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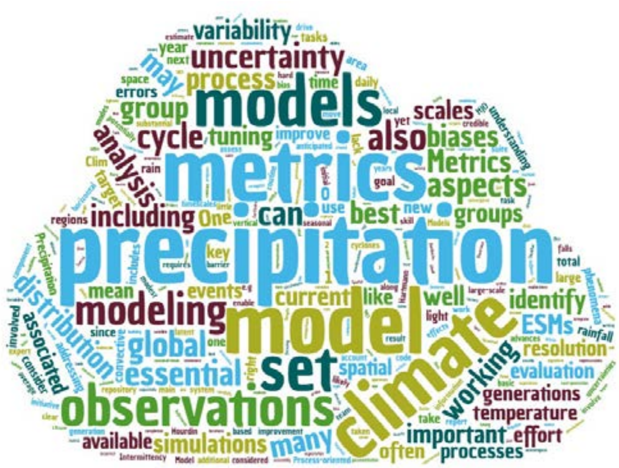
Assessing the Simulation of Precipitation in Earth System Models



Workshop and Working Group
Pre-Workshop Whitepaper

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1.0 Background

Why doesn't precipitation in climate models improve more over time? Precipitation is a primary manifestation of climate. But climate models have struggled and continue to struggle with simulating it accurately – biases have been persistent throughout generations of climate models. A key factor in this lack of progress on precipitation is that it receives little attention in the model developing and tuning process, aside from the spatial pattern of mean precipitation. Instead, the tuning process focuses on the time series of global mean surface temperature, often optimizing temperature at the expense of characteristics of precipitation. One barrier to addressing aspects of precipitation in the model development and tuning process is a lack of consensus about which characteristics of precipitation to target, and what the best observations of these characteristics are. The result is that simulated characteristics of precipitation, like its intensity, are often incorrect.

Modeling precipitation isn't the only challenge involved – observing precipitation is hard too. Model development groups are less than ideally situated to assess which characteristics of precipitation are observed best. Furthermore, uncertainty in observations of precipitation is usually large – including uncertainty information along with observations is essential to avoid over-fitting during the model development and tuning process.

To address this gap in information about the characteristics of precipitation, a prioritized set of precipitation characteristics and a set of observational benchmarks including uncertainty is needed. We propose to gather an expert team on model evaluation and observed precipitation to identify a set of metrics for precipitation that should be targeted for improvement in model development and evaluation, and to identify the best available observations of these metrics, as well as their uncertainty. This set of "observational benchmarks for precipitation" would facilitate a focus on improving precipitation in model development and analysis.

Many characteristics other than precipitation are already entrenched in the model development process, so for this effort to be successfully taken up by modeling groups it will be essential that it is targeted. Key to this effort will be formulating a set of suitable performance measures – or metrics – that succinctly and yet meaningfully summarize model behavior. We will frame the observational benchmarking of precipitation as a challenge for modeling groups. After developing a set of metrics and observational benchmarks, we will evaluate the current (CMIP5 and CMIP6) generations of climate model simulations against the benchmarks. This will provide a clear sense of where model simulations are currently, as well as a target for where improvements can be made.

Faithfully reproducing the many spatial and temporal scales of precipitation is one of the most important and yet also most challenging tasks of Earth System Models (ESMs). With significant efforts focusing on the global mean temperature and the associated energy balance in the past decades, our attention must expand to improving the simulation of regional climate, with precipitation being fundamental to the challenge. Precipitation is also the signature of atmospheric-latent-heating-determining circulation features from global to local scales, and is intimately linked to cloud processes and cloud-radiative effects that dominate modeling uncertainties. Without progress in modeling precipitation, a multitude of barriers will remain. For example, a lack of fidelity in model rainfall will compromise the realism in simulating biogeochemical interactions over land, which in turn will compromise our ability to estimate carbon feedbacks. With a carefully selected expert team, we propose to design and implement a capability that will enable routine and systematic evaluation of simulated precipitation at all scales in ESMs. This analysis suite will capture a diverse set of precipitation characteristics for quantifiably interrogating models with observations across space and time scales. It will provide clear targets to focus modeling priorities toward improving key processes directly linked to simulated precipitation deficiencies.

Just as precipitation is multiscale, model precipitation errors can be found on all scales, ranging from large-scale long-standing rainfall biases in the tropics, to errors in simulating rainfall associated with mid-latitude frontal systems or large-scale tropical circulations, such as the MJO, to local errors in the diurnal phasing and amplitude of precipitation. We intend to probe all relevant phenomena with a unified analysis capability to test the performance of CMIP-class ESMs, with an eye on being able to gauge the quality of higher-resolution models on the horizon.

Despite many years of effort and significant investment, model errors in precipitation have remained large, hindering the use of ESMs in decision making. Progress will critically hinge on mobilizing ideas and resources to address the many problems likely involved in the poor simulation of precipitation, from cumulus parametrization to microphysical processes to the atmospheric thermodynamic environment and circulation. We argue that a re-energized emphasis into improving simulated precipitation is urgently needed. Through its close coupling to clouds and circulation, any improvements in precipitation will likely have significant repercussions in other aspects of the Earth System.

We propose to launch the initiative by initially having a workshop that will help form a small working group to assess the current abilities of climate models in simulating precipitation. The workshop is expected to be in the Washington, D.C. metro area and bring in experts who will decide on the types of metrics that will cover all aspects of precipitation from mean errors to extremes.

1.1 Targeted Climate Models

This effort will target climate models that are global in scale, and the assessment of the current status of precipitation in climate models will focus on CMIP5/6 simulations. A key area of advancement in climate modeling that is anticipated in the coming 5-10 years is an improvement in model resolution in the horizontal as well as the vertical dimension, including the DOE's E3SM effort. One motivation for increasing resolution is to improve the skill of climate models in representing precipitation. As we move toward the next generation of climate models, it will be essential to quantify and document progress, and we envision this initiative as an important contribution to this documentation – providing a comprehensive baseline assessment of precipitation at present and a framework for evaluating the next generations of climate model precipitation.

One challenge will be to strike the right balance by keeping the metrics set small enough to not be overwhelming, and yet large enough to cover independent aspects so that improvements as a whole cannot be achieved through model tuning alone. Special emphasis will also be given to preparing for the evaluation of next-generation high-resolution models.

An active area of research involves understanding the reasons behind precipitation biases, which requires analysis of the mechanisms that generate precipitation in different regions and seasons in observations and in climate models. Such analysis can inform development of new, potentially more sophisticated metrics that may become sufficiently established within the research community to be included in the standard metrics set for use in the future and provides guidance on model development.

1.2 Implementation of the Metrics

PCMDI has significant experience in managing such a code base, which will be closely aligned with the PCMDI Metrics Package (PMP) to ensure that performance tests can efficiently be applied to all models contributed to the ESGF-hosted CMIP database. Achieving these goals requires strong collaboration with the observational community, who will be represented on the working group to provide advice on available observational products and their uncertainties.

We propose to launch this initiative with a 2.5-day workshop in the Washington, D.C. area. As a primary goal, the workshop will bring together the working group that will identify and prioritize the set of metrics, as well as the best available observations to quantify these metrics. The workshop will also include discussion of analysis of precipitation mechanisms for understanding model biases, with the goal of identifying avenues of research that may ultimately lead to process-oriented metrics to be included in the future. It will also assign the writing tasks and completion timeline for the report and review paper.

1.3 Expected Outcomes of the Workshop and Working Group

- A DOE workshop report that includes:
  - A synthesis of existing analysis of precipitation in climate models (CMIP5/6)
  - A list and the rationale of established precipitation metrics that will be used to assess the current ESMs within the year
  - A summary of exploratory process-oriented metrics that may become suitable candidates for expanding the benchmarking suite.
- Formation of a smaller working group of scientists that will work on developing the first set of metrics within the year and implementing them into the PCMDI Metrics Package.
- A review paper that summarizes the main results of the working group and includes the set of metrics and the result of the CMIP6 comparisons.
- A repository of all codes and data developed by the project, facilitated by PCMDI to enable community use for all current and future generations of ESMs.

2.0 Working Group

The working group will consist of scientists actively involved in precipitation evaluation, with particular emphasis on performance metrics. Completion of this task should take no more than 12-18 months and will involve both the existing CMIP5 simulations as well as CMIP6 simulations as they become available.

The primary tasks of this working group will be to (1) develop a set of metrics for key aspects of precipitation and (2) identify the best approach to quantifying each target metric from observations. The set of metrics will be chosen such that they quantify different aspects of precipitation, while remaining observable – addressing observational uncertainty will also be essential. It is anticipated that the initial set of metrics will be drawn from the existing literature, with the expectation that ongoing research may lead to additional metrics that will be incorporated into the code repository.

3.0 Starting Point for Potential Set of Metrics

Below are some initial categories and potential example metrics to be discussed at the workshop. We stress that these are preliminary, as a primary task of the working group is to identify and prioritize the set of metrics for near-term implementation and application.

1. Spatial pattern, seasonal cycle, and global average precipitation

If the goal is to facilitate modeling groups to improve precipitation in their models, our framework needs to integrate their existing practices before building new ones. Currently, the main characteristic of precipitation taken into account in the model development and tuning process is its spatial pattern (Hourdin et al. 2017). Reasonable estimates of monthly- and seasonal-mean precipitation are already viewed as an essential component of having a credible climate model simulation. This is facilitated by the relative ease for model developers of identifying credible observational data sets for monthly average precipitation, like GPCP's monthly product. Nonetheless, assessing the spatial pattern and seasonal cycle of precipitation is an important basic component of assessing climate model precipitation, especially since despite the attention, persistent and pervasive systematic biases still exist – for example, the "double ITCZ".

One of the most basic measures of precipitation for the earth's energy cycle is its global mean. The CMIP5 generation of simulations had a substantial bias in global-mean precipitation relative to the best-available observations that were available upon their release (Stephens et al. 2012). But since that time, new research on the observational side has produced improved precipitation estimates at high latitudes (e.g., Behrangi et al. 2014). Further advances in observational data sets may also include additional precipitation estimates at light rain rates over the ocean observed by CloudSat but not precipitation-focused satellite constellations, and also orographic precipitation not captured by the observing system. The current best estimate of global-mean precipitation and an appropriate uncertainty measure will be useful for integrating our assessment with the existing framework for evaluating precipitation.

2. Diurnal cycle

The diurnal cycle is an essential characteristic of precipitation, varying among locations and seasons. Some aspects of the diurnal cycle, especially those in convective regions, have presented perplexing systematic biases for generations of climate models. As climate model resolution advances and representation of convective processes improves, it is possible that the diurnal cycle will improve along with it, so including this in our assessment is crucial.

3. Distributions of precipitation intensity and frequency

An adage in climate modeling is that models rain "too often and not hard enough." But this statement is often based on looking at the total intensity and frequency of precipitation – the average over all days with precipitation (or with precipitation over a low threshold). In terms of the distribution in intensity of daily precipitation volume, there is an enormous range of skill across climate models (Pendergrass and Hartmann 2014), with some models that are quite skillful compared to observations, and others whose precipitation falls at entirely unjustifiable intensities. This wide variation reflects that many modeling groups do not take the distribution of precipitation into account in their development process. Meanwhile, the bias in total precipitation frequency arises largely from just one type of precipitation event – the very lightest events – which may be unrelated to processes that drive heavier precipitation, and are unconstrained energetically since they involve little latent heat flux. One barrier for modeling groups is that unlike monthly precipitation, daily precipitation volume differs substantially among observational data sets. Providing modelers the best estimates from observations with appropriate uncertainty vetted by observationalists will facilitate identifying and addressing problems with precipitation frequency and intensity.

4. Variability of precipitation

The variability of precipitation on a variety of timescales is one of its primary characteristics. We will quantify precipitation associated with modes of atmosphere-ocean-land variability, including phenomena like ENSO and the MJO, which are already considered in many assessments of modeled precipitation. We will also consider precipitation variability across timescales – daily, interannual, and decadal. An appropriate spectrum of variability is interconnected with many other aspects of precipitation. The variability of precipitation is another arena where input from observationalists is needed to navigate the effects of changes in the observing system that can imprint themselves on measures of variability, and to quantify uncertainty appropriately.

5. Intermittency and sequencing

Recent work has begun to address aspects of precipitation that are essential for impacts, but have often been neglected: the intermittency and sequencing of precipitation events (e.g., Trenberth et al. 2017). Leveraging these relatively new metrics will be important for simulating characteristics of precipitation that are important for its impacts.

6. Process-oriented metrics for tropical and extra-tropical precipitation

Getting the right distribution of precipitation in space and time is not useful if this right answer is for the wrong reasons; including process-oriented metrics will be essential to evaluate this. Process-oriented metrics should differ among regions and seasons driven by different dynamics, so it is especially important to consider the extratropics and tropics separately. Some examples of process-oriented metrics can include the joint relationships between precipitation and circulation (vertical velocity and convergence or divergence of horizontal wind), temperature, and moist static energy. These metrics may also include composite precipitation on tracked tropical cyclones, extratropical storms, landfalling atmospheric rivers, or mesoscale convective systems.

7. Heavy and extreme precipitation events

The most intense precipitation events drive many of the impacts of precipitation, as well as constituting a substantial portion of total precipitation. We will consider heavy and extreme precipitation with multiple metrics. Holistic metrics for precipitation can take forms like the spatial pattern of the heaviest day of precipitation each year, or various percentiles of precipitation. Statistical techniques based on the Generalized Extreme Value distribution can tell us about the characteristics of the tail of the precipitation distribution. In contrast, event-based measures leveraging tracking algorithms, including those developed in DOE’s RGMA program, provide an alternative perspective from which to evaluate precipitation associated with extreme events like tropical cyclones and mesoscale convective systems.

4.0 References

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