HIGH-RESOLUTION CLIMATE SIMULATIONS

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SCIENTIFIC GOALS

This project uses state-of-the-art, high-performance computational resources (Blue Waters) and cutting-edge modeling software—namely, the Community Earth System Model (CESM)—to advance the study of climate and climate change, while also contributing to international and national assessments of the potential impacts of climate change over this century.

A special high-resolution version of the global Community Atmosphere Model version 5 (CAM5), the atmosphere component of the CESM, has been developed and tuned for use on Blue Waters. High resolution challenges climate models because many physical processes that are clearly sub-grid at coarser resolutions become marginally resolved. The project has progressed to focusing on better quantifying future regional climate change by performing long simulations at high resolution, including numerous ensemble members, in order to meet the needs for the next generation of climate change assessments. Such high-resolution modeling studies are likely to produce important findings that will further the understanding of climate change science, contribute to enhanced understanding of the resulting societal and ecosystem impacts, and provide insights for adaptation and mitigation policy-related analyses.

ACCOMPLISHMENTS TO DATE

Accomplishments include: (1) testing of the CESM model with the new HOMME spectral element dynamical core; and (2) ongoing evaluation of the effects of resolution on model uncertainties through analyses of the past and projected future climate on Blue Waters at 0.25 degree (horizontal) resolution in the atmosphere and 1.0 degree in the oceans. In addition, the project is also exploring climate sensitivity associated with structure differences in representing physical processes through the use of the recent Cloud-Aerosol-Radiation (CAR) ensemble modeling system as coupled in the regional Climate-Weather Research and Forecasting model (CWRF).

Testing and tuning the model at 0.25 degree (~25 km) resolution on Blue Waters revealed a mix of changes in the simulated climate, with particular improvement in topographically influenced circulations due to topographic smoothing algorithms and enhanced internal divergence damping. Mesoscale features, such as tropical cyclones, were improved by modifying the treatment of convection processes. Fig. 1 shows a snapshot from a 0.25 degree simulation of the model, clearly showing realistic representations of well-known features such as atmospheric rivers and tropical cyclones; such features are not represented properly with lower resolution models.

We are also using the CAR to define a subset of computationally feasible size (25) of uncertainties in the treatment of cloud, aerosol, and radiative transfer processes especially relevant to climate variability and extreme events. Using the Climate-Weather Research Forecasting model (CWRF) we have analyzed the impacts of cloud-aerosol-radiation interactions on regional climate change projections by comparing ensemble members to estimate uncertainty due to model structure differences. We anticipate the range of future climate change projections at regional scales will be substantial and hence serve as a proxy for a region's response to the potential CESM climate sensitivity.

HOW BLUE WATERS PROJECT STAFF HELPED

In a nutshell, Blue Waters provided ready access to study high resolution model physics which required tuning through careful analysis and continual feedback. Quick turnaround on an HPC platform is imperative in order to achieve the proper fidelity in a climate model that will be used for advancing climate science and as input to U.S. and international policy development. Specific examples are provided in subsequent sections.

WHY YOUR RESEARCH MATTERS

This research is advancing the understanding of climate science and the changes occurring in climate through performing some of the first fully time-dependent high-resolution studies of the Earth's climate system. As a result, this project will also better define remaining uncertainties in climate modeling. In addition, this project will be a significant contribution to coordinated international special computational

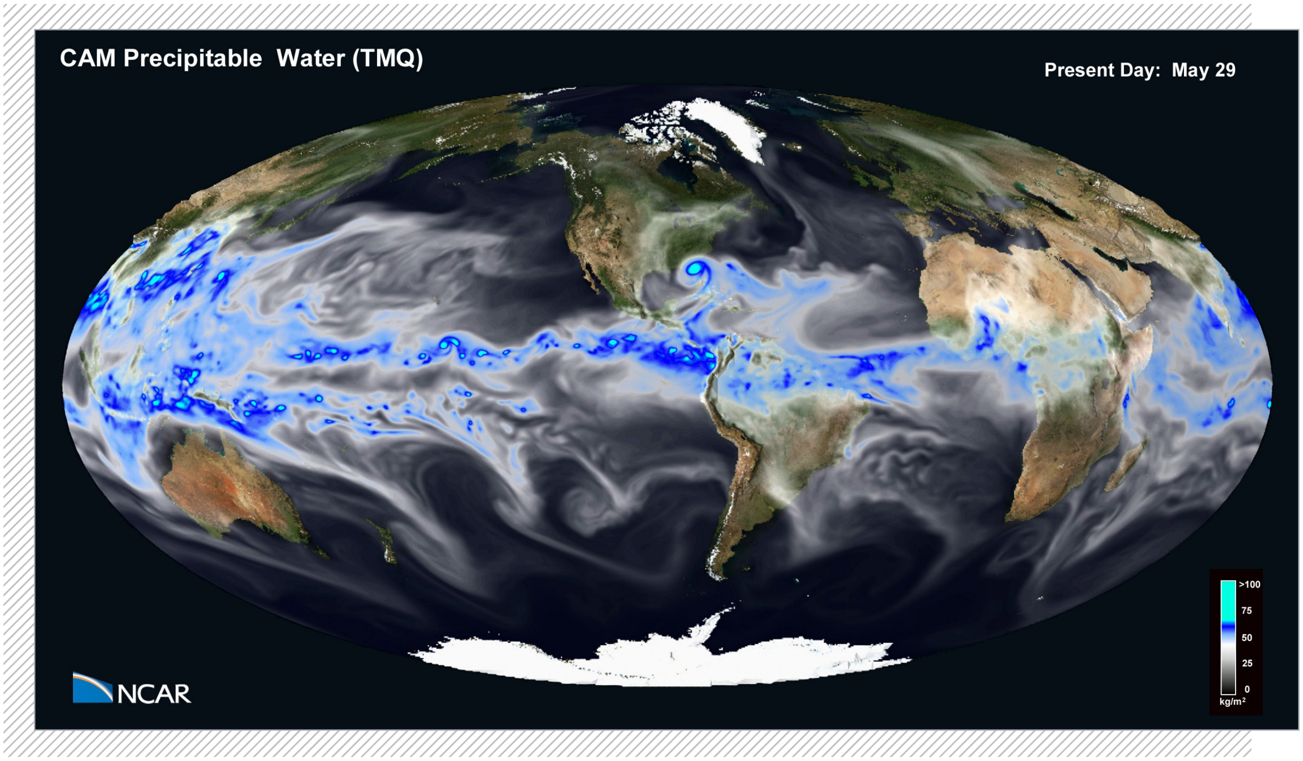

Figure 1. Atmospheric precipitable water as determined in the 0.25 degree CAM model, based on runs using Blue Waters. Features such as atmospheric rivers and tropical cyclones (hurricanes) are now well represented by using such high horizontal resolution.

studies and model intercomparisons to be done to analyze past and projected future changes in the Earth's climate system. The results of these studies will be fully available to the scientific community for further analyses and resulting insights into the processes, mechanisms, and consequences of climate variability and climate change.

WHY BLUE WATERS

A new dynamical core was introduced in CAM—the spectral element dynamical core. This is a highly scalable code that allows full exploitation of massively parallel architectures such as Blue Waters to run a large, high-resolution climate model. When configured at high resolution, and using thousands of cores, the time to complete one decade (10 years) of simulation is roughly five wall-clock days. One decade is considered to be the standard simulation length needed to evaluate the model when performing tuning exercises. The determination of an optimal set of model parameters requires a number of decade-long tests, and must be completed in a timely fashion. Century-long simulations with a tuned model require a few months. Thus, the simulations and analyses at high resolution at minimum require petascale computing resources and could not be completed without a computational platform like Blue Waters

PRE-PETASCALE PREPARATION

DEEP CONVECTION, SEASONAL PRECIPITATION, AND TROPICAL CYCLONES

High-resolution experimentation with CAM5 revealed a mix of changes in the simulated climate. Topographically influenced circulations and the global climatology of tropical cyclones were improved. On the other hand, seasonal mean tropical ocean precipitation degraded over large areas compared to simulations with ~100 km resolution.

The time required for a convective cloud to reach maturity (τcnv), is known to be important to controlling the activity of CAM5's deep convection parameterization. As τcnv decreases, parameterized convection becomes stronger, and we suspected that problems with the heating profile associated with large-scale precipitation contributed to biases at high resolution. To examine the effect of parameterized convection, τcnv was decreased from 3,600 seconds to 300 seconds. Seasonal mean precipitation distribution generally improved when compared to GPCP observed precipitation, but the typical number of tropical cyclones per year dropped from ~100 to <10. Access to Blue Waters allowed us to evaluate and remedy these deficiencies.

EFFECTS OF TOPOGRAPHY

When switching to CAM5's spectral element core, we found that heavily smoothing topography to reduce numerical artifacts removed many of the resolution-based improvements in topographically forced flows that were apparent in the finite volume dynamical core. Extensive development of topographic smoothing algorithms and enhanced internal divergence damping was conducted.

CLOUD-AEROSOL-RADIATION EFFECTS

Cloud-aerosol-radiation effects dominate the global climate model (GCM) climate sensitivity. The CAR ensemble modeling system represents the comprehensive range of the mainstream parameterizations used in current GCMs. We compared the frequency distributions for top-of-atmosphere (TOA) shortwave and longwave cloud radiative forcing averaged over 60°S-60°N in July 2004 for a fraction of CAR. The spread among the members was 30-60 Wm^{-2}, compared to 5-15 Wm^{-2} for the best observational estimates. In a subset of GCMs that produce TOA radiative balance within the observed range, the cloud radiative forcing ranges are still over three times larger than the respective observational uncertainties. Current GCMs appear to be tuned to reproduce the observed radiative balance by creating compensating errors among different components rather than producing the correct physics at the individual process level. Again, access to Blue Waters allowed us to closely examine these differences.

LOOKING FORWARD TO THE NEXT TRACK-1 SYSTEM

The next generation of Track-1 systems is needed in a number of significant ways. First, at the contemporary climate model resolution of 0.25 degree for the atmosphere and 1.0 degree for ocean/sea ice, ensembles of century-long simulations, both historical and for multiple future mitigation scenarios, are needed to quantify and reduce uncertainty (the focus of our 2015 PRAC proposal). The Track-1 system studies will be key to our contribution of high-resolution modeling studies of historical changes in climate and projected future changes in climate for the next generation of international analyses of climate (being labeled CMIP6) that will in turn be integral to the international and national assessments of climate change. These assessments provide important information for both U.S. and international policy considerations of the effects of human activities on the Earth's climate.

The next challenge to the climate modeling community is to further increase the ocean/sea ice resolution from 1.0 degree to 0.1 degree, allowing for a full eddy-resolving ocean simulation within the modeling system. This resolution should enhance understanding of ocean feedbacks on climate and ocean responses to the changing climate. We plan to test the model at this resolution as part of our studies for CMIP6.

The Track-1 system will also be key to achieving even higher resolution for the atmosphere, working towards fully representing cloud processes without using parameterizations that add to model uncertainties. The next generation goal is 1/8 (12.5 km) degree, and improvements in methods would include atmospheric chemical tracers, indirect radiative balance, and nested grids for regional impacts to properly calculate radiative heating rates dynamically within weather and climate models. Striving for 1/16 degree (6 km), which would resolve clouds, should enhance understanding of seasonal prediction of water resources and provide ultra-fine-grain scale to tropical cyclones, which would greatly benefit society.

COMMUNITY IMPACT

It is expected that the results from this study will be an integral part of the scientific analysis of climate change for the next major international climate assessment of the Intergovernmental Panel on Climate Change (IPCC) and the next U.S. National Climate Assessment. Both of these assessments influence policy decisions in the U.S. and internationally. In addition, better understanding of climate will help with water resource and disaster management, agriculture, and myriad other industries.

PUBLICATIONS

Wuebbles, D., Modeling the Earth's Climate System: From Petascale to Exascale. *University of Illinois CSE Annual Meeting,* Urbana, Ill., April 24-25, 2013. (video)

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