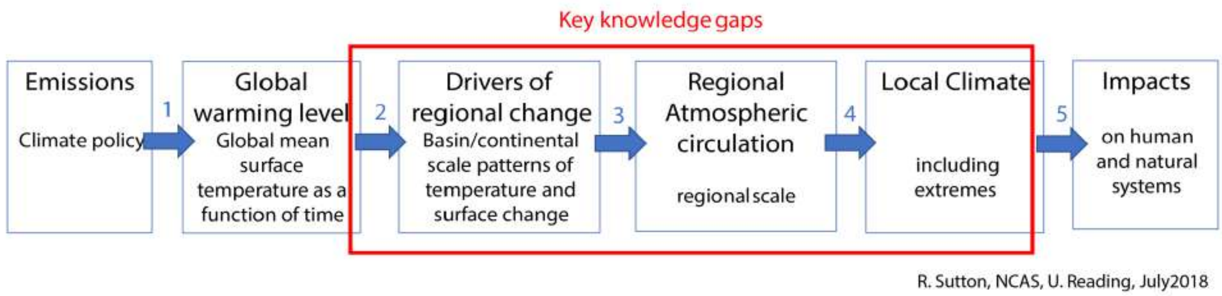


Figure 5: The global-to-regional knowledge gap (R. Sutton, NCAS, U. Reading, July 2018)

Safe Landing Climates

Author(s): P. Friedlingstein, J. Box, P. Braconnot, N. Harris, G. Hegerl, M. Visbeck

Description of the activity

This Lighthouse Activity is an exploration of the routes to climate-safe landing 'spaces' for human and natural systems. It will explore present-to-future "pathways" for achievement of key, if not all, Sustainable Development Goals (SDGs) such as climate action SDG 13, zero hunger SDG 2, good health and well-being SGD 3, clean water SDG 6, life below water SDG 14 and life on land SDG 15. The relevant time scale is multi-decadal/centennial to millennial, consistent with the objectives of the United Nations Framework Convention on Climate Change (UNFCCC) Paris Climate Agreement, contributing to the long-term global response to climate change to protect people, livelihoods and ecosystems.

The Safe Landing Climates Lighthouse Activity will connect climate, Earth system and socio-economic development sciences and provide concrete outputs through new Earth system modeling tools for climate and Earth system change studies on long time scales, contribution to reports and resource available to scientists and non-scientists.

It will promote the development of new methodologies to include risks assessments of impacts on human and natural systems, of climate instabilities, extremes, and irreversible transitions at global and regional scales in the long term.

It will promote development of much improved process-based and highly parameterized models, as well as more conceptual frameworks, to enable robust climate science information to be used by science and decision makers in governments at all levels, and for the private and public sectors.

Form of activity

At the WCRP-level, the activity will consist of a *global research activity (supported by a core working group) bringing together physical climate scientists*, Earth system component scientists (e.g. ice sheet, land/ocean ecosystems, atmospheric composition, social scientists, economists, and sustainable development experts. Its task will be to plan, encourage and coordinate relevant activity across the world; communicate and disseminate key findings; and facilitate user-oriented climate safe-landing tools.

At the scientific community level, the activity will consist of collaboration across climate/Earth system/socio-economic science to design, develop, apply and facilitate the use of comprehensive Earth System modeling tools to represent climate, earth system, natural environments and human socio-economical systems to allow exploration of long-term response of climate and key SDGs for large sets of future human developments scenarios. At the public and policy user level, the activity will ultimately provide knowledge and user-oriented tools for exploration of future scenarios and impact on climate and SDGs from global to regional scales.

What will it deliver and/or achieve?

- Inform all parts of global society on sustainable pathways leading to desirable futures
- Better understanding of the role of climate in the SDGs
- Climate-proofing proposed sustainable development pathways

- Stronger understanding of processes central to quantitative understanding of the long-term climate evolution over the 21st century and beyond
- A new generation of climate/Earth system models to investigate how risks arising from climate instabilities, extremes, and irreversible transitions might affect society and natural systems, with potential feedbacks on the climate system
- New articulation and visualization of potential climate pathways and the consequences of near-term decisions for longer-term climate and the Earth system.
- A new generation of analysis systems (articulation, visualization, etc.) for specialists and non-specialists.

Relation to the World Climate Research Program Strategy, including as appropriate any aspect that is new or novel.

The safe-landing Lighthouse Activity directly relates to the overall vision of WCRP, that is "a world that uses sound, relevant and timely climate science to ensure a more resilient present and sustainable future for humankind." More specifically, this Lighthouse is fully aligned with WCRP Scientific Objective 3 – Future evolution of the climate system, quantifying the responses, feedbacks and uncertainties intrinsic to the changing climate system on longer timescales; and WCRP Scientific Objective 4 – Bridging climate science and society, supporting innovation in the generation of decision-relevant information and knowledge about the evolving Earth system.

Science requirement; including new science and how this draws upon the core research expertise of the WCRP community.

- Significant climate and Earth System model development
- New process studies (e.g. focused on abrupt changes, threshold, non-linear processes, irreversibilities and hysteresis; extreme events breaching the limits of adaptability)
- Planetary boundaries (including input from paleo sciences)
- Risks of climate instabilities and irreversibilities (e.g. permafrost, ice sheets, …)
- Better integration of Sustainable Development Goals (e.g. zero hunger, good health, clean water, life below water, life on land, …) in Earth System Models
- Changing human and ecosystems habitability zones
- Better understanding of urban (built) / rural (natural) environments
- Climate and Earth system response to reducing climate forcings and to climate intervention approaches
- Co-design climate and socio-economic development sciences.
- Articulation and visualization of safe-landing zones tools (e.g. "Safe Digital Earths")
- Explicit attention to union between physical and social sciences.

Partnerships needed to do this Activity; including if WCRP will be the Lead or if it will be a jointly-lead Activity (and if so, who are the key Partners).

WCRP would be leading this activity as the climate system is at the core of this Lighthouse. It would need partnership with Future Earth, the Integrated Assessment Modeling Consortium, the Belmont Forum, the Earth Commission, UN Sustainable Development Goals programme and projects such as the World in 2050. There is a possible connection to the 'digital twin' Lighthouse that would enable to visualize climate-safe landing points and the pathways leading to them at the landscape level.

Digital Earths

Author(s): P. Bauer, C. Jakob, B. Stevens, J. Polcher, P. Braconnot, N. Harris, M. Morgan, N. van der Wel

Description of the activity

Digital Earths is a digital and dynamic representation of the Earth system founded on an optimal blend of models and observations. Digital Earths will enable exploration of past, present and possible futures of the Earth system by adding a new dimension to climate information. Digital Earths will give open access to data, methodologies and software. Digital Earths will create innovation in science and technology in support of the WCRP Objectives and will lay the foundation for future needs of the activity.

Digital Earths will push the co-development of high-resolution Earth-system modeling and the exploitation of billions of observations with digital technologies from the convergence of novel high-performance computing, big data and Artificial Intelligence (AI) methodologies. Under WCRP, Digital Earths will be a key instrument to achieve the goals of the other Lighthouse Activities as they rely on much enhanced simulation and observational capability. There are large overlaps with similar opportunities under WWRP.

Form of activity

Digital Earths will be a *joint activity with existing/novel, technology driven national and international projects supported by new institutions*. While the external institutions will provide the main digital infrastructures, WCRP will implement selected versions for topics where significant progress is required (e.g. other Lighthouse Activities) and in regions where the supporting research and operations context is favorable.

What will it deliver and/or achieve?

The core of Digital Earths is to develop generic software-hardware solutions that allow simulation models and data assimilation to perform several orders of magnitude more efficiently. It will facilitate the extraction of Earth-system sector specific information from vast amounts of environmental data, both simulated and observed. The efficiency gains can be invested, for example, in upgrading simulations, ensembles and/or running more comprehensive scenarios.

While the digital infrastructure developments themselves will be carried out by institutions outside the direct control of the WCRP, there are specific activities that should be driven and supported by WCRP in support of the international research community:

- Lighthouse 'Explaining and Predicting Earth System Change':
  - Global and regional Earth-system reanalyses for climate monitoring at km-scale (observations and models)
  - Seasonal, multi-annual (potentially decadal) predictions at km-scale; ensemble based
  - Support of counter-factual analyses through more (and more frequent) scenario assessments
  - Advanced cause-effect diagnostics through transparent access to Earth-system information
- Lighthouse 'My Climate Risk':
  - Regional reanalyses for climate monitoring at sub-km scale; ensemble based
  - Earth-system component (e.g. hydrology, vegetation) impact assessment
  - Geophysical data - sector specific information - socio-economic risk assessment

- Selected configurations of Digital Earths can be implemented by region thus distributing the workload and empowering more communities. The specifications for such region-specific implementations depend on the regional primary interests and could develop and demonstrate solutions applicable elsewhere. WCRP can drive this selection.
- The set-up as an open access framework for data, methodologies and software supports the use of advanced technologies by less well-developed communities and countries. Digital Earths therefore directly contributes to the capacity building activities of WCRP.

Relation to the World Climate Research Program Strategy, including as appropriate any aspect that is new or novel.
Without Digital Earths, 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 cannot be fulfilled.

Digital Earths will contribute to all four WCRP Scientific Objectives. 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 framework, 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.

Science requirement; including new science and how this draws upon the core research expertise of the WCRP community.
Digital Earths will be based on climate – computational science co-developments. The new digital infrastructure developments (e.g. programming of heterogeneous processor architectures (memory layout, parallelization), task based parallelism, mixed precision, on-the-fly post-processing) influence the design of Earth-system models (e.g. dynamical cores, Earth-system physics, coupling, model uncertainty, minimization algorithms), their workflows and the way data will be made accessible and manageable. This offers yet unprecedented opportunities for Earth-system research and services.

Partnerships needed to do this Activity; including if WCRP will be the Lead or if it will be a jointly-lead Activity (and if so, who are the key Partners).
Given its scale, implementing Digital Earths will require the creation of new multi-national institutions. WCRP must play a critical role in promoting their establishment. Doing so requires engagement with the following partners:

- Main national funding agencies supporting digital infrastructure development (e.g. European Commission's EuroHPC (High Performance Computing (HPC)), Department of Energy, Japan's MEXT and RIKEN etc.); philanthropic support
- WWRP and GAW, national hydro-meteorological services, national climate centres
- Copernicus in Europe, Earth Cube in 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)

Other relevant information
The need for creating one or more new, centralized 'Earth-system and computational science' facilities should be formally assessed because – with sufficient funding – it will accelerate progress and facilitate uptake and future support for the targeted digital infrastructures.

WCRP (WMO) is perfectly placed to carry out such an assessment and in doing so, promote the swift establishment of the facilities or generate the needed expertise and developments through other organizational forms.

6. WCRP Implementation Priorities

It is expected that the Lighthouse Activities will provide high-level guidance to the implementation of the WCRP Strategy, especially to prioritize and focus the very broad Scientific Objectives in the WCRP Strategic Plan and identify the key scientific achievements and outcomes that are required by WCRP to ensure that climate science is meeting societal needs.

Pursuing those Lighthouse Activities will empower WCRP, over the next decade, to provide scientific outcomes that are critical to support emergent societal needs for robust and actionable regional to local climate information. Delivery of robust and consistent regional climate information to stakeholders is needed to inform, for example, the implementation of the Sustainable Development Goals, disaster risk reduction, and climate adaptation, mitigation and intervention strategies. In recognition of this need, WCRP identifies the following Implementation Priorities:

1. Foster and deliver the scientific advances and future technologies required to:

- *Advance understanding of the multi-scale dynamics of Earth's climate system*
- *Quantify climate risks and opportunities*

2. Develop new institutional and scientific approaches required to:

- *Co-produce cross-disciplinary regional to local climate information for decision support and adaptation*
- *Inform and evaluate mitigation strategies*

These priorities should be considered as preliminary and will be taken to the WCRP community for discussion, refinement, consolidation and approval.

7. Next Steps and Workshop Closing

The Workshop closed with a discussion of the key next steps; which are to engage and consult with the broader WCRP community to discuss, refine, and ultimately decide on the final activities and implementation priorities; and the programme elements and structures required to support them.

Detlef and Helen thanked all participants for their efforts over the three-day workshop and the workshop closed at 15:30 on Wednesday 26 February 2020.

References

Marotzke, J., Jakob, C., Bony, S. Dirmeyer, P. A., O'Gorman, P. A., Hawkins, E., Perkins-Kirkpatrick, S., Le Quéré, C., Nowicki, S., Paulavets, K., Seneviratne, S. I., Stevens, B., Tuma, M. (2017). *Climate research must sharpen its view*. Nature Climate Change 7, 89–91. https://doi.org/10.1038/nclimate3206.

Shepherd, T.G. (2019). Storyline approach to the construction of regional climate change information. Proc. R. Soc. A, 475, 20190013, doi:10.1098/rspa.2019.0013.

Stammer, D., Bracco, A., Braconnot, P., Brasseur, G. P., Griffies, S. M., Hawkins, E. (2018). Science Directions in a Post COP21 World of Transient Climate Change: Enabling Regional to Local Predictions in Support of Reliable Climate Information, Earth's Future, 6 (11), 1498-1507. https://doi.org/10.1029/2018EF000979.

Sutton, R. T. (2019). Climate Science Needs to Take Risk Assessment Much More Seriously. Bulletin of the American Meteorological Society, Volume 100, Issue 9, p.1637-1642. https://doi.org/10.1175/BAMS-D-18-0280.1.

WCRP (2019). WCRP Implementation and Transition Meeting, 8/2019, 4-5 May 2019, Geneva, Switzerland. Online: https://www.wcrp-climate.org/WCRP-publications/2019/WCRP-Report-No8-2019-Implementation-and-Transition-Meeting.pdf

WCRP JSC (2019). World Climate Research Programme Strategic Plan 2019–2028. WCRP Publication 1/2019. Online: https://www.wcrp-climate.org/images/documents/WCRP_Strategic_Plan_2019/WCRP-Strategic-Plan-2019-2028-FINAL-c.pdf

Annex 1 - List of Participants

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Annex 2 - Agenda

WCRP High-level Science Questions and Flagship Workshop

Annotated Agenda

February 24-26, 2020

CEN-Universität Hamburg,
Bundesstraße 53, Hamburg

Note: "Flagship Objectives" were subsequently redefined as WCRP "Implementation Priorities" (see Section 6).

Goal of the Workshop:

After it was reviewed in 2017 on behalf of its sponsors, WCRP put together a new Strategic Plan in 2018 to guide WCRP's work during the next decade. It is now time to put it into action. Important steps in this direction will be marked by two high-level workshops that are required to prepare the implementation of WCRP's new research (or strategy?).

The goal of this first workshop is to refine the overarching research objectives of WCRP, and to think about activities/experiments required to reach them. Specifically, the workshop will discuss:

- **What are the one to three major objectives (Flagship Objectives) that need to be undertaken? by the WCRP to fundamentally advance climate science?**
- **Which central WCRP Lighthouse Activities/Experiments need to be organized to make progress toward reaching the new WCRP objectives in support of society?**

Discussions will involve the following issues:

- What are the top three overarching developments that can revolutionize our insight into the climate system and solve many societal challenges ahead of us?
- Is there one experiment that needs to be performed jointly by the international community that cannot be done by individuals because it is too big but that needs to be performed to make progress? Which question(s) would it solve?
- Is there a single big infrastructure item required to make this progress?

Output of the workshop will be the basis for further community discussion that will be required to reach a community consensus regarding WCRP's science challenges and the community-wide steps required to tackle them.

Output of this first workshop will also be the input for a second **WCRP Elements Workshop** to be held from March 23 to 25, 2020[3], which will discuss how the new WCRP could be structured in support of the identified **Flagship Objectives and Lighthouse Activities/Experiments**.

Day 0: Evening Organizing Team meeting

[3] The Elements and Structure Workshop was cancelled due to the Coronavirus Disease (COVID-19) that became a pandemic in early 2020.

Day 1 (24th February): 09:30-18:00

09:30 – 10:00 Registration, coffee and refreshments
10:00 – 13:00 Session 1, 2

(Coffee Break: 11:00 – 11:30)

Session 1: Opening and Welcome
Opening session summarizing the process, where we stand, goal of the meeting.

- Official Welcome from CLICCS Chair
- Official Opening from JSC Chairs
- Background and Goal of Meeting
- Where we have got to e.g. outputs from May 2019 Retreat; AGU/WCRP 40th Town Halls
- Discussion and adjustment of meeting approach

Session 2: Big Questions and Knowledge Gaps
Session setting the scene re. "thinking big", focusing on core WCRP science and providing a thought- and discussion-provoking stimulus for the remaining workshop.

- Big societally relevant questions/needs
- New and novel research required to address these needs?
    - Knowledge gaps
    - Limits to the assessment which are relevant for research directions
- Role of WCRP in the program landscape to address these questions

13:00 – 14:00 Lunch

14:00 – 17:00 Session 3: Proposals for WCRP Flagship Objectives

(Coffee Break: 15:30 – 16:00)

Session bringing in proposals for flagship objectives defining WCRP's highest level aspiration.
They should be equivalent to the WCRP's initial overarching objectives:

- *to determine the predictability of climate; and*
- *to determine the effect of human activities on climate*

17:00 Session 4: Summary and Discussion
This session will be open for external participants to join and provide input

18:00 Reception/Icebreaker (Hosted by CLICCS)

Day 2 (25th February): 09:00-18:00

8:30: Organizing Team meeting

9:30 – 13:00 Session 5, 6

(Coffee break: 10:00-10:30)

Session 5: Discussion of Input from Day 1 and preparation of Day 2

Session to review previous proposals on WCRP Flagship Objectives/Questions and to organize them according to the following categories or lenses:

- Flagship or Project in scope and aspiration?
- Capability "lens"
    a. Fundamental breakthrough in science and understanding
    b. New infrastructure development
    c. New collaborations / partnerships being built
- Feasibility "lens"
    a. Is it feasible in given time frame?
- Role of WCRP:
    a. WCRP to lead and facilitate
    b. WCRP to lead the co-design and co-delivery with Partners
    c. For others to do (i.e. of a national or regional scale); but WCRP could endorse

Session 6: Breakout Groups: Discussion and Refinement of Proposals
Session to discuss and refine previous proposals on WCRP Flagship Questions. The session should start thinking about specific scientific Lighthouse WCRP Activities/Experiments *required to address/answer the flagship questions. Examples: CERN for climate science, a global WCRP experiment, etc.*

13:00 - 14:00 Lunch

14:00 – 17:00 Session 6 continues.

(Coffee Break: 15:30 – 16:00)

17:00 – 18:00 Session 7: Plenary:

This session will be open for external participants to join and provide input

- Discussion of WCRP Flagship Questions
- First thoughts on required instruments/activities to answer the questions.

18:00 Meeting Dinners (hosted by CLICCS)

Day 3 (26th February): 09:00-16:00

8:30: Organizing Team meeting

09:00 – 09:30 Session 8: Summary of the previous Day

09:30 – 12:00 Session 9: Break Out Discussion of Lighthouse WCRP Activities/Experiments

Session to identify specific scientific Lighthouse WCRP Activities/Experiments *required to address/answer the flagship questions.*

(Coffee break: 10:00-10:30)

Discussion should take into account a capability lens as well, i.e.:

a. Infrastructure – what advances in our models and computing are needed; what new observational infrastructure (including networks, experiments etc.) might be needed; what other infrastructure capability needs to be developed?
b. People and skills – involving ECRs, less developed nations/regions, new skills and methods needed, capacity building.
c. Relationships – what new and existing partnerships and collaborations are needed?

12:00 – 13:00 Lunch

13:00 – 14:30 Session 10: Plenary synthesis of WCRP Flagship Questions and Lighthouse Activities and Experiments

14:30 – 15:00 Coffee break

15:00 – 16:00 Session 11: Meeting Summary statement

This session will be open for external participants to join and provide input

- WCRP Flagship Questions
- Lighthouse Activities and Experiments
- Needed advances in our models and computing are needed;
- New observational infrastructure (including networks, experiments etc)
- Required WCRP expertise and partnerships
- Next steps

16:00 Closing of Meeting

Annex 3 - Acronyms

AGU	American Geophysical Union
AR5	Fifth Assessment Report (IPCC)
AR6	Sixth Assessment Report (IPCC)
AR7	Seventh Assessment Report (IPCC)
CliC	Climate and Cryosphere (WCRP Core Project)
CLICCS	Excellence Cluster of Climate, Climatic Change and Society
CLIVAR	Climate and Ocean Variability, Predictability and Change (WCRP)
CMIP	Coupled Model Intercomparison Project (WCRP)
CORDEX	Coordinated Regional Climate Downscaling Experiment (WCRP)
COVID-19	Coronavirus Disease 2019
E3SM	Energy Exascale Earth System Model
ECMWF	European Centre for Medium-Range Weather Forecasts
ESA	European Space Agency
ESGF	Earth System Grid Federation
ESiWACE	Centre of Excellence in Simulation of Weather and Climate in Europe
EU	European Union
EURO-CORDEX	European branch of CORDEX
GAW	Global Atmosphere Watch (WMO)
GC-Carbon	Grand Challenge on Carbon Feedbacks in the Climate System (WCRP)
GC-Clouds	Grand Challenge on Clouds, Circulation and Climate Sensitivity (WCRP)
GC-Extremes	Grand Challenge on Weather and Climate Extremes (WCRP)
GC-Ice	Grand Challenge on Melting Ice and Global Consequences (WCRP)
GCM	Global Climate Model
GC-NTCP	Grand Challenge on Near-Term Climate Prediction (WCRP)
GCOS	Global Climate Observing System
GC-Sea Level	Grand Challenge on Regional Sea-level Change and Coastal Impacts (WCRP)
GC-Water	Grand Challenge on Water for the Food Baskets of the World (WCRP)
GEWEX	Global Energy and Water Exchanges (WCRP)
GOOS	Global Ocean Observing System
HPC	High Performance Computing
IOC	Intergovernmental Oceanographic Commission of UNESCO
IPCC	Intergovernmental Panel on Climate Change
ISC	International Science Council
IS-ENES	e-infrastructure of the European Network for Earth System Modelling
JPS	Joint Planning Staff
JSC	Joint Scientific Committee
NASA	National Aeronautics and Space Administration
RCM	Regional Climate Model
S2S	Subseasonal-to-seasonal (S2S) Prediction Project (WCRP)
SDG	Sustainable Development Goal
SPARC	Stratosphere-troposphere Processes And their Role in Climate (WCRP)
SREX	Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SRM	Solar Radiation Management
SSG	Scientific Steering Group
UNFCCC	United Nations Framework Convention on Climate Change
WASP	World Adaptation Science Programme
WCRP	World Climate Research Programme (WMO-IOC-ISC)
WDAC	WCRP Data Advisory Council
WG I	Working Group I (IPCC)
WG II	Working Group II (IPCC)
WGCM	Working Group on Coupled Modelling (WCRP)
WGNE	Working Group on Numerical Experimentation (WCRP)
WGRC	Working Group on Regional Climate
WMAC	WCRP Modelling Advisory Council
WMO	World Meteorological Organization
WWRP	World Weather Research Programme (WMO)

Annex 4 - Input to the Workshop

Input from the WCRP Task Team on Regional Activities to the WCRP Workshop on Fundamental Science Questions 24-26 February 2020, Hamburg

Prepared by
Clare Goodess and Bruce Hewitson, co-chairs
Working Group on Regional Climate (WGRC)
February 19, 2020

1. What are new and most promising approaches to distill decision- and scale-relevant climate information from across data sources, data types, and relevant scales of time and space through leveraging the multiple sources from the WCRP and related external programs?
2. How can differences and contradictions between data sources be best assessed, understood, and reconciled (e.g. within a CORDEX multi-model ensemble, between RCMs and GCMs, or between model historical simulations and uncertain observations)?
3. What innovative methodologies and analyses can be developed to advance the physical understanding of the combinatory roles of multi-scale climate processes that drive a region's climate in order to improve the relevance and defensibility of regional climate information for society?
4. Which time scales are of priority for research in order to best inform the information needs of a region, and how should these time scales be identified?
5. How can stakeholder knowledge about the information needs for their decision and policy challenges be better leveraged to inform the design and implementation of WCRP supported research?
6. What mechanisms can the WCRP implement to better align research outputs to the key attributes of the climate system that have identifiable relevance to thresholds and vulnerabilities in the coupled socio-ecological systems in a region?

EURO-CORDEX input for WCRP

Scientific challenges
Also in context of WCRP, upcoming WCRP workshop on science questions/challenges, steering the directions of WCRP in next 5-10 years (end Feb.)

- Fully Regional Earth System Approach (human dimension included)
- km-scale / convection permitting RCM simulations
- Realistic representation of extremes and related processes (e.g., land-atmosphere, aerosols, water cycle)

- Looking at statistics is often done, could look more to the dynamics/formation comparing the extreme events, e.g., throughout our simulations.
- Storyline approach, physical based changes in future
- Compound events
- Connection to observational knowledge & meso-gamma modeling
- Inform local scale (e.g., coastal, cities, etc.)
- Trends simulation, particularly in historical (control) runs (Representation in GCMs/RCMs, attribution, persistence, ESD approaches, comparison to ERA5/ERA-interim)
- Regional predictability
- Probability / robustness / distillation

→ Daniela and Jens to refine as input for WCRP (involving CORA)

Input from Frederic Vitart and Andrew Robertson (S2S)

Regarding your request for input for the future WCRP flagship overarching objectives, we would suggest the following evolution of the 2 original WCRP overarching objectives (which have the advantage of great simplicity):

1. Develop the scientific and modeling capabilities to provide reliable seamless environmental and regional predictions from weeks to a decade.
   - This would involve testing and verifying climate models in initialized model at shorter time ranges
   - This would include interdisciplinary research together with sectorial applications communities (e.g. hydrology, energy sector, agriculture...) and co-development of solutions with stakeholder communities
   - Use of AI for calibration, skill assessment. multi-model combination, parameterization, data assimilation...
2. Determine the effect of human activity on global and regional climate
   - This would involve reducing uncertainty in IPCC climate change projections by selecting only "good" models (better to have a reduced set of better models than too many models with poor performance), by analysing model output in S2S initialized model ("transpose CMIP")
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In terms of the 4 Strategic Plan Scientific Objectives, we'd emphasize the importance of Science Objectives 1 & 4, as essential cross-cuts across both of the above (which are roughly Science Objectives 2 & 3, though with initialized prediction being important to both). Maybe the overarching objectives need to be called something other than "objectives," to prevent confusion with the 4 Scientific Objectives in the Strategic Plan?

Input from Bjorn Stevens

Dear Detlef, dear Colleagues,

I had my say in this essay with Tim Palmer: https://www.pnas.org/content/116/49/24390

It is short and hopefully worth reading. As a follow on I would say that WCRP reflects a structure that largely still represents how science worked in the pre-internet days. Many of the things it coordinates now would, and do, function just as well without its help.

If people think climate change is important then why is there no international infrastructure that supports it. Why does our claim to success (CMIP/CORDEX) lie in rummaging like vagrants through the debris of output from outdated modeling tools developed on infrastructures inherited from — here speaking as an early career scientist — our grandparents.

We need a global climate research center, comprised of regional (continental) centers that links to the very best in information technology and professionalize our assessment of the present and past state of the climate and our projections for the future. With the EUs announcement of 'Destination Earth' today there is a window of opportunity to set an example of what I mean. We should grab it.

Input from Alex Hall

Though I won't be able to make the meeting, my take can be found in my AGU Turco lecture, the link to which is below.

https://www.youtube.com/watch?v=NLS89jMpmwI

My thoughts are very much influenced by Bjorn, and especially his sense that our science and scientific institutions are now outdated and not nearly at the scale they need to be to grapple with the challenges. Though of course in other ways my take is different.

I'm sorry I won't be able to join you for this important meeting. Best of luck with it!

Input from Ted Shepherd

My current thoughts in terms of what is needed are represented in my paper

https://royalsocietypublishing.org/doi/full/10.1098/rspa.2019.0013

Not sure this translates into a WCRP activity, however!

The
World Climate Research Programme (WCRP)
facilitates analysis and prediction of Earth system change for use in a range of practical applications of direct relevance, benefit and value to society.

World Climate Research Programme