Research proposal: How well do km-scale climate models represent organized convection beyond surface precipitation?

Societal and scientific relevance

The organization of convection into storms gives rise to various hazards such as derechos, tornados, hail, and flash floods [1] posing a threat to infrastructure, homes, and lives. Moreover, convective storms play a central role in controlling the water cycle, thus affecting societies by determining water availability for agriculture [2]. How convective storms change in a warmer climate and how they influence sub-seasonal to seasonal (S2S) climate predictability are therefore highly relevant questions that have been addressed in many recent studies [3–6]. In particular, predicting extreme precipitation from convective storms is of considerable societal value due to the substantial economic damage caused by these events [7].

Non-hydrostatic, kilometer-scale (hereafter: km-scale) climate simulations are the primary tool for S2S and future climate predictions of precipitation from convective storms. This is because such simulations can properly represent mesoscale processes [8] by explicitly resolving convection instead of relying on convective parameterization. Km-scale climate model simulations have been shown to improve simulations of short-duration and heavy precipitation, orographic precipitation, and the onset of summer convection [9]. However, the added value from km-scale simulations often depends on the study region and model configuration [9]. While it seems reasonable to attribute detected improvements in simulating precipitation to a more accurate representation of convective storms, it is still an open question what aspects of convective storms can be realistically simulated and how they affect other components in the climate system. For instance, km-scale climate simulations in the central US show significant biases in summer storm frequency [5] that have been attributed to the poor representation of land-atmosphere interactions [10]. Moreover, small-scale processes such as entrainment and vertical mass transport are not fully resolved in km-scale simulations [11], which means that the organization of convection depends on multiple parameterization schemes (micro-physics, planetary boundary layer) that still require tuning for specific regions. Because modeling convective processes remains challenging, I propose **to better leverage satellite observations of clouds and precipitation to evaluate previously neglected aspects of convective storms in km-scale simulations.**

Research agenda

Combining the approaches from [redacted] [12] and [redacted] *et al.* [13], the influence of organized convective storms on precipitation can be decomposed into the following factors:

1. **condensation rate** reflecting how much cloud is produced
2. **precipitation efficiency** reflecting how much of the condensed water is converted to surface precipitation
3. **vertical velocity** reflecting the intensity of the developing storm
4. **storm duration** reflecting the total amount of precipitation produced over time

Understanding how well these four factors are represented in km-scale simulations is essential for gauging the reliability of S2S and future precipitation predictions because they control the amount of precipitation produced by a storm and indicate how well the underlying convective organization is captured.

For my research project at NCAR, I propose, therefore, to systematically evaluate km-scale climate simulations against remote sensing observations constraining these factors.

Advances in remote sensing technology over the last two decades offer new possibilities to gain insights into cloud-related processes. While gridded observational datasets of precipitation and brightness temperatures are widely used for climate model evaluation, satellite measurements of other cloud properties and the vertical structure of storms remain largely unused. In particular, cloud ice could provide useful additional information as it represents the currently missing link between converging moisture and surface precipitation. The principal focus of this work is on observations from space-borne cloud and precipitation radars (CloudSat [14], GPM DPR [15]) as well as novel high-resolution observations of cloud ice from geostationary satellites [16].

The proposed work consists of the following three work packages (WPs):

WP1: Matching storm tracks to satellite-derived cloud properties

At the start of the project, I will create an observational dataset wherein storm tracks of different convective modes (e.g. extra-tropical/tropical cyclones, mesoscale convective systems, single cell convection) are co-located with satellite-based measurements of cloud properties. I will use satellite observations of **cloud ice** to approximate how much cloud is produced by a storm (see **condensation rate**). Because observations of cloud liquid water are currently not available at a sufficient spatial and temporal resolution, I will focus on deep convection wherein ice comprises a large portion of the total condensate [17]. I will also use the cloud ice estimates together with satellite-retrieved precipitation to validate **precipitation efficiency** (approximated as the ratio between cloud ice and surface precipitation). The microphysical precipitation efficiency is closely linked to convection dynamics [18, 19] and the melting of cloud ice is a critical process in stratiform precipitation associated with convective storms [17]. Finally, I will co-locate the observed storms with CloudSat and GPM DPR to get insights into their **vertical cloud and precipitation structures**.

WP2: Validating existing regional and global km-scale simulations

I will validate a suite of existing km-scale simulations that allow for comparison between regions in the tropics and mid-latitudes against the created observational dataset from WP1: 1) 4 km-WRF simulations over CONUS (CONUS404), 2) 4 km-WRF and CAM simulations created by the South America Affinity Group (SAAG), 3) CORDEX simulations over East Asia including NCAR models (WRF, MPAS) as well as European models (ICON, COSMO, RegCM) [20]. These regional simulations cover multiple decades, thus allowing for a process-oriented validation with a focus on the climatological representation of storm types. For the model evaluation, I will perform the same tracking as in WP1, in order to extract cloud properties and vertical storm structures for different convective modes in the simulations. In addition, I will compare existing global km-scale MPAS simulations and data from the *System for Integrated Modeling of the Atmosphere (SIMA;* if available) to coarser-resolution global MPAS simulations and regional simulations. While the large-scale circulation in the reanalysis-driven regional simulations is arguably closer to the observed one, the large-scale circulation in the global simulations is physically more consistent. However, global km-scale simulations are currently only performed over limited time periods due to the high computational costs. It is, hence, crucial for the future development of these simulations to validate if their added value compared to coarser-resolution global simulations outweighs the higher costs.

WP3: Using targeted case simulations to test hypotheses and identify systematic biases

I hypothesize that 1) the simulated precipitation efficiency does not show the same dependency on storm intensity (e.g. vertical extent and duration) as in the observations due to uncertainties in the microphysical parameterization; 2) the studied storm characteristics are best represented in the largest convective modes due to the influence of large-scale factors that make these less dependent on the parameterization schemes; 3) mid-latitude storms are generally better represented than tropical storms due to the same reason. To test these hypotheses, I will use existing ensemble-based case simulations (e.g. from storm cases over the Atmospheric Radiation Measurement (ARM) sites of the Southern Great Plains and Amazon) and targeted short-term simulations in addition to the long-term simulations. Owing to their lower computational costs, case simulations can be performed in various model configurations, which helps assess how far identified biases and shortcomings in the climate simulations are systematic.

The proposed research supports NCAR's Strategic Plan 2020-2024 by using state-of-the-art community models (WRF, MPAS, CESM) to enhance the understanding of *Earth system predictability* with the ultimate goal to enhance *societal resilience*. More specifically, the project aims at providing a basis for improving simulations of the water and energy cycle from seasonal to decadal scales and from regional to global scales. In addition, the proposed research would produce valuable insights for global storm-scale simulations as one of the major challenges ahead in weather and climate modeling.

The project would greatly benefit from the modeling expertise gathered at NCAR because the targeted climate model output is produced by NCAR and because the underlying models as well as many of the commonly used parameterization schemes have been developed at NCAR. The goals of this work are particularly relevant for the *Mesoscale and Microscale Meteorology Laboratory*, e.g. the Capacity Center for Climate and Weather Extremes (by enhancing the understanding of processes behind severe weather), the Dynamical and Physical Meteorology Section (by enhancing the understanding of micro- and macrophysical processes in convective clouds) and the Weather Modeling and Research Section (by providing a basis for model improvements). The project also aligns with the activities of the NCAR's Water Systems program (e.g. SAAG) and provides collaboration opportunities with the Climate and Global Dynamics Laboratory as well as the Research Applications Laboratory.

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