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

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

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Workshop Participants: The workshop included over 40 participants from various leading U.S. climate modeling and operational prediction institutions, including representatives from several international groups. Image courtesy of William Chong, NOAA/CPO.

Executive Summary

There is a growing demand for reliable high-resolution, coupled-climate information in two communities: the predictions and projections communities. The climate prediction community conducts both basic and applied research on short-range climate predictability that directly benefits operational forecast capabilities, and the climate modeling and projection community 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 techniques for initializing real-time forecasts and reforecasts, and for producing reanalysis, while the climate modeling and projections community started to adopt data assimilation 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 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 (S2S) climate predictions 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 interactions and communications between the climate-prediction and the climate modeling and projection communities, 2) to summarize and synthesize the current status of the research and 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 September 30 to October 2, 2015, at the NOAA Center for Weather and Climate Prediction.

To address the objectives of the workshop, three themes were identified as the foci of the workshop on the first two days: 1) seamless S2S 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 S2S prediction. These were discussed in the context of the anticipated computational and infrastructure environments for the next 5 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.

Workshop Themes

1 Seamless S2S 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. Improvements in S2S predictions 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 tradeoffs 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 explorations have 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. Therefore, 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 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 regarding the level of sophistication needed for the initialization method, and it is likely to be dependent on the application. There also are 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 rather than global models.

3 Initialization at high resolution and uncertainty sampling for S2S predictions

Data assimilation in a coupled system poses a unique challenge that is currently an active topic of research. Generally, higher-resolution forecasts 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 persists 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 will be 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 choice of ensemble size in high-resolution studies.

Next Steps: 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 to reduce the bias is also expected to reduce prediction errors. Experimentation with models of increasingly high resolution 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 data assimilation 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 two 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. Brief descriptions of the two categories follow.

1. **Common experimental frameworks to identify and improve coupled system biases**

Several suggestions were identified:

- 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)
- 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
- a generalization of the set of standard test experiments and metrics to assess new climate-prediction systems that incorporate new/modified physics parameterizations or new initialization procedures.

2. **Common experimental frameworks to understand and explore high resolution**

Because 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 tradeoffs 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 tradeoffs 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 finding answers to these, several suggestions for potential collaboration across relevant modeling efforts were proposed:

- 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 modeling 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.

Workshop Outcomes

Overall, there is optimism regarding the potential synergies of predictions and climate modeling communities. There are major efforts in both communities to explore the use of high-resolution modeling 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 related to snow-albedo feedbacks, and 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 to 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;" that is, ranges of spatial resolution in which the parameterizations of sub-grid-scale physical processes are inappropriate.

However, workshop participants 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.

Contents

Introduction

There is a growing demand for reliable climate predictions (intra-seasonal to decadal) and projections (decadal and longer, including secular trends) at regional and local scales. In recent decades, a combination of factors, including the use of higher spatial resolution, improved physics, and better methods in data assimilation (DA), has dramatically improved weather prediction skills. In contrast, seasonal prediction skills have only modestly improved compared to our understanding of the processes underpinning weather predictability.

Coarse-resolution climate models do not properly represent potentially important coupled phenomena, such as interactions between tropical cyclones and their wakes and coupling between low clouds and small-scale ocean temperature gradients, as well as interactions between the horizontal gradients in soil moisture and the atmosphere, the sea surface and the atmosphere, etc. (see Figure 1). There are indications from studies (e.g., Bryan et al., 2010; Chelton and Xie, 2010; Kirtman et al., 2012; Doblas-Reyes et al., 2013; Kinter et al., 2013; Small et al., 2014; Wehner et al., 2014; Murakami et al., 2015,) that resolving such phenomena would improve the simulation of the mean climate, variability and extremes, and increase the accuracy of, and confidence in, climate predictions and projections. Higher resolution is not a panacea for all problems and needs to be accompanied by improved modeling of relevant physical processes at the appropriate scale.

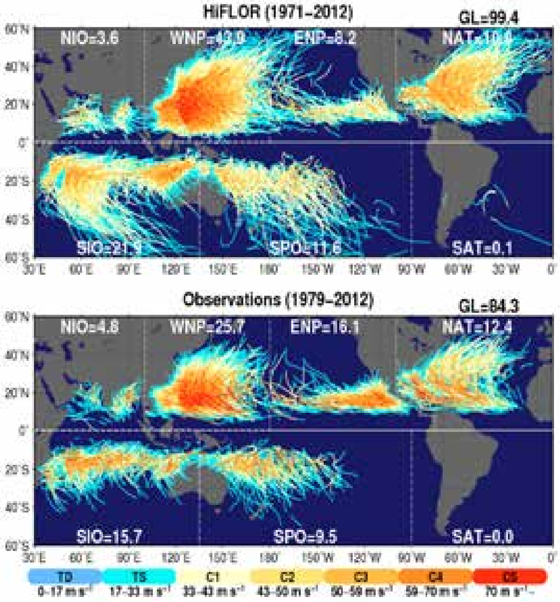

Figure 1. Doubling atmospheric horizontal resolution from the Geophysical Fluid Dynamics Laboratory (GFDL) Forecast-Oriented Low-Ocean-Resolution (FLOR) model to its Higher Resolution Forecast-Oriented Low-Ocean-Resolution (HiFLOR) configuration allows simulation of Category 4-5 tropical cyclones, which are the most destructive storms; however, computational costs increased sixfold. From *Murakami et al. (2015), courtesy of Yang, NOAA/GFDL.*

Several recent efforts have used observationally initialized climate models to address issues from model development to decadal predictability. For example, the North American Multi-Model Ensemble (NMME) (Kirtman et al., 2014) has made significant progress in improving seasonal to interannual predictions. The most recent phase of the Coupled Model Intercomparison Project (CMIP5) included a major component dedicated to evaluating climate models in decadal reforecast(1) mode. Climate models used for predictions and projections are often configured in weather prediction mode (Phillips et al., 2004) to identify climate biases and test new configurations, since many long-term biases manifest within a few days and initialized simulations are valuable when comparing to process-level observations collected in field-campaigns (e.g., the Transpose-AMIP [Atmospheric Model Intercomparison Project]) component used in CMIP experiments or the Cloud-Associated Parameterization

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(1) The term "reforecast" is used here to describe a numerical experiment in which a forecast is produced for a period in the past for which the actual evolution of the climate system is known. Reforecasts are typically done without any input of observational data from the period following the initial time, except decadal reforecasts that use observed forcing. The same method is also referred to as "retrospective forecast," "hindcast," or colloquially "initialized simulation."

Testbed [CAPT]).(2) In all these cases, models are typically run at their standard, relatively coarse, resolution (i.e., 1-degree horizontal grid spacing or coarser), and none of them specifically address the potential advantages or challenges of using high-resolution coupled systems. The communities involved in the various modeling efforts mentioned above are exploring the use of high-resolution coupled systems, but these communities have evolved separately. Enhanced communication among them could help move these efforts forward.

The need to improve climate prediction and its realism at local-to-regional scales, and the need to identify and reduce biases in the coupled system in climate models, motivate an exploration of climate-prediction techniques in coupled models at higher resolution. The majority of the work done to date in prediction and the use of initialized climate models has focused on the benefits of higher resolution in atmosphere-only models (e.g., research using the CAPT framework at U.S. Department of Energy [DOE] laboratories). There has been less work undertaken to explore the benefits of higher resolution in coupled models. Even less has been undertaken in the use of observationally initialized coupled simulations, although some pioneering work in this area is ongoing at several laboratories in the United States, Europe, Japan, and in international collaborations (e.g., the Seasonal-to-Decadal Climate Prediction for the Improvement of European Climate Services project (Doblas-Reyes et al., 2013). Previous work within the scope of the CAPT has shown the benefits of understanding atmospheric processes and biases in the atmospheric model component alone. Experiments have been proposed as part of CMIP6 to examine the impact of increasing resolution in AMIP-type experiments (i.e., high-resolution model interconnections) and also in long-term, non-initialized coupled simulations. However, the importance of understanding the relative roles of process-level representation and resolution on biases in initialized coupled-climate simulations has received less attention.

Workshop Goals

To examine the benefits for prediction of both modeling and initializing at higher resolution, several scientific and practical questions will need to be addressed. Because the issue of model dependency inevitably arises, it may be worthwhile to consider a multi-model setting, which would require multi-center coordination, so as to yield theoretical and practical results that are applicable to the wide array of models. A common experimental framework for experiments and analysis, carefully defined with scientific community involvement, could facilitate evaluation and comparison of model strengths and weaknesses. Initial exchanges of ideas would be needed to determine how to design appropriate numerical experiments that can reliably test hypotheses given the necessary tradeoffs in resources (especially high-performance computing [HPC]) between resolution, length of predictions, ensemble size, and complexity of model processes.

Recognizing the common challenges and capitalizing on the potential synergies, DOE and the National Oceanic and Atmospheric Administration (NOAA) jointly hosted a workshop on High-Resolution Coupling and Initialization to Improve Predictability and Predictions in Climate Models. The workshop brought together two groups of scientific experts: one that focused on seasonal-to-sub-seasonal (S2S) prediction; and the other that focused on using initialized simulations to identify biases in climate models, such as in CAPT. The goals of the workshop were 1) to enhance interaction and communication between the predictions and the climate modeling and projections communities, 2) to summarize and synthesize the current

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(2) **http://www-pcmdi.llnl.gov/projects/capt/**

status of the research and also document 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 held September 30 to October 2, 2015, at the NOAA Center for Weather and Climate Prediction(3).

Workshop Organization

To address the goals of the workshop, three themes were identified that provided the foci of the workshop on the first two days: 1) seamless S2S 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 S2S predictions. These themes were discussed in the context of the computational and infrastructure environments that might be encountered over the next 5 years, which might impose limits on resolution and initialized simulations (see Overarching Workshop Questions). The last day of the workshop focused on capturing the knowledge gathered and discussing frameworks and experimentation for high-resolution climate modeling and prediction.

Overarching Workshop Questions

1. For which components of the coupled system is it most critical to increase resolution for particular time scales?
2. Are there specific processes in the coupled system that drive both prediction error and simulation bias? What resolutions are necessary to adequately resolve these processes? Would increasing resolution improve error and bias?
3. How does prediction skill and fidelity change when resolution is increased in the various components of the prediction system? How can we diagnose and address model behaviors that lead to the sensitivity?
4. Can the CAPT framework be used to address high-resolution modeling and what resolutions and model configurations would be most informative for understanding biases that are prevalent in climate models?
5. What initialization techniques are best applied for prediction at the various spatial and temporal scales? Can more sophisticated initialization techniques as part of CAPT be useful?
6. What is the ideal size of the ensemble needed for this effort, both for prediction and for understanding coupled processes and biases?
7. Can the CAPT framework be extended to support multi-model comparison of initial error growth and/or to isolate initial error growth in individual model components that leads to differences in climate model simulations and predictions by multiple models or uncoupled versus coupled models? Are there systematic problems or weaknesses that seem to apply to all models?
8. What resolution is feasible given the state-of-art HPC systems available to the U.S. community? How will increasingly high-resolution data be stored and shared for community research?

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(3) **http://cpo.noaa.gov/ClimatePrograms/ModelingAnalysisPredictionsandProjections/OutreachPublications/MeetingsWorkshops/HighResolutionWorkshop.aspx**

In addition, the organizers divided themselves as topical leads for the three theme areas identified above, along with a fourth group that focused on computational infrastructure and further developed specific questions pertaining to the four themes. Guiding points served to stimulate the discussion. In all, over 40 participants from various leading U.S. climate modeling and operational prediction institutions and several international groups contributed to the success of the workshop. The multiagency involvement of the workshop was acknowledged by the introduction being given by the Executive Director for the U.S. Global Change Research Program and the closing note by a principal and Chair of the Interagency Group on Integrative Modeling, which is a working group of the U.S. Global Change Research Program.

This report summarizes the workshop proceedings. An overview of the state of the science is provided, and the major pressing questions are posed and the workshop discussion summarized for each of three major workshop themes:

1. Seamless sub-seasonal-to-seasonal predictions – the nexus of resolution, process, and prediction
2. Frameworks for diagnosing fast physics in the coupled system
3. Initialization at high resolution and uncertainty sampling for S2S prediction

All of these themes were discussed in the context of the anticipated computational and infrastructure environment for the next 5 years that imposes limits on resolution and initialized simulations. Suggestions for next steps based on workshop discussions are provided.

Overview of State of the Science

State of the Science in Seamless Sub-Seasonal-to-Seasonal Predictions

There are good prospects for developing the capability to produce skillful, useful, and reliable S2S(4) predictions that have grown out of advances in both numerical weather prediction and climate simulation and projection. The emphasis on "seamless" prediction refers to the notion that the same coupled-climate system is the target for prediction, and the same numerical solution methods of the governing equations can be applied, regardless of time scale. Convergence to the continuous solution is expected, as in any fluid simulation method, as the model resolution gets finer (i.e., the grid spacing decreases or the number of basis functions increases). For the purpose of S2S prediction, "high-resolution" models are those that accurately represent the dynamics and physics of storms (i.e., extra-tropical and tropical) in the atmosphere (<25-km grid spacing or finer; however, this is debatable as is discussed below), eddies in the ocean (at this time, 1/10 degree or finer), and catchment flows (~5-km grid spacing for catchment models [e.g., Crooks et al., 2014]) on the land surface, as well as all phenomena at scales larger than these.

The basis for optimism about S2S predictions is our improving understanding of the predictable components of the Earth's climate system (e.g., Hoskins, 2013). Also, there is a growing consensus that resolving synoptic or even mesoscale phenomena in the ocean and atmosphere may lead to improvements in simulations of the mean climate and predictions of variability,

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(4) Note that S2S predictions involve the climate research community, which has traditionally explored intra-seasonal-to-seasonal phenomena.

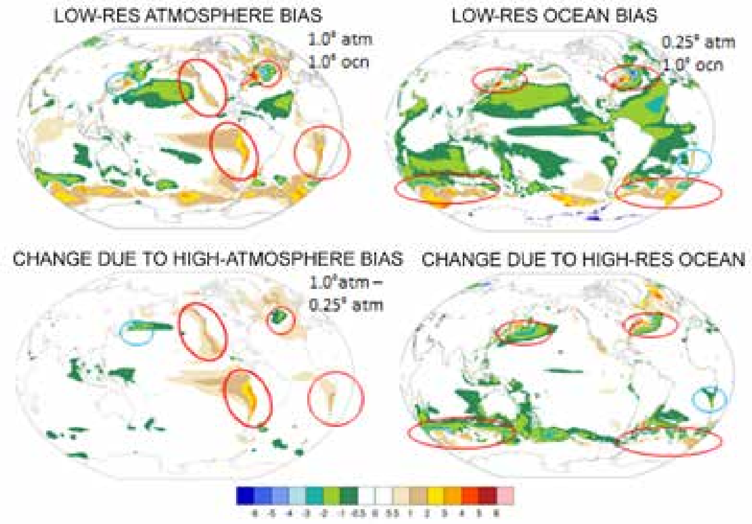

Figure 2. Experiments to understand the impact of changes in horizontal resolution in the atmospheric model and oceanic model in a study with the Community Earth System Model. Adapted from Small et al. (2015). Image courtesy of Jim Kinter, GMU/COLA.

small-scale features, and extremes. There are several examples of success using global coupled models with near-mesoscale horizontal resolution in the ocean and atmosphere (Bryan et al., 2010; Chelton and Xie, 2010; Kirtman et al., 2012; Doblas-Reyes et al., 2013; Kinter et al., 2013; Small et al., 2014; Wehner et al., 2014; Murakami et al., 2015) (see Figure 2). Higher vertical resolution in the stratosphere leads to a better simulation of troposphere-stratosphere interactions (Richter et al., 2014), and higher vertical resolution in the boundary layer atmosphere and ocean may lead to better simulation of atmosphere-ocean interactions, depending on the sensitivity of the turbulence and other parameterizations to vertical resolution (e.g., Blockley et al., 2013; Byrne et al., 2015).

There are many open questions that represent tradeoffs for which modeling and prediction priorities need to be guided by improved scientific understanding. Examples of these questions are listed below:

- Are human and computing resources better spent on improved numerics (e.g., new dynamical cores), improved physics, or increased resolution and re-tuning?
- Should very-high-resolution, atmosphere-only models or fully coupled models with less-than-highest-possible resolution be used for sub-seasonal predictions? How should decisions be made about which components to include as (inter)active? What is the impact of using very different grid spacing in interactive components?
- Should multi-resolution global models be considered that allow for computationally “cheaper” assessment of regional model performance at high resolution(5)?
- Which of the following provides a more substantial improvement in S2S prediction skill or reliability: increasing horizontal or vertical resolution (holding computational cost fixed)? Should the increased vertical resolution be targeted in both the atmosphere and the ocean?
- Should other choices be explored instead of increasing spatial resolution (e.g., using different grids for dynamics and physics, more sophisticated parameterizations or super-parameterization,(6) or increasing ensemble size(7))?

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(5) There may be large performance differences depending on how the grid is handled (e.g., stretching versus nesting).

(6) Super-parameterization bridges the gap between conventional or stochastic parameterizations and global cloud-resolving models (Grabowski, 2001; Khairoutdinov and Randall, 2001). The super-parameterization has been used in ocean-atmosphere coupled forecasts and reforecasts (Stan et al., 2010; DeMott et al., 2014), and results show realistic interactions among relevant small-scale and mesoscale processes on time scales much longer than the lifetime of a cloud system. Superparameterization is equivalent in computational cost to decreasing conventional grid spacing threefold.

(7) Twofold decrease in grid spacing is equivalent to increasing ensemble size sixfold.

- Can lower-resolution ensembles be designed to reproduce statistical properties of higher-resolution ensembles? This would validate a mixed resolution ensemble approach that balances high-resolution dynamics with low-resolution efficiency.
- How should development and testing decisions be made in light of the fact that, while low-resolution models are computationally cheaper, tuning models at low resolution provides no guarantee that the same tuning applies at higher resolution?
- How should the benefits of increasing resolution be assessed vis-à-vis improving prediction? What metrics provide a robust assessment?

The following related research and technical challenges will be addressed:

- What resolution is *required* for S2S prediction? That is, once requirements for S2S prediction have been gathered and products defined that meet those requirements, what models at what resolutions can deliver the necessary data at the required cadence, resolution, accuracy, and reliability? While resolution choices in a given model are often determined by the availability of computing resources, this is a scientific question that depends on the process of interest. Also, there are interesting questions that seem to be universal:
  –What is the origin of threshold behavior in explorations of model resolution?
  –How can we overcome the problem of “gray zones”(8) in component models (i.e., develop more “scale-aware” parameterizations of unresolved processes)?
- We have not yet developed the capability to use existing in situ and satellite observational networks to provide initial conditions and verification data globally at the mesoscale, particularly in the case of the land surface, sea ice, and ocean components of coupled prediction systems. Current practices in global DA are not necessarily appropriate for the mesoscale.
- Very long runs of a century or more may be needed for better determination of biases (e.g., in the deep ocean), which are in practice hard to implement, because they are serial runs that require large commitments of resources and because long-term measurements of the deep ocean are mostly unavailable.
- Considerable diagnostic work (see example of such diagnosis in Figure 3) is needed to determine if high-resolution models can capture the observed organized mesoscale structures, and if not, why not.

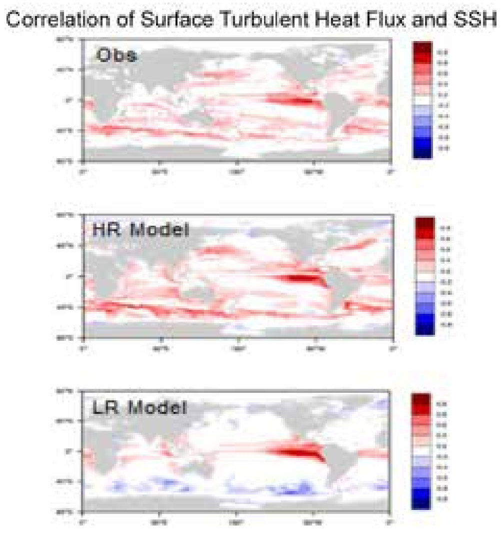

Figure 3. Horizontal resolution impacts the realism of coupled surface fluxes in National Center for Atmospheric Research (NCAR) model simulations. Image courtesy of F Bryan, NCAR.

In addition to the large model comparison projects (e.g., CMIP, NMME, etc.) that are ongoing, several singular projects have begun explorations of some of these issues (see Large Modeling

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(8) “Gray zones” are ranges of spatial resolution representing scales at which there are transitions between one process and another controlling variability and in which the sub-grid-scale parameterization of physical processes may be inappropriate.

Projects). While all of these projects have addressed one or more aspects of the issues raised above, none has comprehensively or definitively solved the scientific and technical challenges set forth, nor has the trade space(9) been fully explored, so no clear guidance has yet emerged.

Large Modeling Projects Exploring Resolution Issues

Seasonal-to-Decadal Climate Prediction for the Improvement of European Climate Services project

This project was designed to identify the main barriers to seasonal to decadal predictions and explore various solutions from a seamless perspective, both in terms of time scale (Palmer et al., 2008) and between information producers and users (Challinor et al., 2009). The research component of the project has a particular focus on the low climate-prediction skill in the European region and includes a number of hypothesis-testing experiments, including explorations of higher spatial resolution. The project achieved an initial capability (Doblas-Reyes et al., 2013), including a retrospective forecast of the apparent global warming slowdown in the early 21st century, and higher resolution was shown to be effective for improving forecast skill (e.g., MacLachlan et al., 2014).

Project Minerva

This collaboration between the Center for Ocean-Land-Atmosphere Studies and the European Centre for Medium-Range Weather Forecasts made use of an experimental version of the global coupled Ensemble Forecast System to specifically explore the sensitivity of seasonal forecasts to the resolution of the atmospheric component, with grids spaced 64, 32, and 16 km apart. While some sensitivities (and insensitivities) to horizontal resolution have been found, the high volume of output of the large number of reforecast ensembles is still being analyzed.

HiFLOR

In recent years, experimental prediction research at the Geophysical Fluid Dynamics Laboratory has focused on the Forecast-Oriented Low-Ocean-Resolution (FLOR) version of the Coupled Model (Vecchi et al., 2014; Jia et al., 2015). However, a variant of FLOR with higher spatial resolution in the atmospheric component (HiFLOR) (Murakami et al., 2015) has been tested and shown to be effective for seasonal hurricane prediction.

PRIMAVERA

The Process-Based Climate Simulation: Advances in High-Resolution Modeling and European Climate Risk Assessment is a European Union Horizon 2020 project that aims to develop a new generation of advanced and well-evaluated, high-resolution global climate models that are capable of simulating and predicting regional climate with unprecedented fidelity for the benefit of governments, business, and society in general. The research component of the project focuses on model fidelity through process understanding and increased spatial resolution to address regional climate-change projection and risk assessment.

ACME

The Accelerated Climate Modeling for Energy project was recently launched by the U.S. Department of Energy to develop and apply the most complete, leading-edge climate and earth system models to challenging and demanding climate-change research imperatives. The project seeks to exploit highly advanced emerging supercomputing resources to improve understanding and simulation of the hydrological cycle, biogeochemistry, and the cryosphere-ocean system.

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(9) Numerics/physics/resolution/ensembles/complexity, fixed/variable resolution, vertical/horizontal resolution, conventional/alternative methods, etc.

State of the Science in Using Initialized Climate Models for Testing Model Physics and Understanding Model Processes and Biases

As climate models have developed and become more complex, the atmospheric components have increasingly been tested using methods that are borrowed or based on techniques used in numerical weather predictions. In particular, the parameterized physics and the interactions between parameterized and resolved processes are sometimes evaluated in short, observationally initialized simulations (hindcasts). Often the aim is to use observations directly to evaluate model performance (Miller et al., 1999; Beesley et al., 2000; Hogan et al., 2001). Hindcast evaluation also is useful for complementing the traditional model development process that emphasizes non-initialized AMIP experiments (see Figure 4). With climate models moving to higher resolution, these techniques are more valuable than ever, because they offer efficient and flexible frameworks for model evaluation. While such techniques, such as nudging (Kaas et al., 1999) or reforecast approaches, are relatively well established for atmosphere models, there are many open questions about the implementation and application to the other components of the coupled system.

This approach to model evaluation in many ways is epitomized by CAPT, in which climate models are configured in "weather forecast mode." Typically an analysis system using a different background model (e.g., National Centers for Environmental Prediction - NCEP - or European Centre for Medium-range Weather Forecasts (ECMWF) operational or reanalysis products) is used as the source of state variables (commonly winds, temperature, and humidity) to initialize the climate model. Any of several approaches can be used to reduce the adjustment (a.k.a., the "shock") at the beginning of the forecast (see Phillips et al., 2004), but experience has shown that the climate model errors tend to be large enough that even fairly crude methods produce useful information in the sense that the climate model quickly drifts away from the analysis toward a preferred state. These methods are nearly identical to those used for S2S predictions with climate models (e.g., Kirtman et al., 2014). Reforecasts can be directly compared to observations, and CAPT projects have often made use of ARM(10) observations (e.g., Williamson and Olson, 2007, Xie et al., 2008).

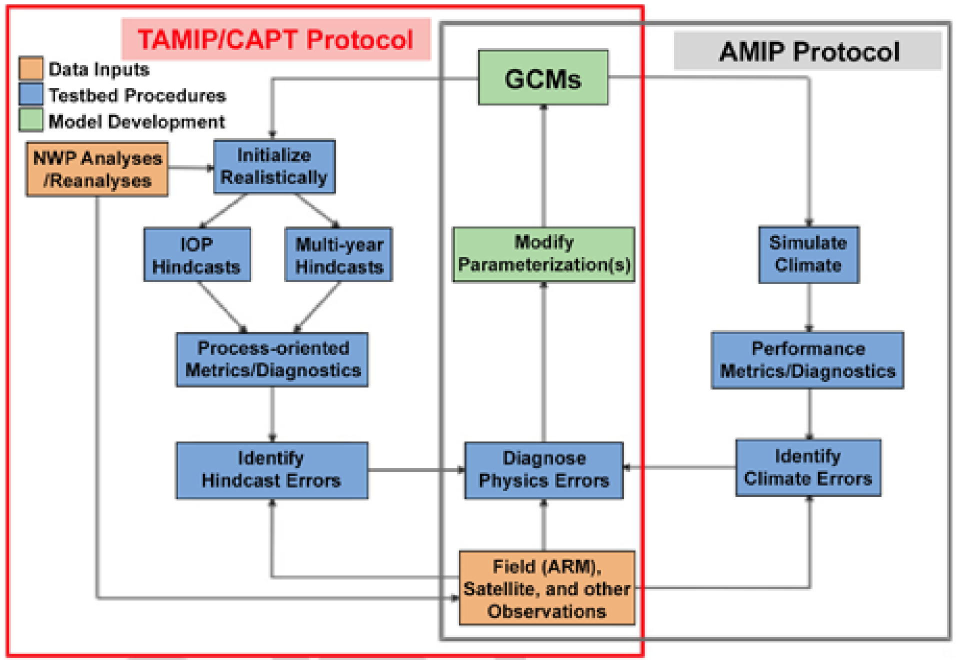

Figure 4. Flow diagram of the Transpose-AMIP/CAPT and AMIP protocols for model development (from Ma et al., 2015). Hindcast simulations, as performed in T-AMIP/CAPT, are a useful complement to the traditional way ("AMIP Protocol") that new atmospheric model parameterizations are tested and developed. The hindcast simulations offer increased ability to use satellite and field campaign data such as produced in Intensive Observing Periods by DOE's Atmospheric Radiation Measurement (ARM) Climate Research Facility.

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(10) **http://www.arm.gov/**

The success of the CAPT approach is evident by its widespread adoption in the climate modeling community. By focusing on common time periods and coordinating experimental design, reforecasts have become a model comparison tool. In Transpose-AMIP II (Williams et al., 2013), for example, several CMIP climate modeling groups produced reforecasts for intervals during the Year of Tropical Convection (Waliser et al., 2012; Williams et al., 2013). Comparing the reforecasts, various climate model biases can be examined to determine if there are shared deficiencies. A number of model biases that form with a lead of about 2 days are quite similar to long-term climate biases (Ma et al., 2014). The Transpose-AMIP II effort has been succeeded by a coordinated model comparison focused on the Madden-Julian Oscillation (MJO) using the same reforecast approach (Klingaman et al., 2015). These coordinated efforts, as well as most individual model evaluation efforts, have focused on atmosphere-land configurations, without coupling to the ocean or sea-ice components.

A few examples of using coupled reforecasts to understand bias in climate models have recently been documented. Vannière et al. (2013, 2014) explored sources of climate biases using coupled hindcast experiments. The timescales of those experiments are longer than in CAPT-like studies, and approach seasonal timescales at which the importance of ocean processes become apparent. One of the challenges in such an approach is to initialize the component models appropriately (see e.g., Keenlyside, 2005, and next section of this report). Vannière et al. (2014) highlighted the role of coupled hindcast simulations in a systematic approach to evaluating model biases that makes use of standalone component models, nudging methodologies, and reforecasts.

The use of hindcast techniques for evaluating high-resolution climate models also is just emerging. The advantage of initialized approaches is that short runs are expected to provide information about sources of errors in physical processes, just as with lower-resolution models. This becomes all the more crucial at high resolution when resources become a limiting factor. An intermediate step may be to evaluate processes at high resolution, but only for regional sub-domains using, for example, variable-resolution grids. This can effect a dramatic reduction in computational cost that potentially allows robust evaluations of the model within the high-resolution regions. An example of such an approach includes a recent study of tropical cyclone forecasts with CAM5 (Zarzycki, 2015). High-resolution coupled simulations also are being investigated, but this has so far been mostly undertaken with regional rather than global models (e.g., Patricola et al., 2012).

Current Initialization Capabilities

Numerical weather and climate forecasts are made by integrating the governing equations forward from a set of initial conditions based on the observed state of the climate system at the initial time. This requires a method for transforming the observations at a given time into a given model's initial conditions, a process called initialization. Data assimilation is the initialization method primarily used at operational centers. However, there are multiple levels at which the climate modeler may use DA. The most fundamental application of DA to the climate model initialization problem is the use of direct observational data and a sophisticated state-of-the-art DA methodology. Somewhat less complex is the use of retrievals and individual objective analysis products as synthetic observations with a more general-purpose DA scheme (e.g., as applied by the Data Assimilation Research Testbed(11); Anderson et al., 2009). Another common approach is to use the DA reanalysis product from an operational center (e.g., the NCEP/NCAR reanalysis

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(11) **http://www.image.ucar.edu/DAReS/DART/**

– Kalnay et al., 1996; NCEP/DOE reanalysis – Kanamitsu et al., 2002; NCEP CFS reanalysis – Saha et al., 2010; ECMWF ERA-40 – Simmons and Gibson, 2000; or ERA-Int – Dee et al., 2011) applied via interpolation and direct insertion into climate models. Such an "insertion" approach has been used with reasonable success in initializing seasonal predictions and evaluating how this differs across time scales of interest (Kirtman and Min, 2009). It is a research question to determine what degree of skill is lost in forecasts initialized via this insertion method versus the use of explicit DA, due to initialization shocks caused by a change in underlying forecast model. The NASA Global Modeling and Assimilation Office (GMAO) uses careful replacement of the DA-generated analysis from other centers for testing and validation purposes in comparison to their in-house analysis. This procedure is described by Takacs et al. (2015).(12)

Coupled DA poses a unique challenge that is currently an active topic of research in the international DA community. Historically, modeling and DA system design have evolved independently for different subcomponents of the climate system (e.g., assimilation in the aerosol module of the NASA reanalysis; see Figure 5). At many operational centers worldwide, this practice has produced separate DA systems for the atmosphere, ocean, land, and other climate components that are difficult to unify. Coupled DA systems are thus broadly classified into two types: 1) weakly coupled and 2) strongly coupled. Weakly coupled DA systems assimilate each sub-domain independently and couple the sub-domains during the model forecast stage. Strongly coupled DA also includes coupling at the analysis time by accounting for error cross-covariances that exist between the different sub-domains (Sluka et al., 2016). This approach has numerous advantages; for example, it allows atmospheric observations to influence the ocean analysis, and vice versa. While weakly coupled DA can only impact "the interface" of the sub-domains on the timescale of the forecasts, strongly coupled DA can include influences from the full vertical extent of observations. For example, a stratospheric temperature observation could potentially impact ocean state at 2000 m depth if such a scheme was appropriately designed (Brasington et al., 2015). Such an impact is possible because the background error covariance information may contain information on much longer timescales than the active forecast length.

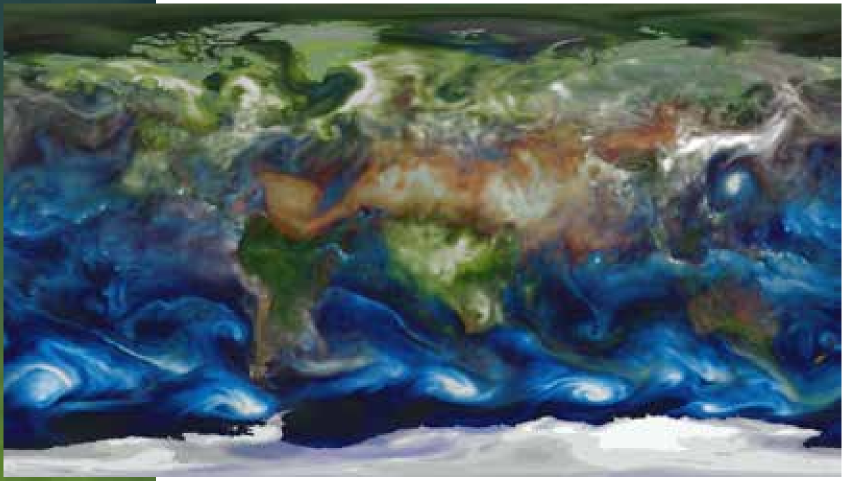

Figure 5. Aerosol data assimilation in the NASA MERRA-2 system. Aerosol Analysis 10 July 2013 1200UTC. Image courtesy of S. Akella, *NASA/GMAO*.

Computational and Infrastructure Environment in the Next 5 Years and the Limits on High-Resolution Initialized Simulations

Heterogeneous HPC architectures that promise peak performance approaching the exascale (1018 floating-point operations per second) are expected to dominate the market over the next 5 years, with the majority of performance gains achieved through fine-grained architectures that use, for example, graphical processing units or many-core processors. Arguably, programming

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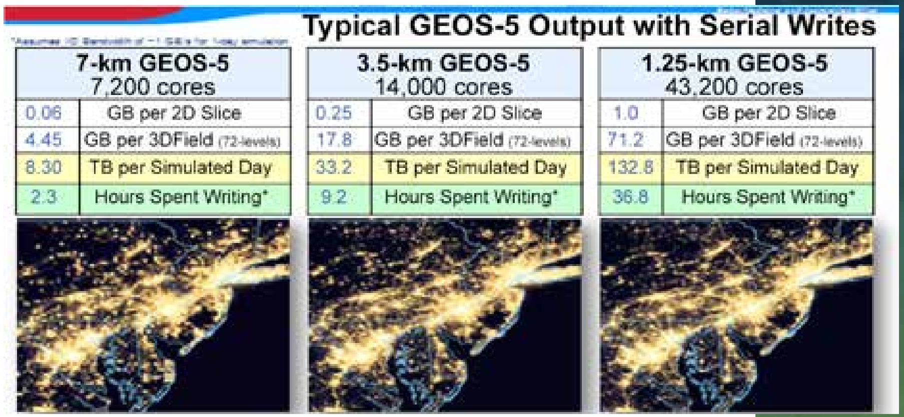
(12) **http://gmao.gsfc.nasa.gov/pubs/docs/Takacs737.pdf, sec. 3b**

models are not expected to change much in that time frame, so current codes need to be adapted to leverage the potential performance. Exploring performance on these systems can effectively be done through the use of kernels and "mini-apps," an example of which is tracer transport in climate models. A move to much larger, but also much slower, memory per node is ongoing, along with the need for orders-of-magnitude-more parallelism to efficiently use such configurations. As the number of processors in a single system grows, power consumption also increases, such that scaling up conventional systems could require 20 to 30 MW of power. This introduces the consideration of much-lower-energy processors and deeper memory hierarchies to reduce data movement.

Models with increasing resolution, in addition to demanding much more computation, will produce prodigious amounts of data. There is a concern that the input/output capabilities of exascale systems will not keep up with computational capabilities (see Figure 6). Suggestions for dealing with large data amounts include in-line analysis at full resolution, storing sub-sampled model output, or storing only analyzed fields (versus state variables). This raises the issue of how the broader community—beyond those building and running large models—can use exascale systems and the data they produce. This is particularly pertinent for scientific questions that can only be answered by new simulations and data or exploring the data at full resolution. Another challenge is that peer-reviewed journals are beginning to require the publication of data used in a paper, which may impact strategies for model diagnostics and data storage.



Typical GEOS-5 Output with Serial Writes

7-km GEOS-5 7,200 cores		3.5-km GEOS-5 14,000 cores		1.25-km GEOS-5 43,200 cores	
0.06	GB per 2D Slice	0.25	GB per 2D Slice	1.0	GB per 2D Slice
4.45	GB per 3DField (72-levels)	17.8	GB per 3DField (72-levels)	71.2	GB per 3DField (72-levels)
8.30	TB per Simulated Day	33.2	TB per Simulated Day	132.8	TB per Simulated Day
2.3	Hours Spent Writing*	9.2	Hours Spent Writing*	36.8	Hours Spent Writing*

Figure 6. An example of model data output at increasing higher horizontal resolutions based on the NASA GEOS-5 model. Image courtesy of Bill Putman, NASA/GMAO.

An important element of the strategy for most effectively using future HPC systems is collaboration. One avenue for U.S. collaboration is the National Strategic Computing Initiative (NSCI), which is based on an Executive Order(13) that seeks to enhance the nation's scientific, technological, and economic leadership position in HPC research, development, and deployment through a coordinated federal strategy. Within this strategy, there are lead agencies (DOE, the U.S. Department of Defense, and the National Science Foundation) pushing the frontiers of HPC, foundational research and development agencies (National Institutes of Standards and Technology and the Intelligence Advanced Research Projects Activity) focusing on future computing technologies and paradigms, and deployment agencies (NOAA, NASA, National Institutes of Health, U.S. Department of Homeland Security, and the Federal Bureau of Investigation) using HPC to support their missions. As an NSCI deployment agency, NOAA may potentially have greater opportunity to participate in interagency collaboration and the co-design process to integrate its mission requirements, and to influence the early stages of design of new HPC systems, software, applications, and connections to the academic community. Code-sharing would especially enhance collaboration between the NSCI participants, yet there is no official national repository of climate codes.(14)

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(13) **https://www.whitehouse.gov/the-press-office/2015/07/29/executive-order-creating-national-strategic-computing-initiative**

(14) There is a nascent effort to provide a code repository for Common Infrastructure for Earth Modeling - **http://www.cesm.ucar.edu/events/ws.2015/presentations/sewg/vertenstein.pdf**.

Several strategic and technical questions can be posed to guide considerations of the impact of HPC on the capability for initialized climate-prediction systems with increasingly higher resolutions. These questions are listed below:

- **Strategic questions**: How do the needs of those who use model output translate into choices of models, experiments, and data storage? How will the strong/weak scalability of dynamics, physics, and assimilation on anticipated architectures drive choices of resolution? As model resolution drives toward the native scales of observations, do we understand the impact on initialization and prediction? At what point does data density impact resolution targets? As resolution increases, how will we choose to process, analyze, and store the escalating amount of data produced by forecasts and reforecasts? How do we balance increased resolution with ensemble size and model complexity? What are the time scales for which there is the most pressing need to improve scientific understanding of resolution-dependent improvements in light of current HPC capabilities? Are there scientific and/or computational opportunities for collaboration between climate modeling and S2S prediction efforts?
- **Technical questions**: How do we develop flexible codes suitable for both operational use on future HPC systems and nimble hypothesis-driven experimentation? Will assimilation systems deployed on multiple architectures for exascale dominate predictions in terms of computational cost? How will we handle the future of targeted observations such as gliders, drones, and autonomously deployable observational networks? What are the principal scientific and technical challenges in developing observing system simulation experiments for the fully coupled system? On a time scale of 5 years (expecting to double resolution from technical advances), what do we gain by 50 to >25 km or 25 to >12.5 km on S2S predictions? How do these gains translate into the ability to predict particularly critical extremes? How do we translate information from reforecast error (in seasonal prediction) to short-range weather prediction?

Answers to these questions will determine the feasibility, and inform the design, of an experimental framework to systematically and optimally address major scientific questions about the use of high resolution in initialized coupled-climate models.

Workshop Themes

The discussion at the workshop was organized along the lines of three themes probing 1) 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 predictions. The workshop addressed these themes through a series of questions that were posed to the invited speakers. The consensus responses to those questions based on the presentations and discussions, as well as the scientific gaps that must be filled, are summarized for each theme below.

1

Seamless Sub-seasonal-to-Seasonal Predictions: The Nexus of Resolution, Process, and Prediction

As described above, there is an expectation that predictions for S2S climate, specifically including forecast probabilities for extreme events, can be substantially improved through the development of models with higher acuity and process fidelity. Also, prediction error is known to be related to bias, so models with large bias tend to have larger prediction errors. Therefore, improved models that reduce bias would be expected to result in fewer prediction errors. Because many well-known model biases have proven stubbornly resistant to attempts to reduce them, and in particular have been shown to be insensitive to model resolution at least in the context of tests done so far, the working hypothesis is that those biases can be ascribed to improper or inexact representation of relevant physical processes, such as convection or mixing (e.g., Prein et al., 2015).

Questions

1) How does prediction skill and fidelity change when resolution is increased in combination for the various components of the prediction system?

The general consensus is that solely increasing the resolution(15) of coupled-climate system models has a positive impact on prediction skill (e.g., Kinter et al., 2013; Zhu et al., 2015). Experiments with separately increasing the resolution in different component models (e.g., the atmospheric and oceanic components) have shown that prediction skill improves (Jia et al., 2015, Murakami et al., 2015). The positive impact is measurable both in terms of broad statistics of model skill as well as climate features and events. There are many examples where mesoscale features improve with resolution in current global atmospheric models (e.g., orographic precipitation, tropical cyclones, and mesoscale complexes in mid-latitudes, and tropical Atlantic thermocline slope) (Figure 7).

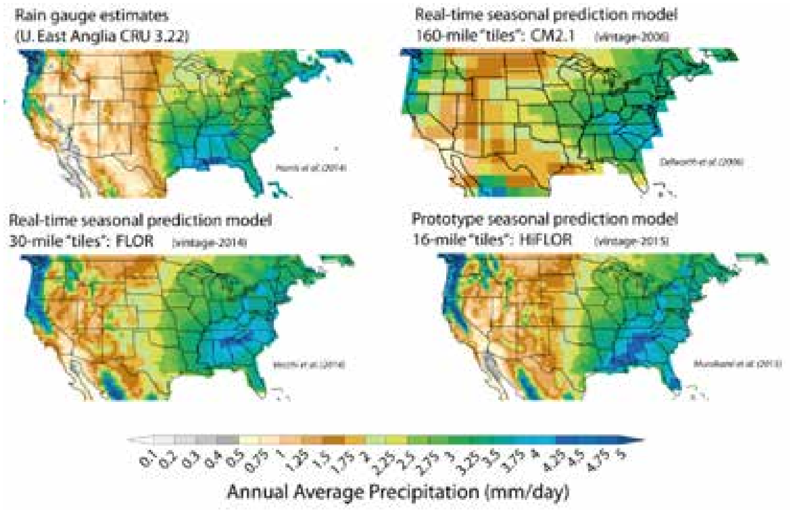

Figure 7. Observed (upper left) and simulated climatological annual average precipitation (mm/day) in the United States. Three different resolutions of the Geophysical Fluid Dynamics Laboratory coupled model are shown: 256-km grid spacing (CM2.1, upper right); 50-km grid spacing (FLOR, lower right); and 25-km grid spacing (HiFLOR, lower left). Image courtesy of G. Vecchi, GFDL/NOAA.

This general consensus must be qualified in two important ways. First, spatial resolution alone is not a panacea; that is, it does not guarantee that all undesirable characteristics of prediction models are ameliorated solely by increasing spatial resolution. Some complex phenomena like the MJO and El Niño - Southern Oscillation (ENSO) are relatively insensitive to model resolution in the tests done so far. However, they are sensitive to the representation of cloud processes (e.g., Neale et al., 2008, DeMott et al., 2014). The ENSO teleconnections to remote regions are significantly better with increased atmospheric spatial resolution in GFDL's FLOR model, hence improving the seasonal prediction skill of ENSO-teleconnected surface air temperature and precipitation patterns over land (Jia et al., 2015).

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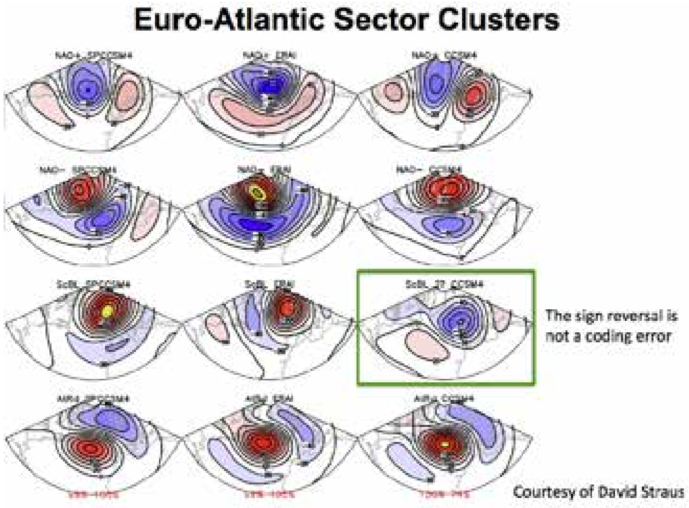
(15) That is, increasing spatial resolution without retuning or using improved physical schemes.

Second, the skill in predicting processes dominated by scale-sensitive parameterizations can diminish as resolution is increased; for example, clouds deteriorate, and the common coupled-model bias of a double Inter-Tropical Convergence Zone worsens. There is evidence that biases set in faster in a higher resolution model (see Section 3.2 for more discussion of these issues). This argues in favor of a broader approach in which spatial resolution and process representation are addressed together, for example, through the development and implementation of scale-aware parameterizations, stochastic parameterizations (e.g., NavGEM - Sušelj et al., 2014; ECMWF - Berner et al., 2009), and super-parameterization of under-resolved or unresolved processes. This is an area of active research with several examples of models already including such types of parameterizations (e.g., SP-CCSM – Stan et al., 2010) and hence enabling experimentation (see Figure 8).



The sign reversal is not a coding error

Courtesy of David Straus

Figure 8. Observed (center column) and simulated sub-seasonal 500-hPa height anomalies as represented using a cluster analysis. Simulations using a conventional cloud parameterization in CCSM-4 (left column) and using a super-parameterization (right column) are shown. Four clusters having the most variance in the Euro-Atlantic sector: NAO+, NAO-, ScBL, and AtRd patterns are shown. Image courtesy D. Straus via C. Stan, COLA/GMU.

2) How can we diagnose and address model behaviors that lead to the above sensitivity?

Taking advantage of the seamless prediction paradigm, short-range prediction (1 to 2 months) with DA can be used to understand the evolution of coupled errors and the deterioration of skill, even in predicting coherent longer-time-scale phenomena like the MJO and ENSO. High-frequency phenomena can be analyzed in the same fashion. Research on the nature and structure of analysis increments may elucidate and quantify the resolution dependence of skill. Because this methodology requires an understanding of the DA process and its impact on prediction skill, there is a need for better interaction and collaboration between model development and DA research.

3) Are there specific or related processes in the coupled system that drive both short-term prediction error and climate simulation bias?

Several processes that contribute to error were identified.

- The vertical structure of moist processes in the atmospheric boundary layer and deep convection is a primary determinant of both prediction error and long-term bias. The challenge lies in the fact that the climatic (mean) state is a primary determinant of this structure, so there is a tight coupling between the two. One common problem is lack of system maintenance.
- Interaction between the coupled system components can drive model error in several ways. For example, the way in which the ocean and atmosphere interact is partially controlled by the location and magnitude of sharp temperature gradients, up to and including the basic question of which component controls variability in the other. Similarly, a proper

understanding of the coupled land-atmosphere system, and especially how anomalous land states are likely to perturb weather and climate, will provide a means to improve forecasts on S2S time scales.(16) For another example, small-scale features in sea ice, which may be highly anisotropic, can be related to large-scale errors through highly nonlinear behavior.

- Several models have a tendency to lose variance over the period of a forecast, which may be a result of overly diffusive representation of unresolved processes.

4) What resolutions are necessary to adequately resolve these processes?

There are diverse opinions on this question in the community. For many coupled and uncoupled models, there appears to be a threshold in atmospheric model resolution at ~25 to 50 km grid spacing, such that models whose grids are coarser have large errors, while the large-scale errors in models with at least this resolution are substantially reduced. At the threshold resolution, these models begin to provide a realistic environment for the propagation of synoptic-scale systems and even tropical cyclones. On the other hand, there is an expectation of reaching another threshold of prediction skill when clouds systems and ocean eddies are explicitly resolved, which requires grid spacing of <4 km (e.g., see Figure 9). Several studies with global cloud-resolving models have been conducted in Japan (e.g., Miyakawa et al., 2014). Between these two ranges of spatial resolution, there is a "flat zone" in which there is very little improvement in skill as resolution is increased. Similar threshold behavior is found in the ocean component of global models, although there is disagreement about whether or not the effects of ocean eddies can be adequately represented in models that do not explicitly resolve such eddies. In both atmospheric and oceanic components, there are "gray zones;" that is, ranges of spatial resolution in which the parameterizations of sub-grid-scale physical processes are inappropriate (see Section 3.2).

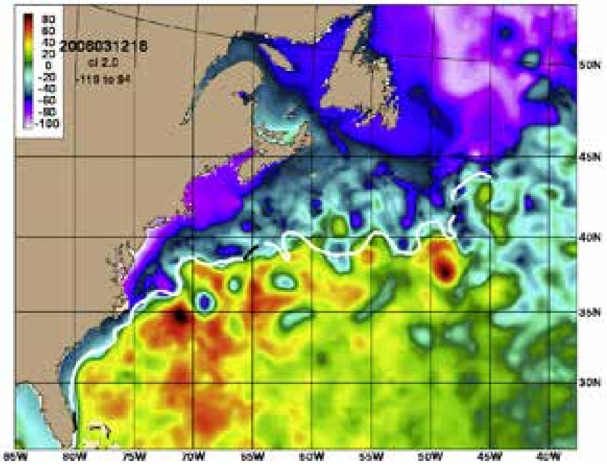


Figure 9. Sea surface height on March 10, 2008, as represented in the HyCOM ocean model with 1/12-degree grid spacing and NCODA data assimilation. Image courtesy of P. Hogan, NRL/Navy.

Gaps

The workshop discussion revealed several gaps in our understanding of the sensitivity of prediction skill to spatial resolution. These gaps are listed below:

- What is the origin of threshold behavior in various component models of the coupled system? For example, why does this grid-spacing threshold behavior occur in common among several independent atmospheric component models? What is the threshold for other coupled system components? Does resolving oceanic temperature fronts enhance sub-seasonal prediction skill? Is there a systematic way to address this question? During the discussion, the following two hypotheses were proposed to address these questions:
  –**Hypothesis**: Grid spacing defines an effective resolution; that is, features and processes that have a natural scale, which is greater than 4 to 7 times the grid spacing, are considered

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(16) **http://www.iges.org/lsm/GMU_KIAPS_White_Paper.pdf**

  to be adequately resolved (e.g., Skamarock, 2004). Behavior changes when this effective resolution becomes less than the Rossby radius.
  –**Hypothesis**: Sub-grid-scale parameterizations are developed and defined with respect to a given grid spacing, so the interaction between resolved dynamics and parameterized physical processes changes as the grid spacing changes. One experiment that could test this hypothesis would be to turn off the parameterization of convection and produce forecasts at various spatial resolutions.

- A number of "gray zones" were identified in the various components of the coupled-climate system that represent ranges of scale at which there are transitions between one process and another controlling variability. For example, there is a transition at about 4 to 10 km between control by large-scale atmospheric circulation and cloud systems. Similarly, there is a transition at about 1 km where resolving individual clouds and variations in the planetary boundary layer becomes important. In the ocean, the explicit representation of eddies at about 4 to 10 km changes the dynamic behavior of the ocean as well as its interaction with the atmosphere. Similarly, ice floes exhibit discrete behavior at a scale of about 10 km. There is currently no consensus on how to deal with these gray zones in single-component, let alone coupled system, models.

- Much less work has been done with respect to vertical resolution in either the atmosphere or the ocean. In general, models used for climate-change research and projections tend to have relatively coarse vertical resolution (~30 levels in either the atmosphere or the ocean component), while S2S prediction models tend to have relatively fine vertical resolution, at least in the atmospheric component (~60 to 90 or more levels). Some testing of vertical resolution impact on seasonal prediction skill was done as part of the Climate-System Historical Forecast Project(17) (Kirtman and Pirani, 2009; Butler et al., 2016).

- Beyond the diagnosis of basic biases in means, it is necessary to determine how well models predict the basic modes of variability (e.g., the intensity and position of features of the Northern Annular Mode, Southern Annular Mode, North Atlantic Oscillation, Pacific-North American pattern, etc.). The predictability of these modes has received some attention (e.g., Athanasiadis et al., 2014), but there is a gap in our understanding of why predictions of such modes are good or bad and, in particular, whether or not prediction of these modes is sensitive to resolution.

- There are several aspects of unresolved physical and biological processes that are essentially missing from current generation models. Examples include:
  –Anisotropy in sea ice leads: Essentially linear open water features between sea ice floes.
  –Variances: Sub-grid variance in land surface characteristics and properties that do not necessarily translate into sub-grid variance in fluxes.
  –Various biological processes: The resolution necessary to represent biological processes may be very different from the resolution necessary to resolve physical processes.

- There are several hurdles to translating S2S predictability into predictions at this very challenging time range:
  –A valuable data set is the international S2S archive (I-S2S(18)). Even though the models contributing forecasts to this archive are all in roughly the same range of spatial

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(17) **http://www.wcrp-climate.org/wgsip/chfp/**
(18) **https://software.ecmwf.int/wiki/display/S2S/Project**

resolution settings, experimental versions of these models with higher (or lower) resolution can be extensively compared with th -S2S data. A more coordinated set of S2S prediction experiments is anticipated as part of a new NOAA Climate Program Office initiative beginning in Fiscal Year 2016.(19)

–The NOAA National Weather Service focuses on the S2S distribution of surface temperature and precipitation anomalies over the contiguous United States, which is a very difficult prediction problem. What are the sources of predictability for these climate variables in this region at this lead time? Are these confined to certain times of the year? For example, antecedent soil moisture anomalies in the spring and summer may be a source of predictability. Are the estimates of predictability of these quantities sensitive to spatial resolution?

–Are there persistent aspects of climate that models ought to be able to predict? Are such events attributable to predictable dynamics and physics or just a manifestation of red noise? How does increased spatial resolution alter prediction skill for persistent events? For example, is the diminution of variance with lead time that is found in many prediction systems responsible for the poor skill of predicting persistent events, and does increasing spatial resolution ameliorate this problem?

–Sub-seasonal predictions have a low signal-to-noise ratio, in comparison with short-range weather predictions and seasonal predictions, so such predictions must be probabilistic and ensemble predictions are required. The optimal choices for ensemble size, expressed as a tradeoff with spatial resolution, have not been determined.

2

Frameworks for Diagnosing Fast Physics in the Coupled System

Modeling groups interested in both long-term climate prediction and S2S prediction are moving toward higher-resolution models and making increasing use of coupled modeling systems. Because of their added complexity and computational cost, these high-resolution and/or coupled models are challenging to develop and validate. To make progress, efficient frameworks for testing the models must be established for investigating individual parameterizations and interactions of system components, and for testing scientific hypotheses. Such frameworks fit nicely into a modeling hierarchy paradigm (Held, 2005; Vannière et al., 2014); Figure 10 outlines the hierarchical approach proposed by Vannière et al. (2014).

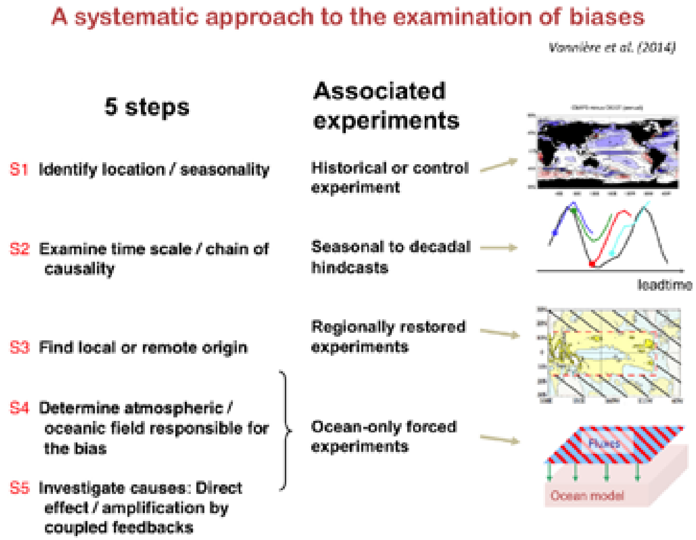

Figure 10. A systematic experimental approach to the examination of coupled-model biases proposed by Vannière et al., (2014). Image courtesy of E. Guilyardi IPSL/University of Reading.

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(19) Climate Program Office FY16 Federal Funding Opportunity as part of the Modeling, Analysis, Predictions and Projections (MAPP) Program competition also involving the NGGPS, ONR and NASA/MAP programs.

Efforts to further develop climate models have largely focused on evaluating the representation of subgrid-scale processes. Although single-column models offer some insight and have a well-established role in the hierarchy of models, it is often desirable to ascertain the performance of parameterizations under more realistic conditions, in particular by including the interaction with the large-scale circulation. A causality issue immediately arises: do errors emerge from a faulty parameterization or an incorrect or unrealistic large scale? Nudging and numerical-weather-prediction-inspired approaches have both proven useful for providing a constraint on the large-scale environment, and both provide efficient and flexible frameworks for evaluating model processes. In this section, we address several questions of relevance for these approaches and point out some gaps in capabilities and understanding that should be addressed with future research.

Questions

1) How does the fidelity of small-scale physical processes in the climate system change as resolution is increased?

High-resolution tests of climate models are showing promising signs of improvement as additional details are resolved, but troubling biases as traditional parameterizations fail to provide appropriate solutions (e.g., Bacmeister et al., 2014).

The role of mesoscale ocean eddies in climate simulations epitomizes the potential benefits of high-resolution configurations. As horizontal grid spacings reach ~10 km, ocean eddies become resolved and strongly impact the general circulation. Effects include regional features such as the Gulf Stream and Kuroshio separation and variability (Bishop and Bryan, 2013; Bishop et al.; 2015), but there are also downstream, remote effects that can impact, for example, decadal climate variability. It is expected that resolution will also impact heat flux characteristics for sea ice (see Figure 11).

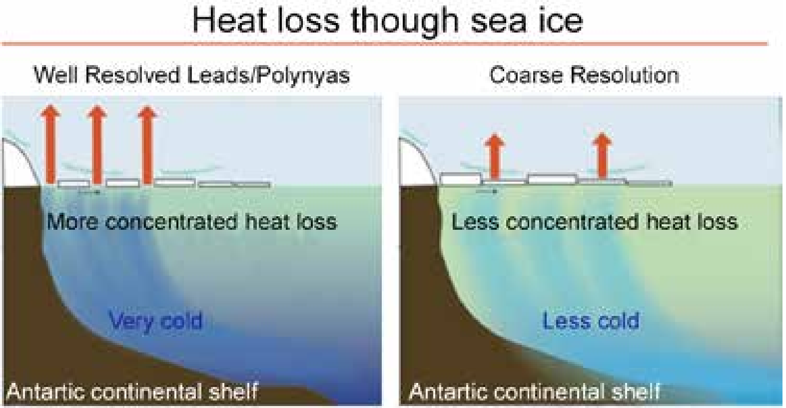

Figure 11. Better sea-ice resolution allows for more concentrated heat loss, increasing the drive of surface waters to densify, and forming more, and colder, AABW. Adapted from *Newsom et al., courtesy of C. Bitz, University of Washington*.

Resolution also has a strong impact on the simulation of the land surface. Singh et al. (2015) show, for example, that significant error reductions in important quantities like soil moisture are achieved with a grid spacing of 1 km, even when the resolution of the forcing data set is not as high. Aspects of this sensitivity to resolution may be alleviated with more sophisticated numerical representations of the landscape. For example, Tesfa et al. (2014) found a reduced sensitivity to resolution when the land-surface model is organized by sub-basin boundaries instead of rectilinear grids.

2) For what phenomena would initialized coupled models (e.g., coupled CAPT) be of use for diagnosing fast physical processes of the climate system?

Although it is clear from the above discussion that these approaches have emphasized atmospheric processes, there is also interest in applying such approaches to coupled problems. In fact, as discussed in other parts of this report, initialized coupled modeling is becoming common in S2S prediction. Initialized simulations also are used for the “decadal prediction” experiments as part of CMIP5. As discussed below, the challenge is to use an appropriate initial condition in the oceanic and other component models for the problem at hand.

The CAPT framework and nudging approaches can be applied in both the coupled and high-resolution settings. Especially in terms of coupled-climate models, these approaches should be used as part of an hierarchical approach to diagnose, understand, and correct climate model errors. This hierarchical approach has been articulated by Vannière et al. (2014) in the context of persistent coupled-model biases. For coupled, high-resolution simulations, this approach can be used to understand the roles of different processes and their interactions. For example, sea-ice models have been developed to represent deformation with weak coupling to the other components, but as resolution increases and coupling with the other components happens more frequently, inertial oscillations will become resolved that potentially have high strain rates that lead to different sea-ice deformation. The role that such processes play for sea-ice simulation are unclear, but could have coupled impacts through effects on the boundary layer (regional) or by altering the large-scale circulation (remote/global).

3) *What can initialized simulations (either single-component or coupled) reveal about fast-coupled processes, such as rapid development of flux errors that lead to long-term bias and prediction error for the climate system?*

Fast-coupled processes can amplify (or introduce) errors in the large-scale circulation through scale interactions (i.e., energy cascades). Only models with explicit representation of turbulence and cloud processes, such as large-eddy simulation or cloud-resolving models, can disentangle the feedbacks between these errors; however, it is still not feasible to use these models for climate applications. Intermediate frameworks (e.g., super-parameterized models or mesoscale-resolving models) are stepping stones toward such solutions. For example, a convection-permitting model without mesoscale initialization will spontaneously generate mesoscale circulations because of interactions between the large-scale forcing and smaller-scale processes. As a result, errors in the large-scale circulation produce errors in the fast-coupling processes and errors in those fast processes can then continue to amplify the initial error. Comparisons between models with parameterized and explicit representation of fast-coupled processes can reveal errors in the representation of the large-scale dynamics.

4) *What level of initialization sophistication is useful or necessary for diagnosing fast physical processes in initialized climate model simulations (e.g., CAPT)?*

Bias should be defined relative to the best estimate of the actual state of the system. Ideally this means comparing a model state against a comprehensive set of observations, even though they are imperfect, but a high-quality analysis may be a better choice in some cases. For diagnosing fast-physical-process biases, as opposed to attempting seasonal forecasts, the highest-quality initialization likely will be the most useful. Many biases visible in seasonal and longer forecasts are evident in the first day when the forecast is started from "reality." If a bias is not visible quickly, then it is a small persistent one, which will be harder to attribute to any particular process formulation(s) of the model. Coupled-model forecasts bring new (biased) interactions into play, which will complicate the attribution. Vannière et al. (2014) have developed and used a framework for diagnosing the sources of coupled-model biases by systematically replacing prognostic forcing of the coupled model with real and/or constant forcing, to see which are necessary for generating the model bias of interest.

Coupled air-sea processes have important feedbacks that are not currently modeled in coarse-resolution coupled-climate systems. Greater modeling attention, observations, and DA formalism are needed to address this shortfall. Chelton et al. (2001) described some of the correlations between observed wind and sea surface temperature (SST) patterns. Later examination by Maloney and Chelton (2006) found that similar correlations in climate models were closer to observations when using higher-resolution SST and atmospheric models. Kirtman et al. (2012) showed improved mean precipitation over the Gulf Stream because of the higher ocean model resolution.

Gaps

As mentioned above, climate models are being run at higher resolutions to resolve mesoscale processes that are thought to be necessary for higher regional fidelity in climate simulations (including extreme and high-impact events). The parameterized physics of climate models do not necessarily converge as resolution increases, and in many cases convergence should not be expected because of the underlying assumptions of the parameterization. For example, many convection parameterizations assume that convection occupies a small fraction of the grid cell and the convective heating and moistening is achieved by an ensemble of convective updrafts; as grid spacing decreases, this assumption cannot hold and the parameterization produces erroneous solutions. Recent efforts have focused on developing smarter parameterizations (e.g., Grell and Freitas, 2014), but much work remains to systematically test such schemes. Similarly, the representation of the effects of ocean eddies by a diffusive parameterization may not be suitable for grid spacing that is relatively fine but still not sufficient to explicitly resolve the eddies.

Not only do current parameterizations (potentially) perform poorly at high resolution, but as smaller scales become resolved, some processes can be completely absent. In the atmosphere, for example, the hydrostatic assumption begins to break down at very high resolution, necessitating the use of non-hydrostatic dynamics to properly simulate intense vertical velocities (see discussion in Section 3.1). The non-hydrostatic effects, however, might not be as important (at some scales, at least) as other effects that are absent from climate-model physics; Bacmeister et al. (2012) offered an example of pressure perturbations caused by condensate loading. These effects are present in other components of climate models as well: the lateral flow of groundwater is neglected by most land-surface models, aspects of sea-ice physics are neglected, etc.

There are also fundamental questions about using initialized approaches to investigate coupled-model behaviors. There is no consensus regarding the level of sophistication needed for the initialization method, and it is likely to depend on application. As an example, it is well known that global ocean models tend to produce a thermocline that is more diffuse than observed thermoclines. It is a valid question whether a coupled-model forecast should be initialized as close as possible to the observed initial state or with a state that more closely resembles the model's climatology. The two approaches will exhibit different error-growth timescales, but it is not clear which would be the preferred approach without considering the scientific motivation for the experiment.

One advantage of initialized approaches is the ability to make better use of observations for evaluating model physics. As models reach higher resolution, it is not clear what observations are appropriate for model evaluation. While point observations can still be used, it is less clear whether satellite products or other large-scale observational products are reliable. For example, observations used for calibration and validation of land-surface models are typically at the point scale (e.g., in situ measurements such as meteorological stations or flux towers) or area averages that are usually much smaller (e.g., satellite pixel) or larger (e.g., river basin runoff from stream gauges) than a given model grid cell. A particular concern is with extreme events such as large rain rates over mountain ranges. In some contexts, if using observations for calibration and validation entail difficulties, an appeal could be made to use much higher-resolution process models (e.g., large-eddy simulation or cloud-resolving models), but those come with their own caveats.

3

Initialization at High Resolution and Uncertainty Sampling for Sub-seasonal-to-Seasonal Prediction

Generally, forecasts with higher resolution will require higher-quality initialization because the resolved dynamics have smaller features and shorter timescales. In any prolonged forecast, the information in the initial conditions eventually becomes overwhelmed by both the chaotic growth of small errors in the initial conditions and errors in the various external forcings acting on the system. Model errors are responsible for further degradation in the forecast, causing the forecast to drift away from the true system state and toward the model attractor. At that point, without an appropriate mapping from the model to the real world, our knowledge gained from the model becomes limited to statistical relationships of climate variability.

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. In examining spatial scales, Kirtman et al. (2012) found that a 0.1-degree ocean interacts with the atmosphere in dramatically different ways than a 1-degree ocean. The higher-resolution features such as mesoscale fronts, loop currents, and eddies persist for much longer than the atmosphere-only predictability limit. While such features persist, they can significantly impact rainfall patterns, the jet stream position, and latent and turbulent heat flux into the atmosphere. Observation system experiments have shown that the impact of a single ocean analysis increment can persist over the course of many months (e.g., Xue et al., 2015). Using a prototype coupled DA system, Laloyaux et al.(20) at the ECMWF showed an improved fit to the near-surface temperature observations in the wake of a tropical cyclone.

As such, it could be argued that the majority of resources dedicated to the initialization of coupled-climate models should be focused on the state of the ocean. The Japan Agency for Marine-Earth Science and Technology has adopted such an approach with their coupled system. However, it should be noted that, because of closely interrelated processes at the air-sea interface, the atmosphere must also be initialized in a consistent manner with the ocean. Otherwise the initialization runs the risk of unnecessarily injecting noise into the system from the start. Furthermore, there is considerable evidence that the initial conditions chosen for the land surface can profoundly influence the subsequent evolution of the climate system, at least up to S2S time scales and perhaps beyond (Koster et al., 2010; Guo and Dirmeyer, 2015; Dirmeyer and Halder, 2016). While much less is known about the effects of sea-ice initialization on S2S prediction, there are indications that the initial sea ice thickness is a major determinant of subsequent sea-ice state (Day et al., 2014; Blanchard-Wrigglesworth et al., 2015), and there is also evidence that the sea-ice state exerts considerable influence on the climate system as a whole (e.g., Holland et

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(20) **http://www.godae.org/~godae-data/OceanView/Events/DA-TT-workshop-May-2015/3.1-laloyaux.pdf**

al., 2006; Francis and Skific, 2015). Ultimately, an integrated approach to initializing the entire coupled-climate system as a whole will be needed.

Questions

1) What initialization techniques are best applied for prediction at the various spatial and temporal scales?

For forecasts longer than the persistence of the information in any of the initial conditions, a single forecast is almost meaningless. The only potentially useful information will come from an ensemble forecast, which provides an estimate of the range of states that can be expected. In addition, the estimate derived from an ensemble forecast will only be as good as the forecast model and whatever external forcing is applied, in the context of the variability in the climate record. At very long time scales (i.e., centuries), climate modelers may focus the majority of their effort on fixing model biases, including variability.

The highest-quality initialization likely will result from a state-of-the-art DA algorithm using a large set of high-quality observations and the same model that will be used for the forecast. The initialization should be consistent across all coupled-model components that comprise the fully coupled Earth system. This concept is called "strongly coupled" DA, and is an area of development in the DA community. Sequential techniques, such as the Ensemble Kalman Filter, are most effective with frequent updates, and are only limited by the model spin-up time after initialization. Variational approaches tend to require a more finely tuned update cycle from which the dominant signal can be appropriately extrapolated in the forecast.

The required quality of initialization may not be available yet. If it turns out that forecast aspects of interest rely on small-spatial-scale features of the ocean, research and development will be needed to establish these features in sufficiently high-resolution ocean model analyses. Resolution of 0.1 degree is needed for a model to generate and maintain mesoscale features, but 0.25-degree resolution (i.e., "eddy-permitting") may sufficiently represent eddies in an analysis generated by assimilation of high-spatial-resolution observations. Then, 0.1-degree ocean forecasts may be able to use such an analysis for initialization. There are sufficiently high-resolution observations, such as AVISO along-track sea-level anomalies (~7 km), but successfully assimilating them at 0.1 degree has not been demonstrated. There are also development efforts to parameterize eddies and other mesoscale features to make the 0.1-degree ocean resolution unnecessary in many applications (e.g., Murakami et al., 2015). Similar questions exist for the land initialization.

The next best initialization is likely to be a high-quality analysis generated with another model, possibly at higher resolution than the forecast model. A leading example is the ECMWF T639 (32 km) ensemble forecast system. Using these to initialize S2S forecasts requires almost no computational resources, and should be sufficient for the atmosphere.

Some researchers initialize from observational data sets using a variety of interpolations to the model grid. This relies on a thorough spatial coverage of the important parts of the model domain because there is no model to fill in gaps, as there is in DA.

Data-assimilation efforts for other component models that may be coupled are in various stages of development, so there are many questions about generating the highest-quality initializations for them. Some, such as land, particularly below the surface, may suffer from insufficient observations for the foreseeable future. In these cases, initialization from an external set of states may be the best choice. Slowly evolving components, which lack extensive observation sets, can be spun up to a realistic state by a long atmospheric assimilation and/or nudging toward observations, assuming that the component is capable of being pushed into a realistic state (e.g., Rodell et al., 2004).

Because initializing from existing analyses is virtually free, it makes no sense to consider lower-quality initializations, such as a “cold start” from a climatological average, or even a uniform state. We assume such initializations have been used to commence the reanalysis products.

2) *What is the ideal size of the ensemble needed for this effort, both for prediction and for understanding coupled processes and biases?*

The ensemble size is of interest both for estimating uncertainty in seasonal and longer forecasts and for estimating error covariance in the DA procedure. For the latter, a combination of localization and hybrid DA techniques has provided some robustness when using small (e.g., O(10)) ensembles (e.g., Hamill and Snyder, 2000; Hunt et al., 2007; Penny, 2014). Experiments with large ensembles on an intermediate atmospheric general circulation model indicate that increasing the ensemble size from O(100) to O(10,000) provides meaningful error correlations at continental scales (Miyoshi et al., 2014). Thus it is anticipated that DA will make efficient use of as many ensemble members as the forecasters find appropriate for their needs.

This question can be reframed to consider estimating forecast uncertainty in terms of the signal-to-noise ratio. Smaller ensembles can be used to represent processes with a large signal, but they will exhibit more noise than a larger ensemble. If only the mean state is to be predicted, a smaller ensemble is needed than if the variance/spread or, even more so, the extremes must be predicted. Understandably, researchers try to choose the minimum ensemble size that will represent the variability of the process, and they likely underestimate it in many cases.

Excellent guidance for the question of ensemble size can be found in Mullen and Buizza (2002), who used precipitation in the eastern United States to illustrate the gains in forecasting skill and in a simple economic value from the two factors. They explored ensemble sizes from 1 up to 102 and resolutions from T159 to T319. The paper treats deterministic time scales, but the trends in the importance of the factors are clear: longer forecasts derive more benefit from increased ensemble size than from increased resolution, especially for infrequent (often high-impact) events. The amount of benefit depends strongly on the forecast aspect of interest. They also recommend exploring the use of multi-model ensembles to overcome the widespread insufficiency of variability in atmospheric models. In this atmosphere-only modeling scenario, they found little evidence that ensemble sizes larger than 100 add meaningfully to the distribution of states. This neglects the impacts of coupling to a high-resolution ocean model, discussed above, which brings up another important factor: improving models.

We may be able to use experiments with lower resolution and varying ensemble size to guide the choice of ensemble size in high-resolution studies. While high-resolution studies will often resolve processes that do not exist in the lower-resolution models, the low-resolution models may contain processes with similar signal-to-noise ratios. These may be used as proxies to study the effects of ensemble size. In that sense, it is critical that new DA techniques be devised to appropriately use the information in mixed-resolution ensembles for initialization and forecasting.

3) What resolution is feasible given the state-of-art HPC systems available to the U.S. community?

An increasing number of HPC facilities in the United States have sufficient processors to handle ensemble forecasts and/or DA using 0.1-degree ocean and 0.25-degree atmosphere. Currently, however, there are serious impediments to using those processors efficiently.

The data volume of a moderately sized ensemble of coupled-model states is hundreds of gigabytes (Gbytes), which are read and distributed among the processors with an effective speed of <10 Gbytes/second regardless of the number of processors requested. So the thousands of processors must wait O(100 s) for the states to be loaded before they can start the forecast. This issue cannot be avoided by using variational DA; the sequence of states around which the tangent linear model and adjoint are linearized must be read in because of the large state size. Only ECMWF has successfully upscaled a pure four-dimensional variational DA system to "high" resolution.

Each state vector is so large that it must be distributed across multiple nodes, rather than residing in shared memory, which has much faster access than internode communication. This can be mitigated somewhat by one-sided communication (e.g., Remote Direct Access Memory) and other techniques, but implementing these techniques in existing models and DA code requires software development resources.

Unless effective failure recovery software is developed and employed, requiring jobs to run on thousands of processors (or tens of thousands of processors) on general-purpose/research computers increases job failure rates due to machine problems to sometimes unusable levels. The queuing systems on the largest machines often favor jobs that have different usage patterns than ensemble forecasts and DA. Such jobs may be stranded in a queue for extended periods (e.g., days).

4) How will increasingly high-resolution data be stored and shared for community research?

Our ability to generate data that might be useful is outrunning the capacity to support the traditional workflow, which involves moving data into storage, storing it for long periods, and retrieving it when needed. It seems likely that centers that routinely generate state-of-the-art (re)analyses will continue to archive those for their own purposes. These will continue to be useful for initialization of other models, which does not require transfer of an unreasonable amount of data to research-focused computers, especially if it is reduced precision and/or compressed. On research-focused computers, new strategies will likely become necessary, such as 1) more re-computing is done than in the past, using periodic full restart sets, where the period is much longer than the typical desired data frequency; 2) carefully considering what needs to be archived and at what resolution, frequency, and precision; and 3) doing more data analysis during the model runs so that just the desired results are archived, rather than impossibly large intermediate data sets. This would require adjustments such as automatic archiving of the experimental setup and model configuration would become more important to ensure functional reproducibility of results. Some of these strategies can only be successful if the bottlenecks identified here have been solved.

The scientific community would benefit from database archives accessible at varying levels of complexity. Such databases should have procedures for approving data to be archived. High-level access should be made available to a larger community, while access to full restart data needed to initialize models can be set up on an institutional basis. A similar approach is already used at NCAR, but greater coordination and uniformity would be advantageous across the whole U.S. climate community.

Gaps

The DA community faces the challenge that model resolutions may increase much faster in the future than the available observational resolutions. Increased observations will be necessary for the ocean, sea ice, and land, all known to have longer time scales of evolution than the atmosphere. In the interim, new DA techniques that best use sparse data to initialize models and correct model biases will be of great value.

Global ocean models used for climate, for which the governing equations are fluid dynamics, will transition through eddy-permitting resolutions to eddy-resolving. As the benefits of tracking evolving, propagating mesoscale features become clear, greater resources may be needed for observing and initializing the upper ocean. Improved modeling of the air-sea interface is needed. Mesoscale and smaller instabilities within the interior ocean that lead to climate variability may become more predictable with proper initialization. Thus, it will become critical that the ocean be initialized in ways that are more similar to today's numerical weather prediction approaches that already resolve the mesoscale atmosphere.

4

Next Steps: Frameworks and Experimentation for High-Resolution Climate Modeling and Prediction

Parallels in the S2S Prediction and Climate Modeling Communities

A primary goal of this workshop was to bring together two related, but largely separate, research communities to share knowledge and to identify whether common experimental frameworks might be developed that could benefit efforts in both communities to move toward high-resolution coupled models. The two communities—the S2S prediction community(21) and the climate modeling and projection community—previously have had different research motivations. The S2S community conducts both basic and applied research on short-range climate predictability that can directly benefit operational forecast capabilities, and the climate modeling community focuses on primarily basic research concerning climate variability and long-term climate change.

However, despite the somewhat different research foci, presentations and discussions within this workshop highlighted several key parallels between these two communities. Both communities share a hierarchy of experimental frameworks, albeit with different nomenclature and goals. Both communities use comprehensive physical climate system or earth system models to simulate, predict, and project future climate. Both communities use DA: the S2S community uses a variety of DA techniques for initializing real-time forecasts and reforecasts, and for producing reanalyses, while the climate modeling community has started to adopt DA techniques for basic research and for short-term reforecasts to diagnose model behavior. In addition, both communities use an intermediate "insertion" method in which a DA reanalysis produced by an operational center

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(21) It should be noted that the climate modeling community and the S2S prediction community are not distinct, as intra-seasonal-to-seasonal (i.e., S2S) phenomena are coupled phenomena that have been studied for decades by the climate community. In context of this report, the term "climate community" is used to identify parts of the community interested in long-term climate.

is used to initialize the state of the climate system.(22) This has been reasonably effective for the climate modeling community for seasonal and longer predictions even though there may be deficiencies with this approach; for example, the initial state is typically determined using a model that is different from the forecast model.

Both S2S prediction and climate modeling communities produce reforecasts. The S2S community has established reforecasts as a viable but computationally expensive method for calibrating forecasts and for exploring issues related to predictability and predictive skill. The climate modeling community has established reforecasts as a diagnostic for identifying issues with fast processes (particularly cloud-related parameterizations) that lead to long-term model errors and biases. Reforecasts have been adopted in a variety of settings, including the Transpose-AMIP experiment and the CAPT project.

It is recognized that large biases in key physical quantities, such as temperature and precipitation, are major barriers to research and operational success in both communities. For the S2S community, biases can directly influence estimates of predictability and predictive skill, even if a posteriori bias corrections are applied to forecasts. For example, a seasonal prediction model with a large negative temperature bias in the ENSO region can drive global weather regimes away from reality, thus negatively impacting predictive skill. For the long-term climate modeling community, such biases can have similar negative impacts on model performance and credibility.

The S2S prediction community explicitly aims to advance the development of operational products that are of the highest possible value to stakeholders and decision-makers (such as energy companies or water utilities that want to make operational decisions about upcoming seasonal demands). While the climate modeling community does not share such a common operational imperative, it is implicitly involved in generating products that are used to make long-term decisions. There is a huge amount of practical research based on the output of the CMIP collectively produced by the climate modeling community that is used in assessments and to inform stakeholders and decision-makers about long-term climate change. While only a small number of laboratories actually produce these simulations, much of the current research in the climate modeling community is devoted to analyzing, understanding, and improving the models that are used to run these simulations. So both communities have parallel connections to stakeholders and decision-makers.

Finally, both communities are invested in the costly task of exploring the benefits of increasing higher resolutions for both increasing prediction skill and reducing model bias, which is described in greater detail below.

Common Issues with High-Resolution Modeling

There are major efforts in both communities to explore the use of high resolution in both the atmosphere and the ocean.(23) For the atmosphere, increasing resolution appears to improve the representation of orographic precipitation, the statistics of precipitation, high-latitude temperature biases related to snow-albedo feedbacks, and the representation of synoptic-scale circulation features and even tropical cyclones (e.g., Kinter et al., 2013, and references therein). For the ocean, increasing resolution improves the structure, placement, and statistics of western

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(22) Operational centers run re-forecasts initialized from reanalyses, ideally, with the same DA and model that is used operationally because the output data are used for calibration of real-time forecasts. The climate modeling community also may run re-forecasts initialized from reanalyses, but for the purpose of analyzing predictability or model behavior.

(23) We assume throughout this report that the land surface component is generally configured at the same resolution as the atmosphere component and the sea ice component is configured at the same resolution as the ocean component.

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 (although this appears to depend also on the resolution of the atmospheric forcing; for example, Kirtman et al., 2013, and references therein).

In both the ocean and atmosphere, increasing resolution can result in nonlinear improvements. Anecdotal evidence from a number of modeling centers, in both the S2S and climate modeling communities, suggests that there is a large improvement in model skill when the horizontal resolution is pushed to a grid spacing less than ~50 km in the atmosphere. Further, there is clear evidence in the literature that tropical cyclones with realistic intensities only manifest in models with horizontal resolutions of ~25 km or less. For the ocean, most improvements arise as horizontal resolutions transition from eddy-permitting (e.g., 0.25-degree or approximately 25 km, and coarser) to eddy-rich (0.1-degree or finer, approximately 4 to 10 km). These resolution-dependent improvements increase the fidelity of S2S forecasts and decadal and longer climate model projections alike.

However, it is quite clear that high horizontal resolution is not a panacea. Experimentation must be done with models having physical representations that can span spatial scales. In fact, a number of prominent biases and model errors persist or even deteriorate 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, and SST biases in the eastern Tropical Pacific Ocean. Such modeling errors are detrimental to the fidelity of both S2S forecasts and climate model projections.

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 (e.g., map-reduce), and software for doing even the most trivial post-processing and analysis operations. Even when experimentation occurs on different supercomputing machines, there is still much room for shared computational investment across the two communities. The two communities share similar (or, in some cases, the same) 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 [e.g., Common Infrastructure for Earth Modeling]), 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.

A Path to Progress on High-Resolution Modeling with Common Experimental Frameworks

A clear outcome of this workshop is the recognition that the S2S prediction and climate modeling communities have been involved in research efforts with common scientific issues, common experimental approaches, similar exploration of high-resolution coupled models, and similar computational challenges associated with increasing resolution. There are clearly some areas in which joint or coordinated research activities would be mutually beneficial and make optimal use of underpinning infrastructure.

Broadly, potential areas for joint/coordinated investment fall into three major categories: 1) common experimental frameworks to identify and improve coupled-system biases, 2) common experimental frameworks to understand and explore the benefits and issues with high resolution in various model components, and 3) common software frameworks for simulation codes, simulation data management, and big-data analysis. The third category was discussed in A National Strategy for Advancing Climate Modeling (NRC 2012(24)). We elaborate on categories 1) and 2) below.

Common Experimental Frameworks to Identify and Improve Coupled System Biases

There are several frameworks that could prove useful for improving biases in models within both the S2S prediction and climate modeling communities. Examples include:

- 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)
- A systematic framework for identifying the origin of SST biases in the coupled system, originally described by Vannière et al. (2014)
- A generalization of the set of standard test experiments and metrics (referred to hereafter as the “test harness”) used to assess new climate-prediction systems (e.g., for CFS or NMME models) incorporating new/modified physics parameterizations or new initialization procedures.

Numerous papers demonstrate the ability of CAPT-like reforecasts to efficiently identify and isolate issues with fast physical processes that result in errors in long-term simulations. To date, this approach has been applied to atmosphere-only simulations, but it is also a compelling experimental framework for high-resolution coupled-model simulations. If errors can be diagnosed in relatively short (i.e., S2S) reforecast simulations in lieu of long coupled simulations, significant computational savings could be realized. Vannière et al. (2013, 2014) adapted the regionally coupled approach (e.g., Alexander, 1992a, 1992b; Cash et al., 2009 and others) and the use of a hierarchy of simulations, including coupled reforecasts, to diagnose biases in the coupled system. The following list of questions, quoted from Vannière et al. (2014), summarizes their framework for diagnosing errors in the SST field (the paper also includes a table of experiments necessary to probe these questions):

1. What is the spatial pattern of SST errors in control and historical coupled simulations and uncoupled atmosphere and ocean simulations? What is their seasonality?
2. What is the time scale of bias development (from monthly to decadal time scale) and the chronology of the appearance of errors? Is there any propagation of the bias?
3. Does the bias develop locally or is it from a remote region?
4. Does the SST bias arise from the ocean or from a direct effect of the atmosphere forcing on the ocean? If the bias is not caused by direct effect of the atmosphere on the ocean, is it amplified by a remote/local coupled feedback?
5. What is the variable ultimately responsible for the bias development?

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(24) **http://www.nap.edu/catalog/13430/a-national-strategy-for-advancing-climate-modeling**

A number of practical and technical issues must be explored with respect to using coupled reforecasts as a diagnostic tool—not least of which is how best to deal with initializing the ocean—but Vannière et al. (2013, 2014) clearly demonstrate that this is an approach worth pursuing. Joint exploration and development of a coupled reforecast diagnostic framework could benefit both communities.

In the near term, the NMME and I-S2S database could serve as a coupled ensemble of opportunity for some initial explorations of using reforecasts as a diagnostic tool. Both of these data sets include output fields from reforecasts for up to 30 years of the recent past, generated using both operational and experimental global coupled-climate models. The output fields could be interrogated to determine common and unique biases in the reforecasts. Tests of hypotheses relating to the sensitivity to model resolution or physics implementation could be made with individual members of these multi-model ensembles. The list of output fields would likely need to be augmented for such tests.

Coordinated multi-model efforts to study the growth of systematic biases in initialized coupled models may be of some use in understanding the commonalities and differences in the sources of model errors. A pilot project currently being organized by the Working Group on Seasonal-to-Interannual Prediction(25) may shed light on some of the benefits and challenges of such efforts. However, given the diversity of modeling approaches needed to address the questions above, it may be more profitable to encourage exploration by individual model groups but report findings in future workshops or sessions of conferences such as the Workshop on Systematic Errors in Weather Climate Models (held most recently in 2013(26)) organized by the Working Group on Numerical Experimentation(27) as part of the World Climate Research Program.(28)

It was also noted that the set of experiments constituting a framework to evaluate new S2S prediction systems like the CFS model or a generalization of such "test harness" could be used more broadly as a basic experimental framework to facilitate testing of updated model components. In this way, the metrics used to evaluate operational forecast models, and parallel implementations, could be used by researchers to more immediately assess the impact of a particular model change (e.g., resolution, physics, coupling method, etc.).

Common Experimental Frameworks to Understand and Explore High-Resolution

The S2S prediction community and the climate modeling community are exploring the benefits and issues associated with increasing spatial resolution, both horizontally and vertically, in both the atmosphere (land-surface) and ocean (sea-ice) model components, and it would be beneficial to coordinate these efforts. To date, there has been only limited systematic exploration of the tradeoffs (which may only be computational) 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. Tradeoffs among these components, in terms of their effect on model skill, fidelity, and usability, have not been

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(25) **http://www.wcrp-climate.org/wgsip-overview**
(26) **http://www.metoffice.gov.uk/conference/wgne2013**
(27) **https://www.wmo.int/pages/prog/arep/wwrp/rescrosscut/resdept_wgne.html**
(28) **http://www.wcrp-climate.org/**

adequately explored. Systematic exploration of this space, which is represented in Figure 12, would be beneficial to both communities.

Several questions pertaining to spatial resolution would benefit from joint and systematic exploration involving both communities:

- How does skill/fidelity change as resolution is increased in the ocean and atmosphere 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 either/both components?

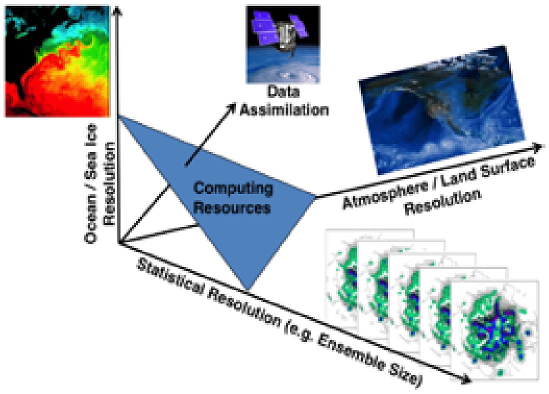

Figure 12. Trade space for spatial resolution in component models, statistical resolution, and data assimilation. The constraint of computing resources cuts across this space. Tradeoffs in model quality and forecast fidelity are less well known.

Recent explorations of higher resolution in coupled models have been largely ad hoc, employing a “try it” approach, often with a single model to determine if there is any sensitivity; there are no existing frameworks for exploring this resolution space. However, the community would benefit from establishing desired aspects of such a framework. A few experimental designs might be modified to address these questions: the Frameworks for Robust Regional Modeling (Leung et al., 2013) experimental design could be adapted to incorporate exploration of spatial resolution in global coupled models, and the regionally restored and globally restored experimental designs described by Vannière et al. (2014) could be adapted to discriminate between local and non-local sources of change in skill. A number of modeling groups also are implementing variable-resolution capabilities in both ocean and atmosphere model components, and these capabilities could be leveraged as part of a computationally efficient experimental design for exploring resolution issues pertaining to both modeling and predictions.

Elements for a Path Forward

Given the many research interests, methodologies, and data sets that are or could be shared by the S2S prediction and climate modeling communities, substantial benefits could accrue by identifying experimentation approaches that could be of shared interest and applicability. These could have the following elements and characteristics:

- Systematically identify and address coupled-climate model biases; for example, via a numerical experimental design that could attribute causes of error, focusing on the spatial pattern, time scale, 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; for example, 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.
- Be applicable to, encourage the involvement of, and foster collaborations among relevant S2S prediction and national climate modeling efforts in the United States.
- Take advantage of the emerging software infrastructure called for in NRC 2012 and under active development by several U.S. groups.
- Link with of other relevant multi-model archives; for example, the CMIP, NMME, and I-S2S data sets.

The ideas identified above could be elements of a multi-faceted strategy that needs to be discussed and developed by the national and international communities to address the challenges of high-resolution coupled modeling and initialization undertaken to improve predictability and prediction in climate models.

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Appendix A: Workshop Agenda

Day 1

8:30 am – 8:45 am	**Welcoming Remarks, Scope of the Workshop and Relevance to NOAA and DOE** Bill Lapenta, NCEP Director Mike Kuperberg, Executive Director, U.S. Global Change Research Program Annarita Mariotti, NOAA Climate Program Office Renu Joseph, DOE Office of Science
8:45 am – 12:30 pm	**Session 1: Setting the Stage – Team talks and discussions on current state of the science** Presentations include input from Team 1-4 participants as part of workshop preparations. A bulleted resume of key points from the presentations and Q&A discussions will inform the meeting report. **Chairs**: Franco Molteni, ECMWF, and Bill Collins, LBNL **Rapporteurs**: Travis O'Brien, LBNL, Steve Penny, UMD/NOAA/NCEP, and Brian Gross, NOAA
8:45 am	**Team 1**: State of the science in seamless sub-seasonal to seasonal predictions Jim Kinter, GMU/COLA, and Shian-Jiann Lin, NOAA/GFDL, Team 1 Leads
9:15 am	Q&A
9:35 am	**Team 2**: State of the science in using initialized climate models for testing model physics and understanding model processes and biases [e.g., CAPT] Brian Medeiros, NCAR, Travis O'Brien, LBLNL, and Steve Klein, LLNL, Team 2 Leads
10:05 am	Q&A
10:25 am	**Break**
10:50 am	**Team 3**: Current initialization capabilities Steve Penny, UMD/NOAA/NCEP, and Kevin Raeder, NCAR, Team 3 Leads
11:20 am	Q&A
11:40 am	**Team 4**: Computational and infrastructure environment in the next 5 years and the limits on high-resolution initialized simulations Bill Putman, NASA, Brian Gross, NOAA, and Bill Collins, LBNL, Team 4 Leads
12:10 pm	Q&A
12:30 pm – 1:30 pm	**Lunch**
1:30 pm – 5:00 pm	**Session 2: The Nexus: Resolution – Processes – Prediction** Chair: Shian-Jiann Lin, NOAA/GFDL Rapporteurs: Jim Kinter, GMU/COLA, and Bill Putman, NASA
1:30 pm	The impact of super-parameterization on the sub-seasonal forecast skill Cristiana Stan, COLA/GMU
1:45 pm	Discussion
2:00 pm	Tackling seasonal prediction of extremes with high-res coupled models: Extra-tropical storm tracks XiaoSong Yang, NOAA/GFDL, and Gabriel Vecchi, NOAA/GFDL
2:15 pm	Discussion

2:30 pm High-resolution sea-ice prediction: Coupled processes and prediction system development
Cecelia Bitz, UW, and Patrick Hogan, NRL

2:50 pm Discussion

3:00 pm **Break**

3:30 pm High-resolution extended-range predictions at ECMWF: Results and expectations
Franco Molteni, ECMWF

3:45 pm Discussion

4:00 pm Addressing the Discussion Questions
Facilitated by Jim Kinter, GMU/COLA, Shian-Jiann Lin, NOAA/GFDL (Team 1)
and Bill Putman, NASA (Team 4)

- How does prediction skill and fidelity change when resolution is increased in combination for the various components of the prediction system?
- How can we diagnose and address model behaviors that lead to the above sensitivity?
- Are there specific or related processes in the coupled system that drive both short-term prediction error and climate simulation bias?
- What resolutions are necessary to adequately resolve these processes?

Questions to be discussed in the context of state-of-art HPC computing and data storage systems available to the U.S. community in the next 5 years. A bulleted resume of key outcomes by the rapporteurs will inform meeting report.

5:00 pm **Adjourn**

Day 2

8:30 am – 12:00 pm **Session 3: Frameworks for Diagnosing Fast Physics in the Coupled System**
Chair: Steve Klein, LLNL, and Brian Medeiros, NCAR
Rapporteurs: Travis O'Brien, LBNL, and Bill Collins, LBNL

8:30 am Prospects for high resolution to improve small-scale atmospheric processes
Julio Bacmeister, NCAR

8:45 am Discussion

9:00 am Prospects for high resolution to improve small-scale land processes and land-atmosphere interactions
Ruby Leung, PNNL

9:15 am Discussion

9:30 am Prospects for high resolution to improve small-scale ocean processes and ocean-atmosphere interactions
Frank Bryan, NCAR

9:45 am Discussion

10:00 am **Break**

10:30 am Using initialized and high-resolution simulations to diagnose the growth of systematic biases in the coupled system and the contribution of fast physical processes to systematic biases
Eric Guilyardi, UR/IPSL

10:45 am Discussion

11:00 am Addressing the Discussion Questions

Facilitated by Steve Klein, LLNL, Brian Medeiros, NCAR, Travis O'Brien, LBNL (Team 2) and Bill Collins, LBNL (Team 4)

- How does the fidelity of small-scale physical processes in the climate system change as resolution is increased?
- For what phenomena would initialized coupled models (e.g., coupled CAPT) be of use for diagnosing fast physical processes of the climate system?
- What can initialized simulations (either single-component or coupled) reveal about fast-coupled processes, such as rapid development of flux errors that lead to long-term bias and prediction error for the climate system?
- What timescales should be targeted by such efforts?

Questions to be discussed in the context of state-of-art HPC computing and data storage systems available to the U.S. community in the next 5 years. A bulleted resume of key outcomes by the rapporteurs will inform meeting report.

12:00 pm – 1:30 pm **Lunch**

1:30 pm – 5:00 pm **Session 4: Initialization at High Resolution and Uncertainty Sampling for Sub-seasonal to Seasonal Prediction**

Chair: Suru Saha, NOAA/EMC
Rapporteurs: Steve Penny, UMD/NOAA/NCEP, and Brian Gross, NOAA

1:30 pm Data assimilation for high-resolution prediction initialization at NASA
Bill Putman, NASA, Guillaume Vernieres, NASA, and Clara Draper, NASA

1:45 pm Discussion

2:00 pm Two promising solutions for the CFS systematic errors: Strongly coupled data assimilation, and bias correction based on analysis increments
Eugenia Kalnay, UMD

2:15 pm Discussion

2:30 pm Initialization of global ocean eddy-resolving coupled simulations
Ben Kirtman, UMI

2:45 pm Discussion

3:00 pm **Break**

3:30 pm Fully coupled data assimilation for high-res initialization in the Data Assimilation Research Testbed
Kevin Raeder, NCAR

3:45 pm Discussion

4:00 pm Addressing the Discussion Questions
Facilitated by Steve Penny, UMD/NOAA/NCEP, and Kevin Rader, NCAR (Team 3) and Brian Gross, NOAA (Team 4)

- What initialization techniques are best applied for prediction at the various spatial and temporal scales?
- What level of initialization sophistication is useful or necessary for diagnosing fast physical processes in initialized climate model simulations (e.g., CAPT)?
- What is the ideal size of the ensemble needed for this effort, both for prediction and for understanding coupled processes and biases?

- What resolution is feasible given the state-of-art HPC systems available to the U.S. community? How will increasingly high-resolution data be stored and shared for community research?

Questions to be discussed in the context of state-of-art HPC computing and data storage systems available to the U.S. community in the next 5 years. A bulleted resume of key outcomes by the rapporteurs will inform meeting report.

5:00 pm **Adjourn**

Day 3

8:30 am – 10:30 am **Session 5: Future HR Experimental Frameworks**
Organized by all Team Leads

Chairs: Jim Kinter, GMU/COLA, and Travis O'Brien, LBNL

- What are key points stemming from Sessions 1–4 to inform future experimentation? [Rapporteur summary from Sessions 1–4, with focus on science gaps identified (10 mins each)]
  – Is there agreement on the science gaps identified; are there others?
  – Is there anything relevant to this workshop that has not been considered?
- What are the timescales for which there is the most pressing need to improve scientific understanding of resolution-dependent improvements in light of current HPC capabilities?
- Is there a feasible experimental framework to systematically and optimally address major questions about the use of high resolution in initialized coupled-climate models?
- What is the interest of the various institutions in participating?

This session will be a discussion guided by the session chairs. A bulleted resume of key outcomes will inform meeting report.

10:30 am **Break**

10:45 am – 11:45 am **Report preparation – Outline, Roles, Tasks and Timeline**

11:45 am – 12:00 pm **Closing Remarks and Impressions**
Gary Geernaert, DOE Office of Science, Division Director
NOAA representatives
Co-organizers and other participants

12:00 pm **Adjourn**

Appendix B: Workshop Participants

Full Name	Affiliation
Santha Akella	NASA GMAO
Heather Archambault	NOAA/OAR/CPO
Julio Bacmeister	NCAR
Dan Barrie	NOAA/OAR/CPO
Stan Benjamin	NOAA/ESRL
Cecilia Bitz	UW
Frank Bryan	NCAR
Jessie Carman	NOAA
Ben Cash	GMU/COLA
Will Chong	NOAA/OAR/CPO
Bill Collins	LBNL
Cecelia DeLuca	NOAA/ESRL
Clara Draper	NASA
Dan Duffy	NASA
Gary Geernaert	DOE
Georg Grell	NOAA/ESRL
Brian Gross	NOAA
Eric Guilyardi	UR/IPSL
Lucas Harris	NOAA/GFDL
Wayne Higgins	NOAA/OAR/CPO
Patrick Hogan	NRL
Jin Huang	NOAA/CPC
Shian-Jiann Lin	NOAA/GFDL
Renu Joseph	DOE
Eugenia Kalnay	UMD
Alicia Karspeck	UCAR
Jim Kinter	GMU/COLA
Ben Kirtman	UMI
Steve Klein	LLNL
Arun Kumar	NOAA/CPC
Ruby Leung	PNNL
Fei Liu	NOAA/ESRL
Hsi-Yen Ma	LLNL
Annarita Mariotti	NOAA/OAR/CPO
Brian Medeiros	NCAR
Franco Molteni	ECMWF
Shrinivas Moorthi	NOAA/NCEP
Masuo Nakano	JAMEST
Travis O'Brien	LBNL
Steve Penny	UMD/NOAA/NCEP
Bill Putman	NASA
Kevin Raeder	NCAR
Suru Saha	NOAA/EMC
Christiana Stan	GMU/COLA
Ali Stevens	NOAA/OAR/CPO
Joe Tribbia	NCAR
Gabriel Vecchi	NOAA/GFDL
Guillaume Vernieres	NASA
Xiaosong Yang	NOAA/GFDL
Colin Zarzycki	NCAR
Ming Zhao	NOAA/GFDL

Affiliation Key

COLA	Center for Ocean-Land-Atmosphere Studies
CPC	Climate Prediction Center (CPC)
CPO	Climate Program Office (NOAA)
DOE	U.S. Department of Energy
ECMWF	European Centre for Medium-Range Weather Forecasts
EMC	Environmental Modeling Center (NOAA)
ESRL	Earth System Research Laboratory (NOAA)
GFDL	Geophysical Fluid Dynamics Laboratory (NOAA)
GMAO	Global Modeling and Assimilation Office (NASA)
GMU	George Mason University
IPSL	Institut Pierre-Simon Laplace
JAMEST	Japan Agency for Marine-Earth Science and Technology
LBNL	Lawrence Berkeley National Laboratory (DOE)
LLNL	Lawrence Livermore National Laboratory (DOE)
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction (NOAA)
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Lab (U.S. Navy)
OAR	Office of Oceanic and Atmospheric Research (NOAA)
PNNL	Pacific Northwest National Laboratory (DOE)
UMI	University of Miami
UMD	University of Maryland
UR	University of Reading
UW	University of Washington

Appendix C: Acronyms/Abbreviations

AMIP	Atmospheric Model Intercomparison Project
ARM	Atmospheric Radiation Measurement (Climate Research Facility)
CAPT	Cloud Associated Parameterization Testbed
CFS	Climate Forecast System
CMIP	Coupled Model Intercomparison (Project)
DA	data assimilation
DOE	U.S. Department of Energy
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño - Southern Oscillation
FLOR	Forecast-Oriented Low-Ocean-Resolution
GFDL	Geophysical Fluid Dynamics Laboratory
GMAO	Global Modeling and Assimilation Office
HiFLOR	Higher Resolution Forecast-Oriented Low-Ocean-Resolution
HPC	high-performance computing
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
MJO	Madden-Julian Oscillation
NCAR	National Center for Atmospheric Research
NMME	North American Multi-Model Ensemble
NOAA	National Oceanic and Atmospheric Administration
NSCI	National Strategic Computing Initiative
SST	sea surface temperature

For More Information

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