Convection-Permitting Models for Climate Research

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4th International Convection-Permitting Modeling Workshop for Climate Research

What: The purpose of the workshop was to discuss the performance of convection-permitting models (<4-km horizontal grid spacing) at global and local scales and also to discuss the potential of CPMs data for hazard and impact studies. Recent advancements in CPM research were highlighted and key challenges discussed. The workshop also focused on the potential of applying CPMs to the Asian region.

When: 2–4 September 2020

Where: Online

KEYWORDS: Cloud resolving models; Model evaluation/performance; Flood events; Risk assessment

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The 4th International Convection-Permitting Modeling Workshop, originally planned as an in-person meeting for September 2020 in Kyoto, Japan, was converted to a virtual meeting due to the COVID-19 situation. We held another virtual meeting in September 2021 due to the ongoing COVID-19 pandemic. Because of the rapid development of the convection-permitting modeling (CPM) field, we felt the need to host a virtual workshop this year to maintain community interactions and to provide a forum where scientific advances are presented and discussed.

The virtual workshop was held 2–4 September 2020 with a focus on the simulation of mesoscale processes and extreme events with CPMs at global and local scales and the use of CPM data for hazard and impact assessments. Recent advancements in CPM research were highlighted and key challenges were discussed. The workshop had 324 participants from 23 countries and regions and featured four sessions with invited presentations (Fig. 1). Participants were able to watch the presentations and ask written questions before the live discussion sessions, which occurred on 2–4 September 2020. The questions were answered during the live discussion period. A recording of the discussion sessions can also be accessed through the above website. In the following, we provide a brief summary of each session and conclude by identifying potential future research areas.

Can CPM improve our understanding of precipitation and its future change?

This session highlighted the advantage of CPMs in gaining a better understanding of the atmospheric phenomena associated with precipitation and its future change. We addressed the reasons why CPMs improve the representation of the atmospheric phenomena associated with heavy precipitation [e.g., convective clouds, mesoscale convective systems (MCSs), topographical precipitation, snowfall, etc.] and focused on new insights regarding the future projection of precipitation that cannot be obtained by coarse-resolution climate models. An important question that this session addressed was the dependence of simulating local-scale precipitation on the structure and organization of convection and the role of local orography.

Fig. 1. A subset of the participants of the virtual 4th International Convection-Permitting Modeling Workshop for Climate Research.

The horizontal scale needed to represent low-level convergence was examined in several talks. In some cases, such as for back-building mesoscale convective systems in Japan or single-cell convective storms, kilometer-scale grid spacing may be too coarse to capture the structure and organization of convection (e.g., Ito et al. 2021). Organized convective storms in the United States, however, are typically well-simulated with kilometer-scale models (Lundquist et al. 2019). Another focus was the performance of CPMs in representing various types of precipitating clouds (single cell, back-building type convection, orographic, and other types) at various locations around the world. In addition, the importance of indices for evaluating the representation of simulated clouds was also pointed out.

Presentations on future climate simulations of precipitation focused on whether scaling rates between temperature and precipitation correlated with the changes in moisture predicted as a function of temperature by the Clausius–Clapeyron (CC) equation. In most cases, changes in the stratification of the troposphere impacted the response of precipitation to the temperature, and both the super- and sub-CC scaling occurred owing to the environment, or the mixture of thermal and dynamic effect (e.g., Nakakita et al. 2020). Adopting the PGW (pseudo global warming) method is valuable to better understand the meteorological mechanism of these issues.

Toward global convection-permitting climate simulations

The second session focused on the development and application of global convection-permitting models. One of the goals of using global CPMs is to improve long-standing biases in global climate models by simulating key physical processes such as convection directly rather than parameterizing them. Global CPMs are currently in an experimental stage, but initial results such as an improved representation of gravity waves, convection, and boundary layer processes are promising (e.g., Neumann et al. 2019). However, major challenges remain in using global CPMs for climate change studies that can be summarized into two categories: 1) model hardware and software and 2) model performance.

The first category is mainly related to technical challenges. Most existing CPMs that can run globally will not be able to run efficiently on future high-performance computers due to fundamental changes in future computer architectures (e.g., Schär et al. 2020). Adapting to future architectures demands rewriting the model code, making it more flexible to run on a variety of platforms. To effectively run global climate CPMs, a speedup of 100 times is necessary, which would allow us to simulate a one-year timeframe in one physical day. The Swiss Federal Institute of Technology in Zürich (ETH Zürich) and the European Centre for Medium-Range Weather Forecasts (ECMWF) have plans to achieve this goal with a 3-km grid spacing model by 2024. An important additional challenge is the storage and sharing of model output.

The second major obstacle in using global CPMs is related to model performance. One key challenge is the simulation of low-level sub-tropical clouds over the ocean, due to their importance in the Earth's energy balance and simulated climate sensitivity. Simulations from the Dynamics of the Atmospheric General Circulation Modeled on Non-Hydrostatic Domains (DYAMOND, www.esiwave.eu/services/dyamond) project show a large variability in the representation of low-level clouds in global CPMs. The source of this variability is not fully understood, but model numerics, the representation of convection, and microphysical processes seem to be important. Additional challenges arise in ocean-atmosphere coupled global CPMs. Initial tests with such models show large drifts in the global mean states.

An alternative pathway to global CPMs is to test the performance of regional CPMs over various climate regimes to detect and improve model biases and to find physics suites that perform well in various climatic regimes. The importance of coupling with other Earth system components such as the ocean and land surface has been exemplified by the strong sensitivity of the simulated summer climate in the central United States to the representation of groundwater

(Barlage et al. 2018). Furthermore, even at kilometer scales, most convective motions are still under-resolved, resulting in systematic model biases such as an overestimation of hourly precipitation extremes. More sophisticated gray-zone convection parameterizations are promising in mitigating these deficiencies. Finally, the use of satellite observations and targeted model experiments that make use of field campaign data were discussed for evaluating global CPMs.

CPM applications for hazard assessment under climate change

The third session focused on the roles of CPMs toward hazard assessment under climate change (Mori et al. 2021). For hazard assessment, high spatiotemporal resolution and quantitatively accurate predictions are required. The appropriate spatiotemporal scale depends on the type of disaster considered. It is hoped that CPMs improve not only the simulation and prediction of hazards, but also our understanding of processes associated with the hazard. Discussions during the session focused on the use and significance of CPM for better hazard risk assessment under both the present and future climate.

As for sediment-related disasters such as landslides, predictions of precipitation and its three-dimensional character related to the slope scale were shown to be important, especially the occurrence of landslides depending on peak rainfall intensity and rainfall pattern. Concerning flooding, accurate predictions across various catchment sizes are very important. Additionally, correctly simulating the trigger process of convective initiation is essential to represent the timing and location of localized events that might cause flash flooding and landslides in small river basins. High-resolution and high-quality observations were identified as crucial for a better understanding of processes and phenomena that cause extreme events and for supporting the development of parameterization schemes.

Since rainfall is expected to intensify at small spatial and temporal scales in future climates, the impact of precipitation on the initiation of landslides in small river catchments becomes increasingly important. This intensification causes the need for a new framework of early warning and evacuation systems. CPMs are playing a vital role in understanding future change for not only total rainfall, but also peak rainfall as well as maximum wind speeds, which are relevant for hazard and disaster assessments. Multimodel and large CPM ensembles in particular are expected to better map future uncertainties and increase our confidence in the magnitude of future changes. The 18th U.K. Climate Projections (UKCP18), which contain an ensemble of current and future climate CPM simulations, were presented as a groundbreaking example of such a research effort.

CPM research in Asia

Session 4 highlighted the important role of CPM in understanding and estimating future projections of representative meteorological phenomena and hazardous weather in Asia. We identified the Asian monsoon processes (mei-yu, baiu, shurin, and changma in East Asia), typhoons in East Asia and Southeast Asia, and MCS in tropical regions as the most important meteorological phenomena concerning impacts. Regional CPMs such as the Weather Research and Forecasting (WRF) Model, the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM), and the Cloud Resolving Storm Simulator (CreSS) are playing a vital role in simulating these phenomena. One to two kilometer horizontal grid spacing was found to be sufficient in simulating typhoons, although subkilometer grid spacing was noted to be ideal. It was also pointed out that CPMs are vital for simulating orographic effects on rainfall.

Regarding future projections, nonhydrostatic regional climate model (NHRCM)-based simulations by the Meteorological Research Institute (MRI) are widely used in Japan and southeastern and tropical Asia. For hazards, rainfall information is needed with spatial resolutions of a few kilometers for hydrological runoff computation and a few hundred meters for sediment hazard. NHRCM and WRF are the most widely used models in Asia for generating

CPM climate change projections, and projects such as the Coordinated Regional Climate Downscaling Experiment (CORDEX, <https://cordex.org/>) and the Integrated Research Program for Advancing Climate Models (TOUGOU, www.jamstec.go.jp/tougou/eng/program/index.html) are playing vital roles. As in previous sessions, the impact of model grid spacing on simulating high-impact atmospheric phenomena and the need for high-quality and high-resolution rainfall observations for model validation and model output statistics were discussed. The observation system could be advanced by increasing the number of in situ rain gauges, installing polarimetric weather radar, and improving satellite-based rainfall products.

Meeting outcomes and future research needs

The form of the virtual meeting (e.g., prerecorded presentations and live discussions sessions) was very well received by the participants and allowed the involvement of scientists who were unable to join previous CPM workshops. Challenges posed by the virtual approach to the meeting concerning the accommodation of major time zones and only allowed limited personal interactions compared to an in-person workshop.

The main outcomes and major future research needs identified during the workshop are the following:

- Multiple global convection-permitting modeling systems are currently being developed, and decadal-long CPM climate simulations will be available within the next five years.
- Closer collaboration between computer scientists and climate model developers is needed to efficiently run CPM models on future high-performance computers.
- CPMs can provide valuable information for climate impact modeling, and future CPM workshops will focus on better connecting CPM researchers to hazard modelers.
- We need an improved understanding of the necessary model grid spacing, model numerics, and complexity of model physics to reliably simulate high-impact weather in various climate regimes.
- High-resolution observational datasets are needed to evaluate and further develop CPMs. Those datasets include surface, ground radar, and satellite observations.
- Important CPM development needs to include the simulations of oceanic clouds, the representation of convection in the turbulent gray zone, coupling to the ocean, and an improved representation of land surface processes and their interaction with the atmosphere.
- Enhanced coordination between CPM modeling studies is needed to improve their comparability and to better understand uncertainties in CPM climate change projections. Such efforts show promising results over Europe and should be extended to other regions. The establishment of joint CPM experiments in Asian countries was a key discussion point.

We are in the process of planning the 5th International Convection-Permitting Modeling Workshop, which is planned for late summer 2021 at DPRI, Kyoto University in Japan. Workshop announcements will be posted through the convection-permitting climate modeling e-mail list (ral-cpcm@ucar.edu) and by GEWEX.

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