1. **Common experimental frameworks to identify and improve coupled system biases**
   Several suggestions were identified that include: 1) a coupled reforecast framework to explore the role of relatively fast physical processes and their representation in driving biases in the coupled system (e.g., a coupled CAPT); 2) a systematic framework for identifying the origin of sea-surface temperature biases in the coupled system using a hierarchy of simulations, including coupled reforecasts, to diagnose biases in the coupled system; and 3) a generalization of the set of standard test experiments and metrics to assess new climate prediction systems incorporating new/modified physics parameterizations or new initialization procedures.

2. **Common experimental frameworks to understand and explore high resolution**
   Since the S2S predictions and the projection communities are exploring the benefits and issues associated with increasing spatial resolution—both horizontally and vertically—in all earth system model components, it would be beneficial to coordinate these efforts. To date, there has been only limited exploration of the computational trade-offs between increasing ocean resolution versus increasing atmosphere resolution. Further, resolution may not always be the most beneficial way to expend computational resources for a given research objective; in many instances, statistical resolution—achieved by running multiple ensemble members—or alternative parameterizations (scale-aware, super-parameterization) may be more appropriate.

   The trade-offs among these components, in terms of their effect on model skill, fidelity, and usability, have not been adequately explored. There are several questions pertaining to spatial resolution that would benefit from jointly-planned, systematic exploration involving both communities:

   - How does skill/fidelity change as resolution is increased in the various Earth system components?
   - What changes in skill/fidelity result from local or global increases in process resolution (e.g., orographic precipitation is a known example for atmospheric resolution)?
   - Are there changes in the emergent behavior of the coupled system that result from increasing resolution in any or all components?

To facilitate these, several suggestions for potential collaboration across relevant modeling efforts were highlighted:

- Systematically identify and address coupled- climate model biases, e.g., via a numerical experimental design that could attribute causes of error, focusing on the spatial pattern, timescale, geographic specificity, dominant domain (atmosphere, ocean, land surface, or sea ice), teleconnectivity, feedbacks, and responsible processes.
- Systematically explore the pros and cons of high-resolution with scale-aware-physics, e.g., defining a numerical experimental design that could quantify and definitively attribute the sensitivity to resolution of prediction skill and/or model fidelity at both large scales and locally, including emergent behavior, possibly adapting aspects of the framework suggested for regional climate models.
- Define and share a set of metrics, including both process-based metrics, that can inform model development choices and operational prediction metrics that are defined by stakeholders.

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ADDITIONAL INFORMATION

Workshop Website
cpo.noaa.gov/MAPP/HR_workshop

Draft report is available at
http://climatemodeling.science.energy.gov/workshop-reports

cpo.noaa.gov/MAPP/reports

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U.S. DEPARTMENT OF ENERGY | Office of Science
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

High-Resolution Coupling and Initialization to Improve Predictability and Predictions in Climate Models

EXECUTIVE SUMMARY

There is a growing demand for reliable high-resolution, coupled climate information in two communities: the predictions and projections communities. The climate predictions community conducts both basic and applied research on short-range climate predictability that directly benefit operational forecast capabilities and focuses primarily on basic research concerning climate variability and long-term climate change. Despite the differences, there are several key parallels between these two research communities—a basic example being that both communities assimilate observational data into comprehensive physical climate or earth system models.

The prediction community uses a variety of data assimilation (DA) techniques for initializing real-time forecasts and reforecasts, and for producing reanalyses, while the climate modeling and projections community started to adopt DA techniques for basic research and for short-term reforecasts to diagnose model behavior. Both communities are also on the verge of increasing the resolution of the climate models while coupling with many more components of the climate and Earth system. While the predictions community explicitly aims to advance the development of operational products that are of the highest possible value to stakeholders and decision- makers at the weeks to seasons timescale, the climate modeling community is implicitly involved in generating products that are used in assessments and to inform stakeholders and decision-makers about long-term climate change.

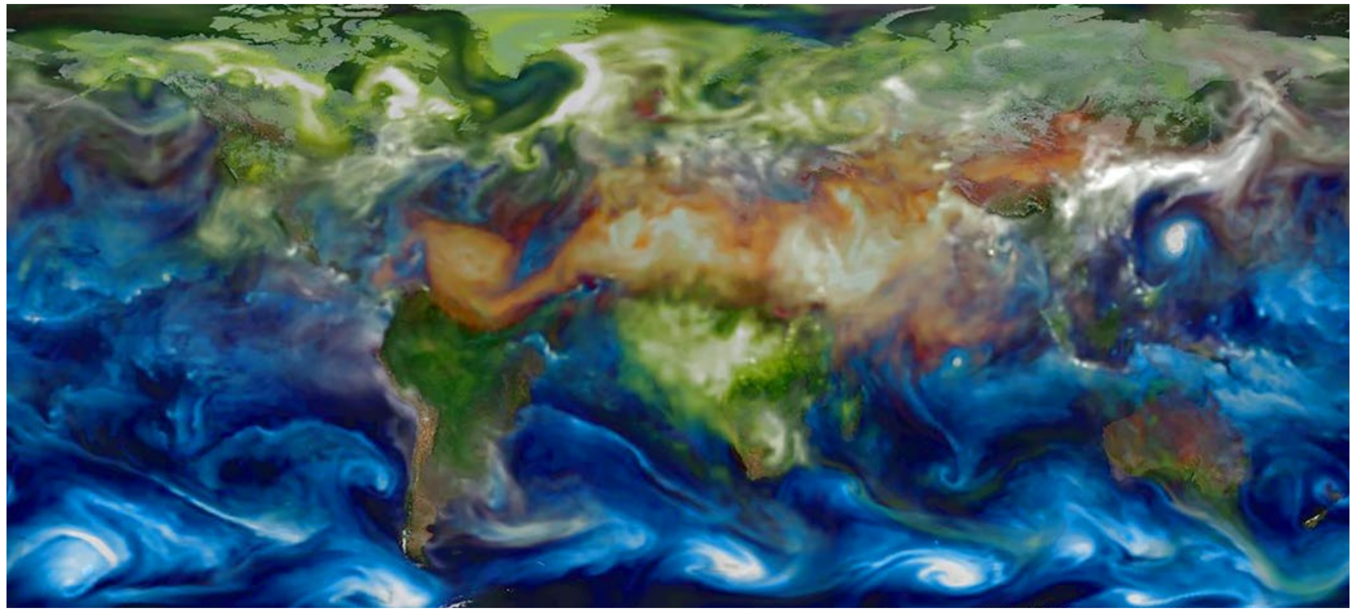
Recognizing the common challenges and capitalizing on the potential synergies, the U.S. Department of Energy (DOE) and National Oceanic and Atmospheric Administration (NOAA) jointly hosted the workshop on **High-Resolution Coupling and Initialization to Improve Predictability and Predictions in Climate Models**. This workshop brought together two groups of scientific experts: one focused on sub-seasonal to seasonal climate (S2S) prediction and the other focused on using initialized simulations to identify biases in climate models, such as in the Cloud Associated Parameterization Testbed (CAPT).

WORKSHOP OBJECTIVES

The goals of the workshop were: 1) to enhance interaction and communication between the climate predictions and the climate modeling and projections communities, 2) to summarize and synthesize the current status of the research and to also document the challenges in initialized high-resolution simulations in both communities, and 3) to identify the criteria for establishing a multi-model experimental framework to optimally address major pressing questions in the context of available computing resources. The two-and-a-half day workshop was hosted at NOAA's Weather and Climate Prediction Conference Center, September 30 to October 2, 2015.

To address the objectives of the workshop, three themes were identified as the foci of the workshop on the first two days: 1) Seamless sub-seasonal to seasonal predictions—the nexus of resolution, process, and prediction; 2) Frameworks for diagnosing fast physics in the coupled system; and 3) Initialization at high resolution and uncertainty sampling for sub-seasonal to seasonal prediction. These were discussed in the context of the anticipated computational and infrastructure environment for the next five years that impose limits on resolution and initialized simulations. The last day of the workshop focused on uniting the knowledge gathered and discussing Frameworks and Experimentation for High-Resolution Climate Modeling and Prediction.

Overall, there is optimism regarding the potential synergies of both communities. There are major efforts in both communities to explore the use of high resolution in all the components of the Earth system. For the atmosphere, increasing resolution appears to improve the representation of orographically-influenced circulation and precipitation, the statistics of precipitation, high-latitude temperature biases



Aerosol data assimilation in the NASA MERRA-2 system. Aerosol Analysis 10 July 2013 1200UTC. *Image courtesy of Akella NASA/GMAO.*

related to snow-albedo feedbacks, and the representation of synoptic-scale circulation features and tropical cyclones. For the ocean, increasing resolution improves the structure, placement, and statistics of western boundary currents; the magnitude and statistics of enthalpy fluxes associated with transient eddies; and the magnitude of zonal and vertical transport in eastern boundary currents. For many coupled and uncoupled models, there appears to be a threshold in atmospheric model resolution at which the dynamical behavior changes—at ~25-50 km grid spacing—and there is an expectation of reaching another threshold of prediction skill when cloud systems and ocean eddies are explicitly resolved, which requires grid spacing of < 4 km. Similar threshold behavior is found in the ocean component of global models. In both atmospheric and oceanic components, there are "gray zones," i.e., ranges of spatial resolution in which the parameterizations of sub-grid scale physical processes are inappropriate.

However, it was acknowledged that high horizontal resolution is not a panacea. Experimentation must be done with models having physical representations that can span a range of model resolutions. In fact, a number of prominent biases and model errors persist, or even worsen, despite increases in model resolution. These include: poor representation of the diurnal cycle of convection, weak or no representation of variability associated with the Madden-Julian Oscillation, sea-surface temperature biases in the eastern Tropical Pacific Ocean, along with similar errors in coupled land-atmosphere, ocean-ice and ice-atmosphere interactions. Such modeling errors are detrimental to the fidelity of both S2S forecasts and climate model projections.

WORKSHOP THEMES

1. Seamless sub-seasonal to seasonal predictions—the nexus of resolution, process, and prediction

There is optimism regarding prospects for developing the capability to produce more skillful, useful, and reliable S2S predictions stemming from advances in both numerical weather prediction and climate simulation and projection. S2S prediction improvements are expected as the understanding of the predictable components of the Earth's climate system improves and as synoptic or even mesoscale phenomena in the ocean and atmosphere are better resolved. Along the S2S prediction improvement path, there are many open questions that represent trade-offs for which modeling and prediction priorities need to be guided by enhanced scientific understanding. A number of projects have begun explorations of relevant issues; however, to date none of these has comprehensively or definitively solved the scientific and technical challenges set forth, nor has the trade space involving numerics, physics, resolution, ensembles, and complexity been fully explored, so no clear guidance has yet emerged.

2. Frameworks for diagnosing fast physics in the coupled system

Methods employed here are nearly identical to those used for S2S prediction with climate models. While such initialized simulation techniques are relatively well established for atmospheric models, there are many open questions about the implementation and application to the other components of the coupled system. One of the challenges has been to initialize the component models appropriately. There is currently no consensus as to the level of sophistication of the initialization method necessary to achieve this, and it is likely to be dependent on application. There are also fundamental questions about using initialized approaches to investigate coupled-model behaviors. However, the clear advantage of initialized approaches is the ability to make better use of observations for evaluating model physics. Overall, the use of initialized techniques for evaluating high-resolution climate models is just emerging, with the advantage that short runs are expected to provide information about sources of errors in physical processes. High-resolution coupled simulations are being investigated, but this has so far been mostly undertaken with regional models rather than global.

3. Initialization at high-resolution and uncertainty sampling for sub-seasonal to seasonal prediction

Data assimilation in a coupled system poses a unique challenge that is currently an active topic of research. Generally, forecasts with higher resolution will require higher quality initialization, because the resolved dynamics have smaller features and shorter timescales. In the context of coupled models, it is desirable to match the quality of the initialization of each component to the length of time that the information from that component's initial conditions persist in the coupled system. There are several limitations as well as areas of active research needed to advance initialization capabilities. For high-resolution forecasts, the required quality of initialization may not be available yet; for forecast aspects of interest that rely on small spatial scale features, research and development will be needed to establish these features in sufficiently high-resolution analyses; for forecasts longer than the persistence of the information in any of the initial conditions, an ensemble forecast is needed.

The question of required ensemble size ultimately comes down to comparing the amplitude of the phenomenon to be predicted (signal) versus chaotic behavior in the system. If only the mean state is to be predicted, a smaller ensemble is needed than if the spread or, even more so, the extremes must be predicted. It may be possible to use experiments with lower resolution and varying ensemble size to guide the ensemble size choice in high-resolution studies.

4. Frameworks and experimentation for high-resolution climate modeling and prediction

Prediction error in S2S models is related to bias in climate models, such that models with large bias tend to have larger prediction errors, so improving models in order to reduce the bias is expected to reduce prediction errors. The experimentation with increasingly high-resolution models explicitly requires major investments in computational capabilities for both communities. These models require access to massively parallel computing architectures, codes that can run efficiently on such machines, huge amounts of transient and permanent data storage, and sophisticated algorithms and software for post-processing and analysis operations. Despite the diversity of supercomputing platforms, there is much room for shared computational investment across the two communities. The two communities share similar codes for DA and simulation; both have similar challenges in dealing with massive amounts of data and both perform similar operations when post-processing and analyzing data. Shared investment in these codes (or in underlying, commonly used libraries), in data management approaches, and in big-data analysis/post-processing software would benefit both communities. Such infrastructure synergies could be facilitated by the adoption of common experimental frameworks.

COLLABORATION OPPORTUNITIES

Potential areas for coordinated investment discussed at the workshop fall into the following categories: 1) common experimental frameworks to identify and improve coupled system biases and 2) common experimental frameworks to understand and explore the benefits and challenges of high-resolution in various model components. Both of these topics were discussed in the context of common software frameworks for simulation codes, simulation data management, and remote big-data analysis.