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A WCRP vision for accessible, useful and reliable climate modeling systems

Report of the Future of Climate Modeling Workshop

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Executive Summary

The World Climate Research Programme (WCRP) convened a strategic online workshop on WCRP's Future of Climate Modeling from 21 – 24 March 2022. The workshop followed the setting up of WCRP Lighthouse Activities and the creation of two new core-projects, the Earth System Modeling and Observations (ESMO) and the Regional Information for Society (RIfS), all of which were approved at the 42nd Session of the WCRP Joint Scientific Committee in July 2021. The workshop was run under the auspices of ESMO.

The task of the workshop was to develop ideas about the future climate modeling landscape and the steps that need to be pursued by ESMO to support WCRP's goals for climate and Earth System Modeling over the next decade. In this respect, the workshop was intended to provide a basis for the ESMO science plan. It built on previous consultation activities and is part of a series of ongoing discussions which include the role of future Coupled Model Intercomparison Project (CMIP) activities and the strategic plans for the ESMO core activity.

The main outcome of the workshop is the urgent and critical need for accessible, reliable and useful modeling systems that simulate the Earth's climate system - across space and time scales - with demonstrable fidelity and process representation. Achieving this requires our community around the world to raise its ambition, building on and amplifying our strong global collaborations and innovation, to meet this challenge. This change is needed to properly address WCRP's science goals as stated in the Strategic Plan and in the Science and Implementation Plan. These changes are also necessary to inform and guide a world that is attempting to transition towards net zero emissions and, at the same time, deal with and adapt to the worsening impacts of climate change by providing improved and more useful information. We now have the opportunity to adopt new technologies and new ways of working that make climate modeling more useful and accessible. Specifically, workshop participants called for a step change across the eight linked modeling dimensions (Figure 1) outlined below.

1. **Enhance scientific fidelity and use of observations.** We need to better understand different types of model uncertainty and model accuracy and understand how they vary across scales. We need to better understand the science associated with risk and limits of knowledge. This includes better use of observations to test, constrain and improve models through comprehensive data assimilation and parameter estimation; use of paleoclimate information and simulations; how to interpret model agreement and where to target improvements and reduce uncertainty. Additionally, we need to enhance process-level understanding of different components of the Earth's climate system and interactions between them to advance representation in models. Key choices such as model resolution need to be made to advance science and optimally represent physical and biogeochemical processes.
2. **Become flexible, responsive and innovative.** Rather than having a single modeling approach dominate, we call for a multiverse of connected modeling approaches to address the many different types of problems, embracing both existing tools and developing new ones (such as process-specific models, digital Earths, improved Earth System Models (ESMs), physical emulators and machine learning approaches). We need to become more responsive and agile to focus efforts on specific scientific discoveries and target user needs.
3. **Grow the diversity of the workforce.** We need to grow a more agile and varied workforce with respect to climate modeling. We need to embrace new skills and new disciplinary backgrounds. A 21st Century approach is needed that supports and facilitates

global north / developed nations to partner with Global South nations to build real capacity in their regions and communities so that climate modeling efforts around the world learns from their expertise and regionally specific insights. To do this we need to support flexible international career paths across computer sciences, data sciences, climate research, academia, and the private sector. It will require developed nations to learn how to meaningfully collaborate with communities in less developed nations and regions and will require significant investment in building and sharing capacity around the world. Progress is needed in data sharing, HPC access and skills.

4. **Move from collaboration to coordination.** The world needs urgent answers on multiple fronts. To best utilize resources, WCRP has a crucial coordination role to focus efforts and improve efficiencies. We envision new partnerships across national centers, international collaborative efforts, universities and the private sector to maximize science and societal benefits and strengthen capacity (as mentioned in #3). We can better harness the private sector, e.g., coordinating directed partnerships; accessing cloud computing and storage and by getting more directly involved in designing hardware platforms - in ways that complement and strengthen our ability to achieve our goals.
5. **Improve accessibility and usability.** Building from the success of the CMIP6 protocols, we need to go further to develop improved standards and software for modeled and observed data and software sharing. We can further develop model analysis tools that work across varied model types and observations to speed up progress and provide easier entry points to the science.
6. **Establish co-design.** To ensure that our modeling tools are fit for answering societally relevant questions, WCRP need to co-design areas of focus, approaches and simulations with the users and key partners, such as the Intergovernmental Panel on Climate Change, programs, such as Future Earth, and the private sector.
7. **Professionalize operational aspects and climate services**. End user needs are distinct from research needs and require better coordination over longer timeframes and with many more users. A standardized robust modeling approach is needed, with greater use of emulators to assess risks in a computationally efficient manner. How climate services spin off from models needs to become more transparent with greater co-design and there are clear benefits for enhancing the feedback between operational and research programs. Different sets of expertise are needed to run such an activity.
8. **Achieve net zero climate resilient modeling.** Our community needs to lead by example and transition to net zero emissions as fast as possible in a way that brings added co-benefits to our community. The computers**,** data storage and data transfer need to be as efficient as possible and powered by renewable energy. The activities of the researchers including their travel needs to be factored into science delivery. We can set a leading example by transparent monitoring of energy use and our emissions. We urge WCRP to work with its many stakeholders to develop a credible net zero emissions pathway. Current and future infrastructure also needs to be resilient to future climate changes.

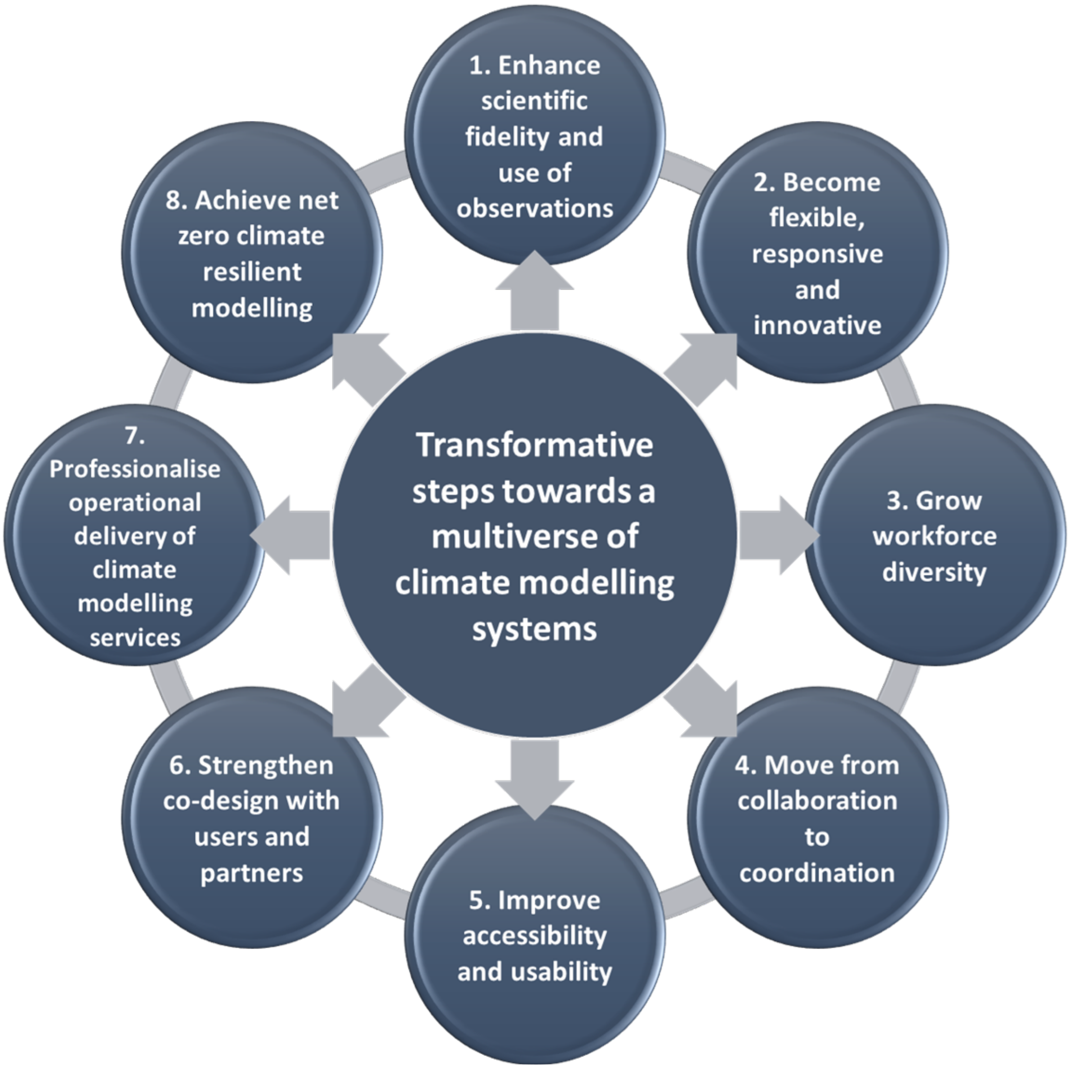

Figure 1. Eight linked steps towards an accessible, reliable and useful climate modeling system.

These steps require a whole-community approach, and investment from many programs and agencies around the world. WCRP, and with it ESMO, has the mandate and experience to lead and facilitate these recommendations for a step change in climate modeling. From the workshop, nine direct recommendations follow for ESMO's future activities, under the leadership of the WCRP, across the eight dimensions of action mentioned above:

1. It was clear from the workshop that a single modeling approach should not dominate the resource, whether this be CMIP-class ESMs or new 1-km resolution global models. To make this point, a review paper on the modeling landscape will be developed showing how different individual and combined modeling approaches are needed to answer specific scientific questions. In other words, assess fitness-for-purpose of models based on the requirements that the model should be scientifically useful, reliable, and feasible. The paper will also identify current gaps in capability.
2. Play a coordination role across national centers and universities to spread the global effort and increase the diversity of approaches for climate modeling. WCRP could form a high-level coordination board based on center leads, and international academic and stakeholder needs.
3. Launch and coordinate a process understanding campaign with obs4MIP to design and improve model fidelity.

4. The community needs to support capacity building in the Global South to develop future leaders. Specifically, workshop participants called on WCRP to support the hosting of a global-south led meeting to develop a vision of their 2030 climate modeling landscape and identify leadership and support opportunities for delivery. WCRP should also start a climate modeling ambassador program and climate hackathons to grow the diversity of the skills base as well as provide information on career pathways. WCRP should also support Global South access to HPC climate centers in the global north where possible or by working with climate data in the Pangeo cloud at Google, Amazon, Microsoft.
5. WCRP can lead on interacting with funders to support a wider set of climate modeling approaches, including private funders. We especially ask WCRP to host a high-level meeting between private sector initiatives (e.g. Nvidia), national computing centers and major public funding bodies (e.g. Horizon Europe) to envision the multiverse of models through a co-design process with a wide range of stakeholders.
6. Extend the CMIP6 analysis tools to work across wider modeling infrastructures beyond coupled models and also to compare observations, overall making them more accessible and interoperable. Specifically, we ask WCRP to work with analysis developers around the world to organize the development of a set of model and observational analysis suites that work in a diverse model landscape where the data and analysis are co-located.
7. Promote co-design and wider stakeholder input by linking with other programs more effectively. Specifically, we suggest that CMIP7 is designed with wide consultation across the IPCC Working Groups and beyond. For example, CMIP7 might be staggered to allow sensitivity analyses on DECK simulations to better understand and constrain key model processes and metrics in concert with a hierarchy of models. Probabilistic physical climate emulators could be incorporated into CMIP7 design in collaboration with the IPCC WGIII community and CMIP7 could better align with impact modeling efforts by adjusting the IPCC WGII timeline accordingly.
8. The UNFCCC or WCRP governing bodies are strongly encouraged to launch a World Climate Operational Modeling Programme. This should have a strong connection to WCRP but have a mandate to develop a standard and transparent approach to deriving timely advice on mitigation and adaptation decisions. For example, operationalizing aspects of bias correction and obs4MIPs as well as impact modeling architectures and climate emulator approaches. This should include a strong emphasis on communication.
9. Take the lead in developing a climate resilient net-zero emission pathway for the global climate modeling community. Specifically, we recommend that WCRP develops a carbon footprinting method based on the Barcelona Computing Centre's protocols, then rolls this out across the community. Further, WCRP should make having transparent carbon footprinting and a published net zero pathway as a prerequisite for joining future intercomparison efforts.

We expect the vision and implementing these associated recommendations will take over a decade to implement and that new approaches will be developed alongside existing methods. To realize the vision, we will need to work hard at building bridges across the various parts of our community and beyond.

Overall, this paper calls for a transformative eight step change in global coordination of the climate modeling effort for impactful, urgent, and net zero science delivery that meets the needs of global society. We should engage a wider group of stakeholders in discussion going forward and urgently begin the co-design process

Contents

1. Introduction

Over 21-24 March 2022 the World Climate Research Programme (WCRP) ran an invitation-only workshop on the Future of Climate Modeling. Invitations were targeted to ensure a representative cross section of career stages, expertise, institutions and geographies. The agenda is available in Annex 1. The purpose of this Workshop was to build a common sense of purpose and ambitious goals for climate modeling going forward. As the WCRP provides worldwide coordination, as it has done for over four decades, we wanted to identify how the role of the WCRP in climate modeling should evolve now and what its priorities should be.

It is a pertinent time to examine the global climate modeling landscape and look at future directions. Two of the earliest climate modeling developers, Syukuro Manabe and Klaus Hasselmann, won half of the 2021 Nobel Prize for Physics for "for the physical modeling of Earth's climate, quantifying variability and reliably predicting global warming". This clearly recognizes the foundational role that climate models have played in climate science and how they are central to attributing and projecting climate change. 2021-23 also saw the publication of the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report series. Like the reports before it, much of its Working Group I assessment was informed by climate modeling studies, especially coupled climate models. WCRP's Coupled Model Intercomparison Project has run parallel to the IPCC cycles, and its latest iteration (CMIP6) was an unprecedented global modeling and analysis effort to probe physical processes, test models and produce future projections of climate. CMIP provides a framework to evaluate, intercompare and improve global models, and support climate assessments. Over 100 climate models participated in CMIP6 and its results were used across the IPCC report, from attributing past changes to projecting climate extremes. Other types of models are also increasingly being used across our community and their results influencing IPCC assessments. High resolution process models are representing the physics of ice sheets and clouds in detail to assess the chance of abrupt sea-level rise and quantify climate feedback, respectively. Simple physical climate model emulators are used to mimic coupled model responses to make constrained probabilistic estimates of future temperature and sea-level change. The benefits of the climate modeling effort over the last 50-years are profound, their role in studies attributing climate change and making projections has aided the world to change direction through the UNFCCC process and especially the 2015 Paris Agreement.

However, in spite of these successes, chronic model problems remain, such as model biases. As an example, uncertainties in the projection of rainfall changes are persistent and wicked (Slingo et al., 2022[1]). The global climate modeling effort requires large hardware, data storage and skill resources, has numerous duplications and has a high barrier to entry. The work is largely focused at publicly funded national centers and universities in a few global north countries. In spite of the level of effort, the modeling effort often lags the policy need. For example, at the time of the Paris Agreement, in 2015 the modeling community had not explored 1.5oC pathways. Increasingly, as the world's governments move to deploy mitigation and adaptation solutions, they are increasingly looking to the climate modeling community for urgent answers. However, unlike weather forecasting models, climate models remain squarely in the research domain and a plethora of rather ad hoc "climate services" approaches have grown up around them to translate their findings.

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[1] Slingo, J., Bates, P., Bauer, P. *et al.* Ambitious partnership needed for reliable climate prediction. *Nat. Clim. Chang.* **12**, 499–503 (2022). https://doi.org/10.1038/s41558-022-01384-8

It is obvious that in a world that needs to rapidly transition to net zero emissions, climate modeling approaches need to change. Less clear is how and the goal of the workshop was to identify exactly this answer which is provided above in the executive summary.

A pre-workshop questionnaire revisited the purpose of climate modeling by asking three fundamental questions:

1. What are the main **societal** challenges that climate modeling needs to address?
2. What are the main **science** challenges that climate modeling needs to address?
3. What should the climate modeling landscape look like in 2030 (and 2050)?

We also asked participants to consider the technical developments that might be required and how WCRP might need to adjust its approach to meet the scientific and societal challenges?

The 56 anonymous responses to these questions and their summaries were shared with workshop speakers to inform their perspectives. Workshop attendees were encouraged to be challenging and gave thoughtful answers. Participants engaged in lively discussions over the four days, both verbally and through written comments, such that the written comments ran to over 200 pages of Etherpad notes.

The three main sessions and seven breakout group discussions are summarized below, with detailed workshop material presented in the annexes.

2. Workshop summaries

2.1. Plenaries

2.1.1. Challenges of Climate Modeling

Chairs: Helen Cleugh and Vaishali Naik
Rapporteur - Laura Wilcox

This session discussed some key climate modeling research challenges from across the climate science community.

Ruby Leung (PNNL, USA) discussed ultra-high resolution modeling at less than 10km resolution in the atmosphere and at eddy resolving scales in the ocean. Such models can be skillful without tuning and can be particularly useful for representing extremes such as storm structure, wind intensity and atmospheric rivers. They are useful for understanding cloud feedbacks and could potentially be used in training for machine learning. Ultra-high resolution models are just one of the tools to address many challenges, some other key challenges identified were modeling sub grid processes, carbon and nutrient cycles, ice dynamics and internal variability. Even at 3km resolution mesoscale convective systems do not have realistic organization in models.

Tim Palmer (Oxford, UK) discussed next generation climate modeling and encouraged the community to think big, such as a large hadron collider or James Webb telescope. He envisions the community working together on a network of exascale computers doing coordinated km-scale ensembles for decadal prediction. Such models would have the benefit of better physics, avoid parameterization of key processes such as deep convection, eddy mixing and orographic wave drag. Overall systematic errors would be smaller and extremes would be better represented. It would also allow for better assimilation of observations and reanalysis products.

Elena Shevliakova (GFDL, USA) discussed challenges with biophysical and biogeochemical feedbacks. These included the representation of marine ecosystems. Models now capture elements of nutrient exchange but coastal processes remain difficult to model. Atmospheric chemistry still needs better connection to the biosphere and ocean. Few models have dynamic vegetation or represent irrigation and other agricultural processes. We still don't understand the major drivers of carbon uptake. These issues are unlikely to be resolved by high resolution alone as key processes are missing from models. We also need targeted observations to provide observationally based constraints.

Sabine Attinger (Helmholtz Centre for Environmental Research, Germany) discussed hydrological and regional modeling challenges, starting from the point that flooding and droughts are two of the most devastating effects of climate change. Climate models have more skill than statistical drought models in drought forecasting. However, flash flooding can only be forecast 1-2 days in advance at best. There is a need for both high resolution, better observations and bias correction approaches. Data assimilation is key as is faster and improved ways of coupling climate and hydrological models.

Baylor Fox Kemper (Brown University, USA) and June - Yi Lee (IBS Centre for Climate Physics, South Korea) examined the challenges of climate modeling from an IPCC AR6 WGI perspective. IPCC used results from a wide variety of models to cover a range of spatial and temporal scales. The CMIP cycle usefully triggered a lot of other modeling activities. Deeper analysis of multiple lines of evidence will therefore benefit from further CMIP-IPCC alignment. Physical climate emulators were used to go beyond the end of SSP simulations for sea-level rise and help understand sensitivities. Overall IPCC would benefit from an improved fitness for purpose tests of models, e.g. in their representation of precipitation and circulation patterns where there are still large biases. Large ensemble runs were only used in a limited way and more could be made of them to quantify uncertainty. It remains an issue that some processes are not represented in CMIP models. There is a large near-term uncertainty in projections and CMIP6 did not particularly target this. Few model evaluation studies focus on processes. Overall AR6 had a broader assessment of scenarios compared to AR5, but many scenarios are not explored with CMIP models and probabilistic predictions remain challenging.

Jean-Francois Lamarque (NCAR, USA) and Matthew Mizielinski (Met Office, UK) discussed CMIP6 successes and where next? The community significantly benefited from the CMIP6 structures, such as common experiments, data standards and metric packages. It would be useful to better understand which common experiments are the most useful for understanding structural uncertainties. Investment in structure is important to support new science. Given large datasets it is increasingly important to co-locate both the data and analysis software. In the future we envision more projects using aligned standards with increased access to data. CMIP6 was a large investment (over $3 billion) in terms of time needed to design, run and analyze results, questions over the best use of this resource e.g., resolution over ensemble size, whether or not to focus on processes or projections? Generally we need to maximize the relevance to support community needs.

Pierre Friedlingstein (University of Exeter, UK) discussed the challenges of working towards net zero for climate modeling practices. Globally, emissions need to halve by 2030 to address climate change. Climate scientists fly more than other researchers and although computers are becoming more efficient, consumption is increasing. We should monitor and report our carbon footprint and challenge ourselves that CMIP7 should have half the carbon footprint of CMIP6. Also we should consider targeting science more towards the green agenda, e.g. by focusing more on low emission pathways or avoided impacts.

Discussion

On high resolution, there was general agreement that ultra-high resolution forces a focus on process-resolving scales, which means that any tuning takes place at these scales rather than global scales, so arguably such models would be getting things such as the outgoing longwave radiation right for the right reasons. However, it was still difficult to assess whether such models would have improved large scale circulations and whether their projections would be more reliable. Uncertainties in observations need to be considered carefully when assessing the skill of these models and there was discussion over the problems that could be addressed just using such models.

On a large focused effort on high resolution it was acknowledged that extra computer power will not solve everything if processes are not represented well and as much as flooding and other high impacts benefit from high resolution, they also depend on other processes at different scales - such as circulation patterns. The consensus was that a connected model hierarchy - or multiverse - was needed, and these needed to be at a range of scales; fragmented modeling efforts at both high- and low-resolution scales would not be helpful. It is also important to understand how societal information might feed into these tools and how society might benefit. How, for example, would high-res models help decadal prediction? Generally much more progress is needed to understand and agree on the interpretation of model fidelity. AR6 really demonstrated the value of model hierarchies as ESMs did not span the full uncertainty range.

The discussion of complexity covered how we test which processes are needed for a given purpose and issues with empirical parameterizations. High resolution would improve carbon uptake by ocean but the land sink would still be poorly constrained. Overall progress is limited by a lack of observations and a separation between the modeling and observational communities. Sometimes when models give similar results it may be a lack of understanding rather than evidence of a constraint. Generally observational gaps and the quality of paleo data makes constraining models challenging.

The dual role of CMIP6 for both science and operational planning was discussed. How can it better support climate services when designed more as a research exercise? How could large ensembles of PPEs reduce uncertainty and estimate errors. Generally, it was felt that CMIP would benefit from collocation of data and analysis tools and well as stronger links to the IPCC and user community.

On greening the working practice, we all agreed on the importance of setting a transparent leadership example and discussion focused on how a new generation of researchers could take the lead in designing and using remote-working collaboration tools.

2.1.2. Societal Needs for Climate Information

Chairs: Rondrotiana Barimalala, Silvina Solman
Rapporteur: Chris Smith

This session presented some external views on what the societal needs for better climate modeling tools and processes are.

Kristie Ebi (University of Washington, USA) discussed the human health needs for climate information. Climate change interacts with a broad range of health risks, including heat-related illnesses, malnutrition, vector-borne disease, poor air quality and decreased worker productivity. Low- and middle-income countries are already dealing with multiple issues and climate change, health and poverty cuts across all these issues. Development pathways (e.g., SSPs) are as important for health adaptation to climate as temperature change is. It would be helpful for epidemiologists and climate modelers to understand what the other community requires. For epidemiologists: are the scenarios useful? For climate modelers: which model diagnostics? There exist studies where one community tries to produce climate and health research without consulting the other, and often get things wrong. Future challenges in health-climate research include detection and attribution by determining the magnitude and burden of climate change on the extent of illness, injuries and deaths, projecting the magnitude and pattern of health risks under a range of climate and development scenarios, estimating the costs to individuals and health systems of the health risks of climate variability, and estimating the health co-benefits of mitigation policies and technologies. Early warning systems for climate-related health risks should be a priority and would save lives and money.

Rob McSweeney (Carbon Brief, UK) discussed communications around the carbon budget. The remaining carbon budget (to e.g., 1.5°C) is a simple concept that relates cumulative CO_2 emissions to global warming, using the fact that a near-linear relationship exists between these variables. Although carbon budgets have been used in a fashion since the 1990s (e.g., Greenpeace in 1997 came up with a 1°C budget) the concept really took off in the 2009-2013 period with the realization of the linear cumulative CO_2 to temperature relationship and ultimate highlighting in the IPCC Fifth Assessment Report. Conversations about carbon budgets abounded in the media and beyond and by 2015 carbon budgets had established themselves as a key element of international climate policy. Like many simple concepts, it gets misused and mis-communicated, and this simple linear relationship hides many nuances and uncertainties. Millar et al. (2017)[2] showed that the remaining carbon budget from observations of CO_2 emissions and temperature was about 300 $GtCO_2$ greater than Earth system models (the figures reported in AR5). This caused an uproar in the sceptic media, with accusations that climate scientists were getting the models wrong or being deceptive, in some cases also arguing that scientists could not agree. The media narrative shifted also to attack climate policy ("swingeing green taxes") which were little to do with carbon budgets. In the years since, the media landscape has changed but there are still voices looking to jump onto anything perceived as a course correction. The importance of careful communication of seemingly simple but deceptively complex concepts like carbon budgets is now apparent.

Joeri Rogelj (Imperial College, UK) and Malte Meinshausen (University of Melbourne, Australia) discussed IPCC Working Group III report and mitigation policies. A key focus of the IPCC Working Group III report is to provide emissions pathways of potential socioeconomic scenarios. The SSPs are but a small subset of these, with over 1200 scenarios used in the 2022 IPCC Working Group III report. Therefore, there are too many scenarios to run in Earth system models, requiring tools such as climate emulators (reduced complexity models). This enables us to answer one of the key questions which is how much warming we would expect for a given pathway of emissions. IPCC Working Group I-Working Group III integration enabled this to be performed successfully in AR6, but there are other challenges that require attention such as whether mitigation strategies are resilient to climate change and how we can better integrate Earth system science and mitigation studies. Current challenges include refining carbon budgets and net zero commitments, to include the warming from non-CO_2 emissions, zero emissions commitments to all forcers, emissions-driven runs, links to UN climate policy and better quantification of carbon cycle feedbacks and uncertainties. For many in the mitigation community, carbon budgets are equivalent to temperature. As discussed in Rob McSweeney's talk, this needs to be carefully nuanced. Exciting developments are occurring in some Earth system models, for example the capability to run with methane emissions in UKESM.

Chris Lennard (University of Cape Town, South Africa) discussed impacts and adaptation in the context of IPCC Working Group II - Based on the IPCC WGII assessment, scientific evidence

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[2] Millar, R., Fuglestvedt, J., Friedlingstein, P. *et al* Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nature Geosci* **10**, 741–747 (2017). https://doi.org/10.1038/ngeo3031

is unequivocal in the way climate change affects people and goods. About half of the world's population live in hotspots of high vulnerability to climate change. To avoid mounting losses, urgent action is required to adapt. When we talk about adaptation, the goals are to strengthen resilience and reduce risk and vulnerability. This includes enhanced biodiversity, achievement of SDGs, reduction of GHG emissions and reduction of climate risk. Risks in this context include compound extreme events. Climate modelers can contribute by developing early warning systems for drought, heat, disease, floods with modeling at relevant time and space scales. Timescales required for adaptation are currently underserved by climate models, with a "valley of death" between S2S (sub-seasonal to seasonal) and S2D (seasonal to decadal) modeling. Reduced uncertainties in the climate models or improvement in the understanding of uncertainties are also relevant for the impacts and adaptation communities. Additionally, several variables important for adaptation could be better derived from climate models. This includes water availability, fisheries, health, REDD+ and land use, and renewable energy availability. The communication of climate information - what it can and cannot be used for - is important to avoid maladaptation. Regional models with high resolution (e.g., CORDEX) are very important for this community.

Mandira Shrestha (ICIMOD, Nepal) discussed the role of communities in the Global South. The case study of Mandira's talk was the Hindu-Khush-Himalaya region known as the "third pole" with the largest reserve of snow and ice outside of Antarctica and Greenland. High mountain and polar regions are warming much faster than the global mean with consequential extreme and erratic events. In a 1.5°C world glacial lakes will lose a third of their volume by 2100. Economic and natural impacts are increasing – a third of disasters are from floods. Impacts are transboundary. For example, in 2021 a huge rockfall happened upstream which caused floods downstream. In this region (though applicable to many regions in the Global South), challenges to adaptation are caused by remoteness, network densities, limited data sharing and limited capacity. Much climate and adaptation information are not tailored. Gender aspects need to be considered for responsive climate services. The end goal is to provide an entire chain from production of climate data through to use. Opportunities include tools and technology for capacity building, frameworks for reducing risks (hazard, exposure, vulnerability), gender mainstreaming, institutional capacity building and use of projections, Identification of gaps and needs, understanding and mapping the user landscape, stakeholder consultations, developing of modeling tools for monitoring and modeling, Earth observation. Finer resolution models are desirable, as we want to be able to describe what it means to the farmer or the planner.

Discussion

There was discussion around the most policy-relevant scenarios to invest significant computing resources for Earth system science. There should be more of a focus on deep mitigation scenarios, overshoot scenarios around 1.5°C and 2°C, and to avoid wasting resources on non-plausible and too many high-warming scenarios. Large ensembles of realistic mitigation scenarios will allow attributions and analysis of extremes. Alongside this we need to continually develop emulator tools and to invest more in climate post-processing and make them available to WGIII.

A key issue was that many CMIP6 results were not available in time for the production of the IPCC Working Group II report, and that many assessments relied on CMIP5. There was discussion around making WGII come first to deliberately lag the newer model results.

During the general discussion of this session, interesting issues arose about using the experience of the weather modeling to identify strategies that provide information relevant to societal needs and on the need to enhance the communication between the modeling and impact communities.

2.1.3. Science and Technology

Chairs: Roland Séférian and Angeline Pendergrass
Rapporteur: Aiko Voigt

The session presented ongoing developments in the wide realm of Earth system modeling and covered a broad range of topics that span many orders of magnitude in space and time. Figure 2 gives an indication of the current and future evolution of the diversity of Earth System Modeling.

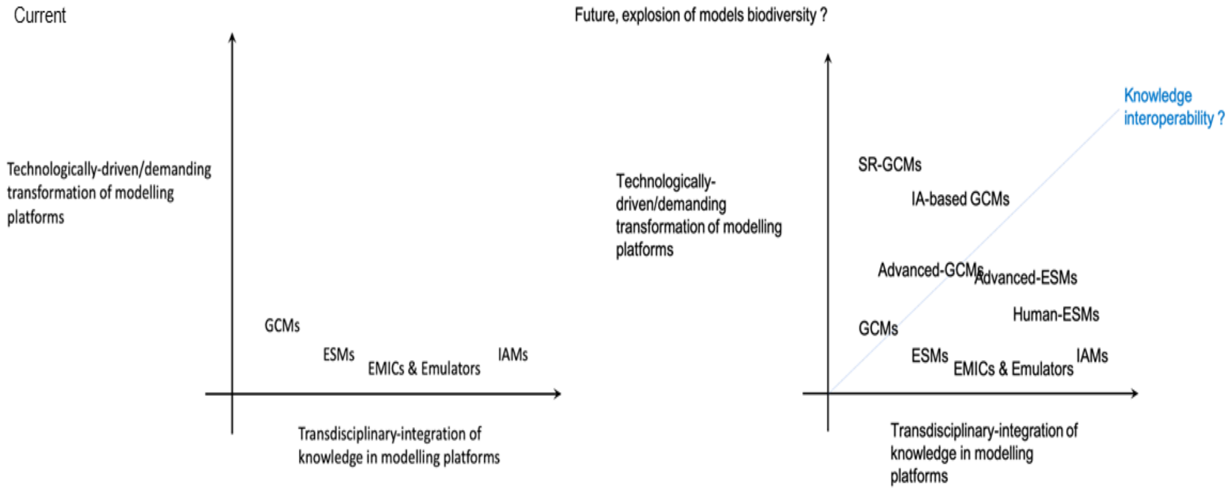

Figure 2. A vision for Earth System modeling (Aiko Voigt, Roland Séférian)

Daniel Klocke (MPI-M, Germany) presented work with so-called storm-resolving models that aim to represent the global Earth system with horizontal resolution of 1 km. Such models are currently being developed in a few large-scale research efforts, including the EU-funded NextGEMS project. Recent work indicates that model throughput of several simulated years per day might soon be achieved. Daniel emphasized that the promise of these models is not in solving long-standing challenges such as clouds in a miraculous way, but rather in providing a digital representation of the Earth system that is much better anchored in physics that we understand. As such, one hope is to test the extent to which the climate change signal of km-scale models might be structurally different from that of current coupled climate models with parameterized convection and ocean eddies, as this might allow us to avoid surprises (i.e., unknown unknowns) in the climate change response.

Stephanie Fiedler (University of Cologne, Germany) showed work on chemistry composition-climate models. This work in particular aims to understand how aerosols affect patterns of regional climate change via their impact on sea surface temperature, the AMOC and atmosphere and ocean circulation. Stephanie discussed the continued presence of trade-offs between model resolution and ensemble size that arises because interactive aerosols are a computationally expensive model component. She provided the example of the Tri-MIP project, which is an intersection of AerChemMIP, RFMIP and PDRMIP, which is rather costly. Participant discussion highlighted methane (CH_4) as a needed addition to chemistry-climate modeling, and wrestled with the question, how much climate-chemistry coupling can we avoid?

Zeb Nicholls (University of Melbourne/IIASA, Australia) presented work on the use of emulators and reduced complexity models. Past work with these models was very successful at the global scale for temperature and sea-level rise and has shown that these models can be used to explore a wider range of emission scenarios (assessed in IPCC WGIII). Open questions include how to apply them at regional scales, the extent to which they can be applied for extremes and precipitation, and how they should be calibrated and validated. Some coupling with regional emulators such as MESMER is currently being investigated in Europe. Zeb also pointed out the importance of remembering that emulators fundamentally depend on the simulation data generated by CMIP ESMs; without continuing improvement to ESMs, emulators have much less that is new to use for calibration.

Claudia Tebaldi (Lawrence Berkeley Lab, USA) addressed the challenge of combining ESMs with impact assessment models (IAMs), which is crucial for societal and political decision making. She discussed two approaches to achieve this combination. IAMs could be “hardwired” into ESMs to make emissions and land use endogenous components of ESMs. However, it seems much better to keep IAMs and ESMs separate and to use emulators to translate information between ESMs and IAMs; participants pointed out that this is relevant to the ongoing ESM2025 project, which includes ESM-IAM integration and emulator work. This would also enable consideration of feedbacks between the ESM and IAM worlds. To achieve this, the emulators need to contain spatially resolved, multi-variable and high-frequency information. An example is the recently developed STITCHES emulator. Participant discussion raised the possibility of using emulators to free modeling centers from the burden (in terms of computational cost) of scenario runs, i.e., to make climate models machines for understanding again.

Katja Frieler (Potsdam Institute for Climate Impact Research, Germany) discussed the translation of ESM climate change information to socio-economic impacts. The translation has typically been done by means of empirical models that are developed based on observed weather. Yet, these methods omit the intermediate step of how society and the economy are affected by weather events. To address this shortcoming, Katja proposed that instead biophysical indicators should be used to fit the empirical models. ISIMIP3 was highlighted as an opportunity for making progress on this problem.

Tomoki Miyakawa (University of Tokyo, Japan) discussed recent and ongoing work with storm-resolving models (SRMs). The Japanese climate modeling community group began investigating the impacts of km-scale models on climate features several years ago (using the NICAM model) and has interacted with HPC companies to craft computing platforms fit for climate simulations with high throughput. The talk made three important points. First, km-scale models have clear advantages in simulating moist atmospheric phenomena including convection and the MJO, and these simulations can be used to improve the parameterizations of coarse-resolution models. Second, it is much easier to run an ensemble of decadal km-scale simulations than one long (100 year) simulation. Third, important challenges remain in km-scale models, including the ocean-atmospheric coupling and cloud microphysics.

Paul Durack (Lawrence Livermore National Lab, USA) addressed model evaluation. Thanks to CMIP, there is now a global community of tools, including ESMValTool, CliMAF and the PCMDI Metrics Package. Opportunities for continued scientific discoveries include the move from global to regional scales, process-based evaluations, and seamless analyses from weather (timescale of days) to climate scales (centuries). Paul also highlighted the importance of the provenance of model data and reproducibility, and the importance of establishing ways to credit data providers, which is important for funding the large-scale infrastructure that is behind CMIP and ESGF. The talk also emphasized the need to break silos and build connections between scientific communities, e.g., between climate and health, and between the three IPCC working groups.

Nicola Maher (University of Colorado-Boulder, USA) presented work with large ensembles, which are now available for at least seven ESMs. Large ensembles are important for separating internal variability from the forced response to climate change, and also to separate structural model uncertainty from internal variability in order to identify what aspects of models need to be improved. By quantifying internal variability in global-mean surface temperature, the large ensembles can also play an important role in setting short-term expectations for mitigation efforts and for communicating these expectations beyond the climate science community. Many important scientific topics can benefit from large ensembles, including studies of the signal-to-noise paradox of global models, work with AI/ML methods, a more complete sampling of extreme events, and an improved evaluation of climate models via comparison to observations. A point of tension about large ensembles that arose in the participant discussion is what the balance should be between increasing model resolution to km scale against additional realizations needed to create a large ensemble.

Nick Golledge (Victoria University of Wellington, New Zealand) highlighted interactive ice sheets as a missing process in current ESMs, with a particular focus on the Antarctic. The recent ISMIP6 (driven by CMIP6) has found differences in sign in the future response of the Antarctic ice sheet, with some models projecting a mass gain and some projection a mass loss. Emulators play an important role in driving ice sheet models. In particular, the coupling between the ice sheets and the ocean needs to be considered, as this can lead to important feedbacks.

Libby Barnes (Colorado State University, USA) presented work on AI/ML, a genre of techniques that has been gaining a lot of traction as a new tool for climate science in the last few years. A promising development is the use of so-called explainable AI methods (xAI), such as backward propagation of information in neural networks, which allows one to gauge trust, optimize AI methods and learn new science. The applications of (x)AI are manifold. Existing examples include climate reconstruction, weather prediction, downscaling and climate communication, convection parameterization, and equation discovery. Exciting frontiers include knowledge-guided ML, transfer learning, and the improvement of climate model projections by AI-assisted model evaluation and bias correction.

Discussion

The Carslaw Test

A provocative discussion focused on the insufficiency of the Turing test for km-scale models, instigated primarily by Ken Carslaw (University of Leeds, UK). Specifically, Ken argued that the "Turing test"[1] for climate models is insufficient for out-of-sample future projections, i.e., passing a Turing test for today does not necessarily build trust for projections of the future. This led to the idea of a "Carslaw" test (coined in the Q&A) for verifiability and reliability of projections. Key to this test is quantifying uncertainties. Ken asked, "If we had 20 models that passed the Turing test, would they have high accuracy in making the same projections, or would they just scatter like our current ensemble of CMIP-class ESMs?" This is challenging since there is only one climate system and the time scale of climate change is many years, meaning that methods from weather prediction are not directly applicable. This highlights the need for testing against paleoclimate proxies and for building confidence in the models by means of physical understanding and process-based studies, and hence for hierarchies of models.

Participants discussed how to name the very high-resolution models with explicit atmospheric deep convection, and many thought that km-scale might be a better label than "storm-resolving" model (SRM). Participants also discussed the expectations attached to km-scale models. While they capture some phenomena (convection), they leave others unresolved (small scale turbulence, microphysics) and meanwhile break some assumptions (like those underlying coupling for evaporation and other fluxes at the surface). Others, in contrast, argued that km-scale models should be put in the center of future modeling efforts, so that ten years from now the CMIP-workhorse models can be km-scale instead of current coarse-resolution models.

Practicalities of managing all the model output, and evaluating all the simulations (at high resolutions, for large ensembles, and even for the current CMIP6 multi-model ensemble) were discussed; they are already bottlenecks for progress of the community. At the same time, another point of discussion was that many changes in our model-development practices will change because of technological changes (including but not limited to changes in HPC architecture, the rise of AI, improvements in coupling, observational benchmarking and model evaluation).

2.1.4. Technology and Accessibility

Chair: Izidine Pinto
Rapporter: Matthew Mizielinski

This session discussed how future technological changes can support climate modeling efforts and how we can improve accessibility.

Hisashi Yashiro (NIES, Japan) discussed computing hardware development. The development of the Fugaku HPC in Japan has taken an innovative approach by co-designing hardware suitable for weather and climate science models with the manufacturers. This is a different approach to most HPC facilities, where the inclusion of general-purpose GPUs (GP-GPUs) is becoming common. The co-design approach for processors could allow significant improvements in performance through wider availability of memory caches at different levels within the processors themselves as climate model performance is generally bound by the memory performance. Alongside this the flow of data through processor, memory and different tiers of storage, from solid-state drive (SSD) to longer term storage is key for sustaining high performance levels. The performance of the NICAM model for both 3.5km and 870km was reported with rates of 0.024 simulated years per day (~9 simulated days per day). Other performance improvements are also available via the use of reduced precision and careful use of memory and storage at various levels within the infrastructure. The discussion noted that there are other technologies in pipeline, e.g. TPUs (Tensor Processing Units) and MPUs (Memory Processing Units) that could have a role alongside traditional CPU, GPU and FPGA (Field Programmable Gate Arrays) in future, from which valuable performance increases could be obtained. Co-designing CPU architecture could provide an order of magnitude performance increase, but the continuing costs of design and production of specialized chips would require community wide engagement and commitment to a strategic development program. This would be a valuable topic for the weather and climate HPC community to collectively consider.

Francois Engelbrecht (University of Witwatersrand, South Africa) discussed model development in South Africa and the Southern Hemisphere. The Global Change Institute and the University of Witwatersrand (Johannesburg) are putting together a new ESM with support from CSIRO. Their new model (CCAM - Conformal Cubic Atmospheric Model) is based upon the cubed sphere grid with the aim to apply it to global climate change and paleoclimate research, with downscaling through stretched global grid via Schmidt transformation allowing focused resolution enhancement over particular regions to allow convective scale modeling. The new model collaboration is facilitating the work on important areas for impact on the climate of the African region including tipping points in tree-grass-fire feedbacks as the climate dries, the Southern Ocean carbon cycle and eddy parameterization, and the impact of paleo-climate on the evolution of hominids. Having an ESM developed within Africa is key to ensuring that Africa can develop its own capabilities in climate science and regional climate services, and a career pathway for African climate scientists. It would be valuable to consider how we can link new institutes and initiatives such as this into the global community, particularly regarding the sharing of data and access to analysis facilities to support scientific activities.

Mario Acosta (Barcelona Computing Centre, Spain) discussed how to minimize the carbon footprint of climate modeling. BSC have looked at their carbon footprint including commuting, computing infrastructure, buildings and travel. 2018 results for BSC show that roughly half of the 800 tCO_2e annual emissions are attributable to computing infrastructure with just under a third from travel. Of the computing infrastructure almost two thirds of this cost is incurred by data storage. Incorporating all these costs the annual emissions of BSC are around 10 tCO_2e per member of staff or almost double the population average for Spain. To monitor this BSC plan to update this analysis annually and incorporate CO_2 accounting into management tools and decision making. In addition, studies of the infrastructure have identified significant savings in energy through careful choice of data transfer tools. Metrics of energy consumption of many CMIP institutions and models have been collected for CPMIP through IS-ENES and were presented here, showing the range of costs both in the models themselves and the infrastructure used to deliver their results. These figures, and indeed others across all parts of the model workflow, are valuable for understanding the full impact of our field. The cost of running a distributed system such as ESGF should also form part of this analysis. The impact of the use of cloud facilities for data storage and analysis needs careful consideration too. In isolation this is more expensive, but if single central copies of data could be constructed and maintained this could be more efficient. Such an endeavor would require a collective, potentially international, funding mechanism that could be challenging to initiate and maintain.

Tapio Schneider (California Institute of Technology, USA) discussed novel climate modeling approaches as well as AI-aided hybrid modeling. The requirements we have for models are challenging; we need to rapidly iterate, increase accuracy and have quantified uncertainties, to get there we need to include tools to learn from data. The drive towards higher resolution is valuable but will not necessarily answer all questions we have. To get generalizable, interpretable models with quantified uncertainties we should look to combine the best aspects of the reductionist scientific approach with deep learning techniques from data science. Deep learning relies on over-parameterization based on large amounts of data, making generalizability, interpretability and quantifying uncertainty challenging, while the reductionist science approach relies on choosing limited sets of parameters, which struggles in complex systems such as the Earth system. A hybrid approach could combine the best of both approaches, particularly in cases such as closure functions within convection and entrainment, by embedding machine learning methods within parameterizations. The algorithms for this approach are readily available but implementing them will require careful integration of new methods to augment the reductionist process models we have in our current models. This may require greater focus on the data required to support machine learning which can best be supported by tight integration with our models.

2.2. Breakout groups

2.2.1. What can be learned (collectively) with Earth system models that we don't already know?

Chair: Olivier Boucher
Rapporteur: Amanda Maycock

The group addressed the topics of Earth System Models, model complexity, uncertainty, tipping points, low likelihood high impact outcomes, informing adaptation and mitigation policies and the interface between IPCC WGI and WGII cycles.

ECS has been widely studied, but for ambitious mitigation pathways TCRE and ZEC are also critical for assessing whether mitigation options are resilient to climate change. This requires Earth System Modeling with *inter alia* a representation of CDR options.

Regional climate change information is critical for adaptation. Both atmosphere and ocean circulation change are integral to this, but there remain leading order questions about these changes. Models show a range of outcomes but these cannot be readily constrained. Many changes, especially at local and regional scales, and cannot simply be inferred from the global temperature level.

There has been emphasis on producing probabilistic projections, but there is increasing acknowledgement of deep uncertainty in some Earth System components that means probabilities cannot be readily quantified. This requires a better identification of sources of uncertainties and favors the perspective of investigating implications of possible outcomes (within some physical constraints) and constructing storylines for these outcomes. In some adaptation instances, knowledge of possible outcomes is sufficient without precise probabilities.

We already have a lot of useful information (CMIP), but have we achieved the aim of better informing/guiding policy decisions? Need machinery to bias correct properly across all models and regions so we can deliver joint distributions of impacts easily. Can we not make models good enough that bias correction is not needed? Or perhaps we shouldn't try to get to this point and accept bias correction, whether online or offline, will be necessary for some time.

Can CMIP7 approach multi-model ensemble in a more intelligent, less opportunistic way? E.g. Can we guide groups towards specific areas aligned with their interest: LES, High Resolution, Earth System Model, Earth System models of intermediate complexity etc, so we have a more structured, distributed space. Not every model has to do every multi-model experiment protocol. It would also be good to move away from ensembles of opportunity.

WGII tends to assess information based on a CMIP generation earlier than that used by WGI (e.g., in AR6, WGII assessment was based on a lot of information from CMIP5 era whereas WGI included CMIP6 information too). Need to co-design a common approach with WGII and move beyond our WGI thinking (i.e., what information do WGII need from WGI?). WCRP should be thinking about what is fit for purpose for IPCC and how WGII can get aligned with WGI. We cannot be in the same place in 10 years. Climate is changing fast and adaptation strategies are needed in the short term. We have information for adaptation already, the issue is using it while new models can help deliver new information more fit for purpose through co-design. WCRP Lighthouse activities are relevant here.

Observations for modeling – is the observation network fit for purpose, especially for evaluating storm resolving models? A better connection with the observational community is needed.

CORDEX has historically been biased towards western nations. Need more information on high impact weather in other regions. Global storm resolving modeling can help, though probabilities of e.g., extremes cannot be accurately calculated from very short simulations.

It is an easy soundbite to say we want to reduce uncertainty, but we need to identify sources of uncertainty before we can quantify uncertainty and then consider routes to reduce uncertainty. Reducing uncertainty in a meaningful way is very difficult and, in some cases, impossible.

Tipping points, compound extremes, unprecedented events are all of growing interest. To address these, we will need new types of models, with more coupling and components. However, this raises issues for capturing Earth System feedbacks; we cannot get feedbacks right if e.g. rain is in the wrong place.

Discussion considered whether having additional Earth System components (e.g., coupled dynamic ice sheets) is a high priority for many CMIP centers? It was also acknowledged that generating a stable ESM is hard as many coupled feedbacks occur that can lead to climate biases.

2.2.2. What is the right balance between model resolution, model complexity and ensemble size?

Chair: Ted Shepherd
Rapporteur: Zebedee Nicholls

Overall, the breakout group was in broad agreement on two general points:

1. We're going to need a range of approaches on the resolution/ensemble size/complexity spectrum for a long time (there is no 'sweet spot' or 'one approach to rule them all')
2. Following the first point, the key question is how to combine the information we gather from different parts of the resolution/ensemble size/complexity spectrum together and be flexible in our approaches so they can be tailored to the questions of interest

The first point is almost self-evident: it would be institutionally impossible (if not also unwise) to try and impose some rule about how different research groups should tackle the resolution/ensemble size/complexity spectrum. Groups will want to examine different things, for example high resolution modeling, large ensembles or adding more processes to earth system models. The second reason for not being able to pick a particular part of the resolution/ensemble size/complexity spectrum is that it seems unlikely that there is a scale break that is achieved at some point on the spectrum, rather the spectrum and its synergies/tradeoffs seem to be continuous.

The second point raises many more questions. There are two key ones. The first is a question of interoperability: much time is spent making our tools talk to each other and making output analysis ready (known as 'data cleaning'). The challenge here is that these steps are not traditional research steps, but rather data handling and management steps. Yet they should be (and increasingly are) treated with the same seriousness as more traditional research efforts. Sharing knowledge and practices across communities, especially those who don't have strong software and data capabilities, to further improve their compatibility is the next challenge. The other key challenge is one of openness and reusability, specifically how can components be shared and reused in multiple contexts. Such practices reduce duplication of effort and unlock new research avenues, but they require new approaches to model development, licensing and sharing to be used. Addressing these key questions will be key to the next generation of climate modeling, primarily because their answers will greatly reduce the friction felt when moving between different parts of the resolution/ensemble size/complexity spectrum. Beyond these key questions, we provide a list of other questions from the day:

- Do we have the tools required to place our existing approaches on a resolution/ensemble size/complexity spectrum? Or is such a spectrum already too great a simplification?

- How can we facilitate the use of interoperable data formats? Do we simply need tools to translate between the different formats? Or do we need to converge on a common format that can serve the entire resolution/ensemble size/complexity spectrum?

- How can we facilitate interpretability across the resolution/ensemble size/complexity spectrum? Given the different setups, it is not trivial to compare outputs of different approaches.

- Should we encourage flexibility in modeling approaches so that tools cover a greater part of the resolution/ensemble size/complexity spectrum? Does greater flexibility come with challenges/costs that must be considered? If we do encourage greater flexibility, how do we do this?

- Should we encourage modularity in modeling approaches and exercises so that tools can more easily be combined for new applications? Does greater modularity come with challenges/costs that must be considered? If we do encourage greater modularity, how do we do this?

- (Slightly off the topic of the resolution/ensemble size/complexity spectrum) Does CMIP need to think about its approach to the number of models/number of experiments/type of experiment etc. spectrum? Should CMIP be more directly policy-focused, or should it provide more deep science analysis and let others build the policy link on top? Would such a change require rethinking some of the multi-model approach used in CMIP?

- Should we, as a community, have some more spear-head work/institutions (a bit like CERN for atomic physics)? These could allow us to access parts of the resolution/ensemble size/complexity spectrum that we currently cannot.

- How can we encourage groups to think about the question of interest first, then the tool they're using second?

- How can we improve our understanding of the strengths and weaknesses of our tools for answering different questions? How can we capture this understanding so that it can be interrogated by others? For example, let's say that one group realizes that adding a carbon cycle to their earth system model was a waste of time for climate projections because their hydrological cycle was so incorrect. How can that link between approach, application, strength and weakness be captured? Then how can it be made easy for others to build on this learning? Perhaps applying this approach to a different question with better results? Or changing the approach to answer the question of interest?

2.2.3. How to improve models?

Chair: Masa Kageyama
Rapporteur: June-Yi Lee

This group broadly discussed how to improve models including making a better use of data, better utilizing existing resource and evaluation tools. It also considered coordination and communication needs.

There is a need to improve the links to observations, improving observations themselves as well as making better use of reanalysis and paleoclimate information. There is a need for ultra-high-resolution observations to validate km-scale simulations, a need for better observations of land surface variables including soil moisture and vegetation; more coordinated field experiments across centers, particularly for the vertical structure of cloud, vertical structure of ocean, etc. EarthCARE (European Space Agency's Cloud, Aerosol and Radiation Explorer) will usefully provide vertical velocity from space, but it will be delayed. The community can also better utilize paleoclimate information to assess climate models.

Regarding better coordinating and communicating to better utilize existing resources, there is an urgent need to bridge fields and communities by filling the gap between global climate assessment/metrics and regional information for impacts; between model development and evaluation; between the conventional climate modeling community and the storm-resolving modeling community; between climate modeling and NWP groups. We can further learn from seamless modeling efforts across operational centers including data assimilation for NWP

Generally there is a need to better coordinate across a hierarchy of models to address various problems. To do this we could consider a common framework for enabling groups and centers to plug into the different scales: e.g., high resolution simulations should be shared, and assimilation methods should be made more standard.

It was all agreed that WCRP should play the key role for better coordination and communication.

We also discussed how the community could further develop common evaluation tools and metrics. Common metrics and evaluation tools (such as CLIVAR metrics and ESMVal tool) are very useful to share among communities. More efforts are need for developing common metrics especially for ocean models. Conventional evaluation approaches may not fully address issues to improve models and we need metrics that are better at capturing spatial patterns and regional details. We also need to improve how higher climate sensitivities are addressed in some models by acknowledging that improvement in models cannot always guarantee a better prediction or projection. To aid this we need to develop better metrics and model tuning approaches.

The group also discussed the assimilation of soil water and vegetation into land models, the need to address missing processes and how we can better utilize ensembles and machine learning approaches. There was a debate about how much machine learning could act as a supplement to actual learning and understanding. However, it was agreed that it was useful when combined with large data assimilation/model physical tendency datasets to learn about key aspects of parametrizations uncertainty and model growth. We also discussed the need for km-scale ocean models, the need for data sharing efforts for km-scale modeling, the role of perturbed parameter ensembles and the need for clarity on the targets for model development.

2.2.4. Roles of different models, resolution, complexity, ensembles beyond CMIP6

Chair: Helene Hewitt
Rapporteur: Claudia Tebaldi

The breakout group was tasked with discussing ‘Roles of different models, resolution, complexity, ensembles beyond CMIP6.

Most of the group discussion was around the number of models needed and the recognition that there is a lot of interdependency between CMIP6 model configurations (discussed in Brunner et al., 2020[3]). There are dependencies in CMIP6 which mean that models labelled as different models from different centers could be considered as a number of physics ensembles from a number of centers. Although the multi-model mean performs better than any individual model, this lack of independence may lead to a bias in the multi-model ensemble. In summary, there was no convincing argument for a large number of models given the current dependencies. In the feedback it was suggested that improved model coordination across groups or fewer models might allow improved coverage of the different experiments (some experiments in CMIP6 were poorly covered).

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[3] Brunner, L., Pendergrass, A. G., Lehner, F., Merrifield, A. L., Lorenz, R., and Knutti, R.: Reduced global warming from CMIP6 projections when weighting models by performance and independence, *Earth Syst. Dynam.*, 11, 995–1012, https://doi.org/10.5194/esd-11-995-2020, 2020.

We then discussed the format of CMIP7 and how it should look different to CMIP6. The suggestion in our discussion was that WCRP and representatives from the WGII and WGIII communities should jointly work together to identify an appropriate structure for ESM simulations (e.g. in CMIP) to serve the needs of these other research communities, including number of different models, ensemble size, etc., in order to capture the priority variables, time horizons, regions, etc. One way to prioritize would be to target the needs of major impact models, e.g. those in the ISIMIP activity. ISIMIP might then partner with CMIP to produce impact model simulations based on CMIP scenarios.

There was recognition that now was a good time to push ultra-high resolution but some hesitation as to realism of km scale models for producing realistic water vapor fields on longer time scales. This highlights the need for traceable hierarchies. We need a consistent model hierarchy and for development to learn from one type of models to improve other models. For instance, ultra-high-resolution models can lead to development of parameterizations/emulations of unresolved phenomena in lower resolution models, but low resolution models may potentially help for spinning up slow components of the Earth System. We discussed that it was important for future generations to have skills in AI so that we can take advantage of model hierarchies.

Large ensembles are very useful for sampling uncertainties and providing knowledge on extreme events, which is needed to assess impacts for climate services. However, different communities need to work together rather than sequentially. For instance, it would be beneficial to have the climate modeling and climate impact modeling communities/climate services work together on key "problems", so that ESM developers know in advance what is important for users, and which aspects need to be improved. This is difficult to organize, of course, but could be worth trying in case studies.

2.2.5. A vision of the climate and Earth system modeling landscape in 2030

Chair: Masa Watanabe
Rapporteur: Philip Stier

Before assessing the future climate and ESM modeling landscape, it is key to assess the purpose of models and user needs, which broadly split into climate services, supporting decision making and fundamental climate science questions, noting that also climate services need to be underpinned by fundamental climate science. In times of evident and increasing climate impacts, societal needs, user questions and solution focused modeling are becoming increasingly important.

The resolution and complexity of climate models in 2030 needs to be adequate for a wide range of use cases and communities – in particular also for users in the Global South. This includes increasing the skill and reliability of seasonal-to-decadal predictions, while recognizing and exploring fundamental limits of predictability. This will require significant local capacity building, which will be aided by the move to cloud computing and the move of compute to being co-located with data. However, the setup of such repositories is currently restricted to high-income countries – inclusive approaches will be key and major investment in global infrastructure could be beneficial.

There exists a clear need for a hierarchy of different models in terms of ESM complexity and resolution for a broad range of applications. Already now there exists a significant market demand for climate services and the private sector and big tech companies are rapidly entering this sector – the interface between climate modeling as a public good and a commercial opportunity will require careful attention.

Climate modeling will undergo a paradigm shift between now and 2030. Global GCMs and the related CMIP intercomparison exercises will continue to be a major pillar and play a major role for climate scenarios and decision making. However, at the same time we will experience the advent of global cloud resolving climate models and will have developed Digital Twin Earths, which can be seen as the high-resolution equivalent of ESMs but limited to shorter simulation periods, far from the number of CMIP simulations years. In addition, we will see the rapid development of public and private sector AI/ML climate impact models at resolutions appropriate for climate impact studies. Step changes will be required in terms of i) accessibility, ii) scientific fidelity and iii) usability / usefulness of capabilities.

There exists a strong need for cross-cutting activities between global GCMs and CRMs between CMIP7 and the GEWEX-GASS (Global Energy and Water Exchanges Project Global Atmospheric System Studies Panel and the DYAMOND (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains) type activities to minimize the current parallelism / competition between these communities. Ultimately, we will need to come up with clever ideas about how to combine the strength of the two different approaches. This will require the community to develop traceable model hierarchies across model resolutions, complexities, and applications.

2.2.6. Operationalizing climate modeling vs research?

Chair: Cath Senior
Rapporteur: Eleanor O'Rourke

Rather than a question of operationalization vs research the group discussed the importance of a balanced relationship with the need for close interaction and feedbacks between operations and research, lessons learned from CMIP and the requirements for, and opportunities of, future operationalization, the challenges to be addressed and WCRP's role. It is clear that there is often a national requirement or duty to provide operational delivery in addition to research, but how this is structured varies considerably across countries and regions and there is a need to maintain inclusivity across the wider modeling community and beyond. The question of whether bridging the weather and climate gap is the primary research direction with a focus on increasing accuracy, rather than necessarily improving understanding was raised with recognition that there remains a lot to be learned across the timescales. Single modeling configurations for seamless prediction from weather through to centennial timescales are being developed with a clear need to focus on skill at the NWP end but without necessarily undermining the focus on understanding found at the climate timescales. It was highlighted that there is a need to support and ensure inclusion of centers who do not operate the full range of models across timescales and additionally that there are alternative ways to constrain the models beyond the seamless prediction approach including artificial intelligence and machine learning. The standardization that has been offered by CMIP was seen to have been very beneficial, with the operational format providing structure to research activities. The progress realized during CMIP6 has seen systematic evaluation, along with more coordinated forcing datasets, become a reality, reducing the need for reproduction of analyses and potentially freeing up operational investments by modeling groups to flow back into research. There is great potential to further support research activities through the development of this infrastructure but it is difficult to fund.

The question of whether CMIP alone can meet operational demands was raised with the suggestion of exploring a separate globally coordinated operational effort co-designed with other communities. The example of new climate policies being developed at greater frequencies than previously was posed and how that can be adequately evaluated without combining with emulators and bias correction in some standardized manner, with emissions aligned to reality and likely policy choices, assimilation of observations, and a range of impact models. With appropriate investment it was felt that the CMIP structure could potentially accommodate these needs and planning for CMIP7 should include discussion of these ideas.

The flow from research into operations was seen to be happening more than the operations to research feedback. It was felt that there was an opportunity to take more advantage of the CMIP 'operational' cycle for research purposes. Operationalizing the forcing would allow for co-development with the modeling centers, and the evaluation can be included within the feedback loops. An operational Obs4MIPs alongside metrics packages to support model evaluation and development could offer the opportunity to look at issues such as climate sensitivity.

All agreed that operationalization is a long-term process that must have sustained and consistent infrastructure and funding to be successful. Some specific needs were identified as:

- Need to think about all the processes - the drive to higher resolution will not necessarily solve all these issues; however, it is very important for processes such as the hydrological cycle.
- Effective quality control - a screening to filter out poor results.
- Commitment to, and regular updating of, forcing for historical and scenarios using realistic and policy driven emissions. How best to achieve this whilst not compromising model intercomparison (which needs stable forcing) needs further discussion.
- Coordinated and comprehensive observational coverage to support model evaluation, validation and forcing.
- Robust, maintained standards for documentation, experimental design, data formats etc.
- Continuing development of community evaluation tools.
- The importance of people in supporting both operations and research.
- Combining with emulators and bias correction in a standardized way.
- Enhance the co-design approach into the development of any operational service with policy and a wide range of other user communities.

The question of whether there is a need for so many climate models to be delivered to the IPCC and national projections through CMIP was raised. There was a general feeling that there were too many models, but no clear consensus was reached on what the ideal number is and there are clearly strong political elements and national interests driving this. Also WCRP needs to ensure that inclusivity is not compromised in any recommendations. No clear solution emerged either for the difficult balance of maintaining model independence and diversity while addressing the need to optimize compute spend for a reduced carbon footprint.

There was seen to be a gap between the operational centers decision making and the research community. How can the operational centers utilize the research inputs and how can operational insight/data be shared back to the research community, particularly for those not within centers delivering operations and research. Enhancing the connection, and strengthening the feedback, between the operational centers and research centers was seen as a key potential role for WCRP.

2.2.7. Improving climate models

Chair: Kirsten Findell
Rapporteur: Tilo Ziehn

The discussion in this group was focused on four broad areas:

- **Component Parts** (mainly around new and improved processes)

- **Better Model-Observation Integration** during model evaluation as part of the model development process but also in terms of planning for observations
- **Platform for development efforts** (so focused on high resolution but also more targeted to a specific problem)
- **Better integration or communication** between modeling centers and other communities (such as health, impacts, mitigation)

The aim was to find commonalities from the diverse perspective and background of the group but also to come up with a roadmap for our strategy for the future of climate modeling. Our discussion started with some fundamental questions around:

- What is meant by model improvement, and does it relate to a single model or ensemble of models?
- How can we make models agree better?
- Do models actually need to agree?

Model improvement is generally associated with including more processes, but this doesn't necessarily improve the performance of the model. Including more processes in our models also leads to an increase in the number of parameters which could increase uncertainties in the model output and therefore overall lead to a less constrained model. Observations can help us to constrain model parameters, but we require a better framework to include observations in the model and tuning process.

It is important to address what processes are currently missing in our models (e.g., Antarctic processes and ice sheet dynamics) and prioritize what processes we should include in the future (e.g., to further improve projections). This should be a coordinated effort.

We need to understand why models are different and for what reason. Models do not necessarily need to agree, there is a lot to learn from the differences and we need to understand how we can exploit those differences more.

What else can we do? Improving models also comes down to improving biases and more effort should be spent here. We also need to focus on teleconnections, signal to noise ratio and sensitivity analysis. Large ensembles can help us to address uncertainties, however model performance (runtime and compute resources) need to allow for this. To understand their diverse needs, better communication between the communities is required.

The two key messages that came out from our discussion are:

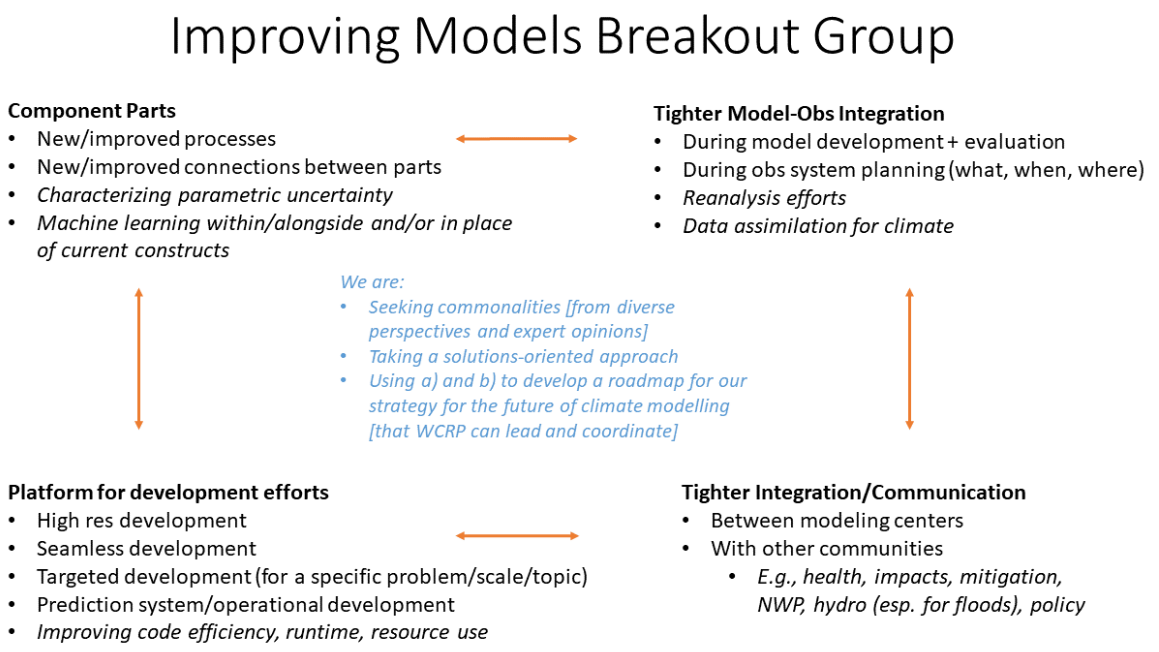
1. We need to improve the things that we care about (this related to the processes and including new processes, but highlighting that we should only add new processes if there is a good reason)
2. We need to make the models more trustworthy; we need to evaluate the components as best as possible and improve existing processes.

Concrete recommendations for the role that WCRP (or WCRP entities like ESMO) can play to improve the process of model improvement (or ideas for ESMO to consider):

- Can we define a hierarchy of processes that we want to include and how we involve the community in this?
- This could mean including paleo simulations during model development/tuning so the range of circumstances tested is larger (than just during the historical period).

- Add sensitivity tests as part of the CMIP cycle, to ensure this is done in a broad way, e.g., doing historical, DECK, and PMIP runs and releasing them first, and then scenarios only after that is done & reported.
- CMIP can have staggered deadlines.
- ESMO could look at incorporating/evaluating/assessing a High-Tune-type strategy (https://agupubs.onlinelibrary.wiley.com/doi/pdfdirect/10.1029/2020MS002217) for more systematic parameter selection.

Kick-off slide:



Improving Models Breakout Group

Component Parts
- New/improved processes
- New/improved connections between parts
- *Characterizing parametric uncertainty*
- *Machine learning within/alongside and/or in place of current constructs*

Tighter Model-Obs Integration
- During model development + evaluation
- During obs system planning (what, when, where)
- *Reanalysis efforts*
- *Data assimilation for climate*

We are:
- *Seeking commonalities [from diverse perspectives and expert opinions]*
- *Taking a solutions-oriented approach*
- *Using a) and b) to develop a roadmap for our strategy for the future of climate modelling [that WCRP can lead and coordinate]*

Platform for development efforts
- High res development
- Seamless development
- Targeted development (for a specific problem/scale/topic)
- Prediction system/operational development
- *Improving code efficiency, runtime, resource use*

Tighter Integration/Communication
- Between modeling centers
- With other communities
    - *E.g., health, impacts, mitigation, NWP, hydro (esp. for floods), policy*

Annex 1 - Agenda

March 21 (Day 1)
Day 1, Sessions 1 to 4: 20:00 to 23:00 UTC

Session 1 – Plenary: Welcome, Introduction and Workshop Goals [15 mins total]
Chair/Moderator: Helen Cleugh

a. Welcome and Housekeeping (Vaishali Naik, Workshop Co-Lead)
b. Introduction and Scene Setting (Detlef Stammer, JSC Chair)
c. Workshop Aims; Incl. written input from survey (Piers Forster, Workshop Co-Lead)

Session 2 – Plenary: Challenges of Climate Modeling [70 mins total]
Co-Chairs: Helen Cleugh and Vaishali Naik. Rapporteur – Laura Wilcox

2.1. Science perspectives (drawing on written input prior to Workshop). (10 mins each)
a. Ultra-high-resolution modeling - Ruby Leung (USA)
b. Next generation climate modeling - Tim Palmer (UK)
c. Challenges in Earth System Modeling - Elena Shevliakova (USA)
d. Hydrological /regional modeling - Sabine Attinger (Germany)
e. IPCC AR6 - June-Yi Lee (South Korea) and Baylor Fox Kemper (USA)
f. CMIP - successes and where to next? - Jean-Francois Lamarque (USA) and Matthew Mizielinski (UK)
g. Greening of climate modeling - Pierre Friedlingstein (UK)

2.2. Discussion (10 mins)

5 min break

Session 3 – Plenary: Societal Needs for Climate Information [50 mins total]
Co-Chairs: Silvina Solman and Rondrotiana Barimalala. Rapporteur – Chris Smith

3.1. Stakeholder needs and perspectives – what are the community needs? (10 mins each) (Reflecting the impacts, adaptation and mitigation communities; representing IPCC, governments, media and the public)

a. Health impacts - Kristi Ebi (USA)
b. Carbon budgets and communications - Rob McSweeney (UK)
c. Mitigation (IPCC Working Group III) - Joeri Rogelj (UK) and Malte Meinshausen (Australia)
d. Impacts and adaptation (IPCC Working Group II) - Chris Lennard (South Africa)
e. Communities in the Global South - Mandira Shrestha (Nepal)

3.2. Discussion (10 mins)

Session 4 – Plenary: Discussion and Reflections on Day 1 [10 mins]
Co-Chairs: Detlef Stammer and Vaishali Naik

March 22 (Day 2)
Day 2, Sessions 1 to 5: 20:00 to 23:00 UTC

Session 1 – Plenary: Welcome, Reflections on Day 1 and Guidance for Day 2 – Vaishali Naik and Piers Forster, Workshop Co-Leads [5 mins]

Session 2 – Plenary: Science and Technology – exciting and relevant science that can be done using Earth System Models [45 mins total; 5 mins each]

Chair/Moderator: Angeline Pendergrass and Roland Séférian. Rapporteur – Aiko Voigt

a. High resolution models - Daniel Klocke (Germany)
b. Composition-climate models - Stephanie Fiedler (Germany)
c. Model emulation/simple models/reduced complexity model - Zeb Nicholls (Australia)
d. Societal decision making and model integration - Claudia Tebaldi (USA)
e. From climate change to socio-economic impacts - Katja Frieler (Germany)
f. Model improvement - Tomoki Miyakawa (Japan)
g. Model Evaluation - Paul Durack (USA)
h. Large Ensembles - Nicola Maher (USA)
i. Processes that are currently missing in the models - Nick Golledge (New Zealand)

Discussion (20 mins)

5 min break

Session 3 – Plenary: Technology and Accessibility [25 mins total; 5 mins each]
Chair/Moderator: Izidine Pinto and Peter Caldwell. Rapporteur – Matthew Mizielinski

a. AI in Climate Science - Libby Barnes (USA)
b. Computing hardware development - Hisashi Yashiro (Japan)
c. Model development in South Africa and Southern Hemisphere - Francois Engelbrecht (South Africa)
d. Towards minimising carbon footprint of climate modeling: Modeling centre perspective - Mario Acosta (Spain)
e. Novel climate modeling approaches - Tapio Schneider (USA)

Session 4 – Breakout Groups [60-mins total, including brief break as needed]
All participants to be allocated to a Breakout Group, with Leaders and Rapporteurs appointed

Group 1: What can be learned (collectively) with Earth system models that we don't already know? **Chair: Olivier Boucher. Rapporteur: Amanda Maycock.**
Group 2: What is the right balance between model resolution, model complexity and ensemble size? **Chair: Ted Shepherd. Rapporteur: Zeb Nicholls.**
Group 3: How to improve models? **Chair: Masa Kageyama. Rapporteur: June-Yi Lee.**

Session 5 – Plenary: Report-back from Breakout Groups and Wrap-up of Day 2 [15 mins total]
Co-Chairs: Helen Cleugh and Piers Forster
Brief report back from Breakout Group Rapporteurs (5 mins each)

March 23 (Day 3)

Day 3, Sessions 1 to 3: 20:00 to 23:00 UTC

Session 1 – Plenary: Recap of what we heard in Days 1 and 2 [80 mins total]
Chair/Moderator: Detlef Stammer

1. **Welcome back and Guidance for Day 3 – Vaishali Naik and Piers Forster, Workshop Co-Leads (up to 10 mins)**

2. **Summary Reports from Session Rapporteurs (10 mins each)**

Day 1 (D1), Session 2 (S2) Plenary - “Challenges of Climate Modeling”. D1-S2 **Laura Wilcox.**
Day 1 (D1), Session 3 (S3) Plenary - “Societal Needs for Climate Information”. D1-S3 **Chris Smith.**
Day 2 (D2), Session 2 (S2) Plenary - “Science and Technology”. **Aiko Voigt.**

Day 2 (D2), Session 3 (S3) Plenary - “Technology and Accessibility”. D2-S3 **Matthew Mizielinski**.
Recap of Key Points from Day 2 Breakout Groups 1 - 3

3. Discussion (20 mins)

5 min break

Session 2 – Breakout Groups [70 mins total, including brief break as needed]
All participants to be allocated to a Breakout Group, with Leaders and Rapporteurs appointed

a. Group 4: Roles of different models, resolution, complexity, ensembles beyond CMIP6. **Chair – Helene Hewitt. Rapporteur: Claudia Tebaldi.**
b. Group 5: A vision of the climate and Earth system modeling landscape in 2030. **Chair – Masa Watanabe. Rapporteur: Philip Stier.**
c. Group 6: Operationalizing climate modeling vs research? **Chair – Cath Senior. Rapporteur: Eleanor O’Rourke**.
d. Group 7: Improving models. **Chair – Kirsten Findell. Rapporteur: Tilo Ziehn.**

Session 3 – Plenary: Report-back from Breakout Groups and Wrap-up of Day 3, look ahead to Day 4 [25 mins].
Co-Chairs: Helen Cleugh and Piers Foster
Brief report back from Breakout Group Rapporteurs (5 mins each)

March 24 (Day 4)
Day 4, Sessions 1 to 4: 20:00 to 23:00 UTC

Session 1 – Plenary: Summary from days 1-3 [50 mins total]
Chair/Moderator: Helen Cleugh

1. Recap from days 1-3 - Piers Forster and Vaishali Naik (20 mins)
2. Discussion regarding the way forward (30 mins)

10 min break

Session 2 – Plenary: White paper writing tasks [60 mins total]
***Chair/Moderator:* Detlef Stammer**

Session 3 - Summary and wrap up (Vaishali Naik and Piers Forster) [15 mins total]

Annex 2 – List of participants

Silvina Solman	Argentina
Andy Pitmann	Australia
Helen Cleugh	Australia
Julie Arblaster	Australia
Malte Meinshausen	Australia
Simon Marsland	Australia
Steve Sherwood	Australia
Tilo Ziehn	Australia
Zeb Nicholls	Australia
Andy Hogg	Australia
Aiko Voigt	Austria
Adelle Thomas	Bahamas
Iracema Cavalcanti	Brazil
Regina Rodrigues	Brazil
Bill Merryfield	Canada
Greg Flato	Canada
Bian He	China
Fangli Qiao	China
Jiankai Zhang	China
Lijuan Li	China
Qing Bao	China
Tianjun Zhou	China
Zhaohui Lin	China
Masa Kageyama	France
Olivier Boucher	France
Pascal Braconnot	France
Roland Séférian	France
Aurore Voldoire	France
Armin Mathes	Germany
Carl Schleussner	Germany
Daniel Klocke	Germany
Daniela Jacob	Germany
Detlef Stammer	Germany
Jana Sillman	Germany
Katja Frieler	Germany
Nils Wedi	Germany

Sabine Attinger	Germany
Stephanie Fiedler	Germany
Tatiana Ilyina	Germany
Thomas Jung	Germany
Claas Teichmann	Germany
Krishnan Raghavan	India
Swapna Panickal	India
Chihiro Kodama	Japan
Hiroaki Miura	Japan
Hisashi Yashiro	Japan
Masa Watanabe	Japan
Masaki Satoh	Japan
Tomoki Miyakawa	Japan
Genito Maure	Mozambique
Mandira Shrestha	Nepal
Nick Golledge	New Zealand
Olaf Morgenstern	New Zealand
Ben Sanderson	Norway
Bamba Sylla	Senegal
Asmerom Beraki	South Africa
Bruce Hewitson	South Africa
Chris Lennard	South Africa
Francois Engelbrecht	South Africa
Izidine Pinto	South Africa
Rondrotiana Barimalala	South Africa
Willem Landman	South Africa
GyunDo Pak	South Korea
Jin Ho Yoo	South Korea
June-Yi Lee	South Korea
Seok-Woo Son	South Korea
YoungHo Kim	South Korea
Hyungjun Kim	South Korea
Mario Acosta	Spain
Paco Doblas-Reyes	Spain
Thorsten Mauritsen	Sweden
Michael Sparrow	Switzerland

Niki Gruber	Switzerland
Nico Caltabiano	Switzerland
Wilco Hazeleger	The Netherlands
Amanda Maycock	UK
Anja Schmidt	UK
Cath Senior	UK
Chris Jones	UK
Chris Smith	UK
Doug Smith	UK
Eleanor O'Rourke	UK
Gabi Hegerl	UK
Helene Hewitt	UK
Joeri Rogelj	UK
Ken Carslaw	UK
Laura Wilcox	UK
Matt Mizielinski	UK
Philip Stier	UK
Pierre Friedlingstein	UK
Piers Forster	UK
Rob McSweeney	UK
Rowan Sutton	UK
Sean Milton	UK
Ted Shepherd	UK
Tim Palmer	UK
Irina Sandu	UK
Daniel Marsh	UK
Marcelo Barreiro	Uruguay

Amanda Lynch	USA
Andreas Prein	USA
Andrew Gettelman	USA
Angeline Pendergrass	USA
Baylor Fox-Kemper	USA
Brian O'Neill	USA
Chris Davis	USA
Clara Deser	USA
Claudia Tebaldi	USA
Elena Shevliakova	USA
Jean-François Lamarque	USA
Kirsten Findell	USA
Kristie L. Ebi	USA
Libby Barnes	USA
Ming Zhao	USA
Nicola Maher	USA
Patrick Heimback	USA
Paul Durack	USA
Peter Caldwell	USA
Ruby Leung	USA
Sara Pryor	USA
Tapio Schneider	USA
V. Balaji	USA
Vaishali Naik	USA
Gavin Schmidt	USA
Gokhan Danabasoglu	USA
Robert Pincus	USA

Annex 3 - Acronyms

AerChemMIP	Aerosol Chemistry Model Intercomparison Project
AI	Artificial Intelligence
AMOC	Atlantic Meridional Overturning Circulation
AR5	Fifth Assessment Report (IPCC)
AR6	Sixth Assessment Report (IPCC)
BSC	Barcelona Computing Centre
CCAM	Conformal Cubic Atmospheric Model
CDR	Carbon Dioxide Removal
CERN	European Organization for Nuclear Research
CliMAF	Climate Model Assessment Framework
CLIVAR	Climate and Ocean Variability, Predictability and Change (WCRP)
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
CPU	Central Processing Unit
CRM	Climate Regional Models
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DYAMOND	DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains
EarthCARE	European Space Agency’s Cloud, Aerosol and Radiation Explorer
ECS	Equilibrium climate sensitivity
ESGF	Earth System Grid Federation
ESM	Earth System Model
ESM2025	Earth system modelling and climate research in support of the Paris Agreement Project
ESMValTool	Earth System Model Evaluation Tool
ESMO	Earth System Modeling and Observations (WCRP)
FPGA	Field Programmable Gate Arrays
GCM	General Circulation Model
GEWEX	Global Energy and Water Exchanges (WCRP)
GASS	Global Atmospheric System Studies (GASS) Panel (GEWEX)
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gases
GPUs	Graphic Processor Units
HPC	High Performance Computing
IAM	Impact Assessment Models
ICIMOD	International Centre for Integrated Mountain Development
IOC-UNESCO	Intergovernmental Oceanographic Commission of UNESCO
IPCC	Intergovernmental Panel on Climate Change
ISC	International Science Council
IS-ENES	Infrastructure for the European Network for Earth System Modelling
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ISMIP6	Ice Sheet Model Intercomparison Project

LES	Large eddy simulation
MESMER	Modular Earth System Model Emulator
MJO	Madden-Julian Oscillation
ML	Machine Learning
MPI-M	Max Planck Institute for Meteorology
MPUs	Memory Processing Units
NCAR	National Center for Atmospheric Research
NextGEMS	Next Generation Earth Modelling Systems
NIES	National Institute for Environmental Studies (Japan)
NICAM	Nonhydrostatic ICosahedral Atmospheric Model
NWP	Numerical Weather Prediction
Obs4MIPs	Observations for Model Intercomparison Project
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PDRMIP	Precipitation Driver and Response Model Intercomparison Project
PMIP	Paleoclimate Modelling Intercomparison Project
PNNL	Pacific Northwest National Laboratory
PPE	Perturbed Parameter Ensembles
REDD+	Reducing Emissions from Deforestation and forest Degradation
RFMIP	Radiative Forcing Model Intercomparison Project
RIfS	Regional Information for Society (WCRP)
S2D	Seasonal to decadal
S2S	Sub-seasonal to seasonal
SDG	Sustainable Development Goals
SRM	Storm-resolving models
SSD	Solid-state drive
SSP	Shared Socioeconomic Pathways
TCRE	Transient climate response to cumulative emissions of carbon dioxide
TPUs	Tensor Processing Units
UN	United Nations
UNESCO	United Nations Educational, Scientific, and Cultural Organization (UN)
UNFCCC	United Nations Framework Convention on Climate Change
UKESM	United Kingdom Earth System Model
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
ZEC	Zero Emission Commitment

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.

WCRP
World Climate Research Programme