There is an urgent need for more actionable and reliable climate information on regional to local scales that cannot be delivered by state-of-the-art dynamical climate models because of their inability to explicitly simulate key processes such as deep convection or the interaction of atmospheric flow with the surface (e.g., orography). Convection-permitting models (CPMs) are novel and very promising tools to generate more reliable and process-based climate information on small scales owing to their small horizontal grid spacings of ≤ 4 km. At this resolution, deep convection can be simulated explicitly and the representation of land–atmosphere interactions is significantly improved [see Prein et al. (2015) for a review].

The goal of the Global Energy and Water Exchanges project (GEWEX) Convection-Permitting Climate Modeling Workshop was to foster communication and collaboration among the rapidly growing CPM community. The main focus was on discussing major challenges and future strategies in this research area. More than 70 scientists participated in the workshop from 13 countries, representing a large cross section of the climate and weather community.

**KEY TOPICS AND RESULTS.** The two-and-a-half-day workshop featured six keynote talks and 27 oral and 44 poster presentations. The book of abstracts and recordings from most presentations and posters can be downloaded from the workshop website (https://ral.ucar.edu/events/2016/cpcm).

The workshop covered five main scientific topics:

1. CPM evaluation and added value,
2. climate change assessments with CPMs,
3. land–atmosphere interactions in CPMs,
4. observational datasets for CPM evaluation, and
5. CPM for simulating tropical phenomena.
Evaluation and added value. The contributions to the first topic focused on assessing the quality of CPM simulations of the current climate in different regions and quantifying their benefits compared to large-scale models (LSMs) that have to parameterize deep convection. Impressive progress has been made in quantifying added value on a process level. A robust finding is an improvement representation of the diurnal cycle of convective precipitation that was shown for many regions and in multiple models. This is based on the ability of CPMs to simulate realistic convective storms, which was assessed by using novel feature-based evaluation methods. The main identified benefits of CPM simulations include

- improved representation of physical processes, which results in reduced uncertainties (e.g., convective storms, terrain–flow interactions),
- simulation of impact relevant processes and scales (e.g., extreme events such as mesoscale convective systems or tropical cyclones), and
- better representation of hydrological processes (e.g., snowpack, orographic precipitation).

Climate change projections. A main focus of the studies that investigated climate change projections was the assessment of changes in extreme precipitation, especially on subdaily time scales. There is a large consensus between the individual studies that subdaily extreme precipitation increases with climate change and that environmental conditions will be more favorable for extreme convective events. Studies that investigated the changes of subdaily extreme events dependent on future temperature increases show intensifications of extremes that are close to 7% °C⁻¹, which is in line with the Clausius–Clapeyron relationship that describes the dependence of saturation vapor pressure on temperature. Another stream of research uses CPM to assess changes in future snowpack and snow cover. Results show substantial losses in future snowpack and snow cover especially at lower elevations, where snow is typically falling close to the melting level. The loss of snow cover leads to strong warming signals in springtime owing to the snow–albedo feedback.

Land–atmosphere interaction. The land–atmosphere interaction studies in the third session showed that CPMs can add significant value in simulating snowpack dynamics in mountainous regions. Coupling more realistic land surface models can lead to improvements of snowpack and snow cover simulations. The correct treatment of canopies in the land surface model was highlighted because of the strong effect of canopies on the surface albedo (Liu et al. 2016). In summer, CPMs might have a stronger coupling between the land surface and the atmosphere. LSMs tend to produce more low intensity, high-frequency, and large spread precipitation than CPMs, which leads to a lower coupling strength.

Observational datasets. Throughout the workshop, the importance of high-quality, high-resolution observational datasets was emphasized and new developments were presented in the fourth session. A novel method that generates an ensemble of probabilistic gridded observational datasets allows quantifying observational uncertainties and their effect on CPM evaluations (Newman et al. 2015). Within the European Intelligent Use of Climate Models for Adaptation to Non-Stationary Hydrological Extremes (INTENSE) project, hourly precipitation data are collected globally, which will benefit CPM evaluations since publicly available subdaily precipitation observations are sparse so far. Using satellite products is especially attractive because of their close to global coverage and relatively high spatiotemporal resolution. However, satellites cannot provide measurements on the resolution of CPMs, which partly inhibits the evaluation of local-scale features. Because of the large number of variables that are derived from satellite observations, they can be of particular value for process-oriented model evaluations.

Tropical processes. In the fifth session, the benefit of applying CPMs in tropical regions was discussed. CPMs have been shown to improve the simulation of tropical cyclone dynamics, including eyewall features, wind speeds, and minimum pressure, that cannot be captured by LSMs. Global simulations with convection-permitting resolution in the tropics aim to improve weather forecasting capabilities in midlatitudes due to teleconnections. Particularly, the improved simulation of the Madden–Julian oscillation is hoped to overcome longstanding biases in LSM forecasts.

MAIN CHALLENGES AND FUTURE RESEARCH. A central goal of the workshop was to identify key challenges associated with CPMs and strategies to overcome them. These key challenges are as follows:

1) The large demand of computational resources that constrains CPM simulations to short
periods and/or small domains. Making use of new computer architectures and running models mainly on accelerators [e.g., graphical processing units (GPUs)] instead of central processing units (CPUs) can lead to significant speedups and enable CPMs to run on larger domains and longer periods (Leutwyler et al. 2016).

2) The big model output data volume makes it challenging to store, analyze, and share data. Evaluating the CPM simulation online (during the processing), storing data on cloud-based platforms, and analyzing data at central computational systems are promising future pathways to overcome these challenges.

3) Assessing uncertainties in CPM simulations is difficult because of their high computational costs. Defining common experiments and standards for data output and model evaluation will help to investigate uncertainties in a systematic way.

4) Missing high-resolution, high-quality observational datasets make CPM evaluation and development challenging and often constrains their application to data-rich regions. Missing observations also constrain model evaluation to a small set of variables such as precipitation and temperature. International projects that focus on the collection of high-resolution data, quality assessments, and the distribution of data in common formats are needed.

5) The relevance of CPMs in areas beyond precipitation including processes such as local wind systems, snowpack dynamics and hydrology, land–atmosphere interactions, evapotranspiration, and the representation of clouds and radiation should be further explored.

6) The model physics such as turbulence, radiation, microphysics, and land surface processes are adopted from LSMs and have to be reassessed for their applicability on CPM scales. A major challenge in CPMs is the treatment of turbulence since traditional approximations (i.e., Reynolds averaging) are not valid on the kilometer scale and turbulence cannot be fully resolved. Studies that investigate the dependence of the model performance on the applied grid spacing, the influence of different planetary boundary layer schemes, and the role of parameterizing deep convection with traditional and scale-aware convection parameterization schemes at convection-permitting scales show strong sensitivities to these changes. Closely cooperating with the numerical weather prediction community that uses CPMs for weather forecasting would accelerate future model developments.

CONCLUSIONS AND NEXT STEPS. Collaborations and community building were identified as the most promising pathways to efficiently identify and resolve these challenges. Working in a community helps to avoid duplication of work; fosters the exchange of data, code, and knowledge; and a coordinated effort for CPM simulations will make simulations more comparable and enables the assessment of uncertainties. A community standard for common data formats and metrics would significantly improve the capability to intercompare model results. A strong CPM community might also help to generate funding opportunities for CPM research and will facilitate the collaboration with other communities such as hydrology, meteorology, or stakeholder communities. The formulation of clear objectives such as simulating convection in the central United States, modeling the Madden–Julian oscillation, or intercomparing different approaches to convection-permitting modeling (see Fig. 1) will be helpful for efficient collaborations.

As a next step, connections to the hydrology community will be established since CPM simulations can provide large benefits for hydrologic modeling because of their added value in simulating precipitation, snowpack, and evapotranspiration. A joint workshop between hydrologists and CPM modelers will be organized in 2017. Connections with other GEWEX and World Climate Research Programme

![Fig. 1. Four approaches to convection-permitting modeling: (a) superparameterizations, (b) variable-resolution modeling, (c) regional climate modeling, and (d) global convection-permitting modeling (Prein et al. 2015).](image)
(WCRP) activities and initiatives launched under the Coordinated Regional Climate Downscaling Experiment (CORDEX) Flagship Pilot Study (FPS) framework will be established. A very promising CPM community initiative is the “Convective Phenomena at High Resolution over Europe and the Mediterranean” FPS lead by Stefan Sobolowski and Erica Coppola. To foster communication within the CPM community, we will create an online blog to accommodate discussions and to exchange novel results. We already have an active e-mail list to efficiently share information within the community. Furthermore, a special issue on convection-permitting modeling in a peer-reviewed journal will be organized. Based on the success of this workshop we aim to organize a successor workshop in 2018 and will host sessions at the main atmospheric science conferences such as the American Geophysical Union, European Geosciences Union, and the American Meteorological Society general assemblies.

REFERENCES


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