The first case presented here is of a 90-degree diversion at Reynolds number 20,000, with 50% of the total flow going into the lateral channel [2]. The time-averaged velocity magnitude of the flow near the bottom has been plotted (Fig. 1a) along with the position of the sediment particles (Fig. 1c). The majority of the sediment moves into the lateral channel, which is in agreement with the laboratory experiments. This highly non-linear behavior can be attributed to the fact that most of the flow near the bottom moves into the lateral channel, even though only 50% of the total flow moves into the lateral channel. Another important flow feature that influences the dynamics of the sediment at the diversion is the clockwise rotating vortex near the right-wall of the lateral channel (Fig. 1c). Instantaneous velocity magnitude near the bottom of the channel for different flow splits has also been presented for the 90-degree diversion at Reynolds number of 25,000 (Fig. 2). It shows that even when only 35% of the total flow moves into the lateral channel, most of the flow near the bottom moves into the lateral-channel (Fig. 2c). These results hint toward the underlying mechanism behind the non-linear Bulle Effect.

We are conducting more simulations with poly-disperse sediment for different flow-splits, Reynolds numbers and diversion-angles. The completed study will not only help to fully understand the underlying mechanism behind the Bulle Effect, it will also help in developing a reduced-order model for the phenomenon. This study provides new insights into the hydrodynamics and sediment transport at bifurcations, and it also shows that high-resolution LES can be used to study complex river-mechanics problems.

WHY BLUE WATERS

The current study **pushes the limit** of the scale at which high-resolution large-eddy simulations have been used to study complex multi-phase river mechanics problems, warranting the use of Blue Waters, which can provide sustained computing power at an **unprecedented scale**. For the current study, simulations have been conducted for up to 243.648 million computational points, with the code scaling strongly up to 32,768 MPI ranks. Without access to a petascale high-performance computing system like Blue Waters, completing the study in any realistic time-frame would be impossible. One of the most useful ways to understand a phenomenon is through visualization, thus we are working with Blue Waters staff to create an animation of the flow and sediment transport for one of the simulated cases.

NEXT GENERATION WORK

Access to the next generation of Track-1 HPC system will allow us to step up the scale at which we work, thus allowing us to conduct high-resolution LES of environmental flows at scales and with complexity similar to that of nature. This will allow us to fathom the underlying mechanisms of different environmental phenomena, thus aiding in improved predictions of different natural processes.

HIGH-RESOLUTION EARTH SYSTEM MODELING FOR INTERNATIONAL CLIMATE ASSESSMENT

Allocation: NSF PRAC/31.5 mnh
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EXECUTIVE SUMMARY

This is a collaborative project to investigate climate change and regional climate processes using higher model resolutions that would not be possible without resources such as Blue Waters. These simulations allow us to investigate climate change, specifically regarding extremes; regional model performance through dynamic downscaling; and to examine regional model uncertainties about atmospheric processes. These studies are on the **leading edge** of high resolution global and regional climate modeling and provide the pathway for the next generation climate models and assessments. Our studies also allow better understanding of model uncertainties. No previous global modeling study has provided such high-resolution information at the regional scale to fully analyze the potential impacts of climate change on human society across many different sectors (e.g., health, food, water, energy, transportation) and on ecosystems.

INTRODUCTION

This project has several objectives. One objective is to quantify changes in future climate extremes using two high-resolution versions of the Community Earth System Model (CESM): one with a high-resolution atmosphere (0.25° atmosphere, 1.0° ocean) and the other with high-resolution atmosphere and ocean (0.25° atmosphere, 0.1° ocean) where ocean eddies are derived internally instead of being parameterized. Another objective is to evaluate the effects of dynamical downscaling (DD). DD inputs time varying boundary conditions from a lower-resolution, limited-area, global climate model (GCM) into a regional climate model (RCM) [1,2], which is the Weather Research and Forecast (WRF) model. Finally, work on climate parameterization uncertainty continues via a multiple physics ensemble (MPE) analysis.

METHODS & RESULTS

CESM: The CESM pre-industrial (PI) control simulation with a fully coupled 0.25° atmosphere and 1.0° ocean has completed 100 years of simulation. In extended control simulations, it is desirable to have the radiative balance at the top of the atmosphere below |0.1| W/m^2 so that model drift is small and follow-on simulations, such as twentieth century historical or associated climate sensitivity simulations, can be branched with suitably balanced and realistic initial conditions. The PI control run on Blue Waters reached 0.03 W/m^2.

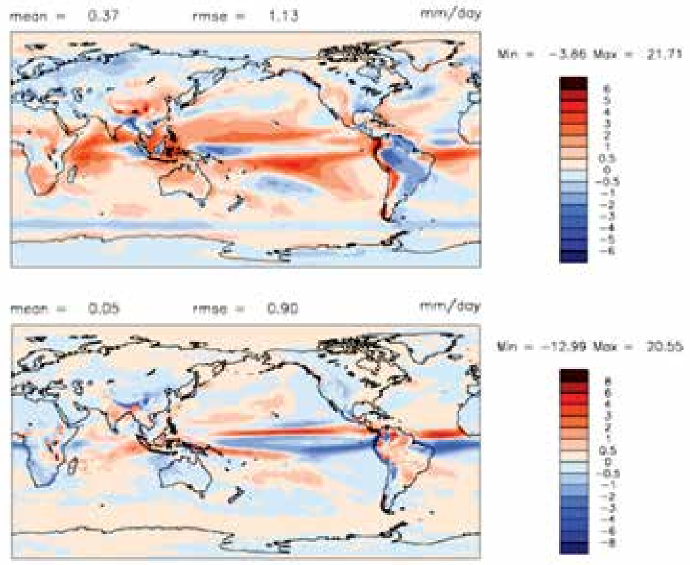
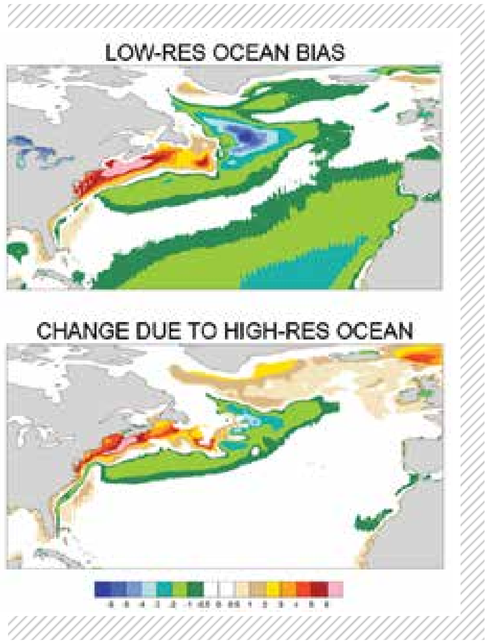


FIGURE 1: Annual mean total precipitation rate difference between a baseline low resolution (1.0°) PI control and GPCP observations (top panel) and between the high resolution (0.25°) PI control conducted on Blue Waters and the baseline low resolution PI control (bottom panel). Wherever the color is opposite in these two panels are regions in which high resolution represents precipitation rate better than low resolution.

FIGURE 2: Sea surface temperature difference (°C) between the high resolution model (0.25° atmosphere / 1° ocean) and (top panel) observations [6] and (bottom panel) the high resolution ocean model (0.25° atmosphere / 0.1° ocean). Wherever the color is the same in these two panels are regions in which high resolution represents sea surface temperature better than low resolution.



The expectation in conducting climate simulations at higher resolution is not necessarily to improve the modeled mean climate state but to capture many aspects of extreme events and diurnal cycle patterns that cannot be resolved at a lower resolution. However, we have observed improvements in the mean state, notably in precipitation, in the PI control and anticipate that this will translate to a better representation of precipitation extremes. Figure 1 compares precipitation rate from the low and high-resolution models to observations. Three regions of improvement stand out: the Andes and interior Amazon, the Indian Monsoon region, and North America.

We are also studying Earth's climate at an **unprecedented** resolution (0.25° atmosphere and 0.1° ocean) with a CESM configuration validated recently for present-day climate [3]. It produces a smaller climatological sea surface temperature (SST) bias in the topics than standard resolution runs, and also a more realistic interannual variability of Eastern Pacific SSTs. At this very high resolution, increased confidence is given to potential future regional climate changes arising from natural and anthropogenic forcing mechanisms. For example, by resolving ocean mesoscale features, we get a better representation of the SSTs off the US East coast, due to a better Gulf Stream path (Fig. 2), which in turn modifies the atmospheric precipitation and storm tracks.

Dynamic Downscaling: The WRF model of the RCM was used to evaluate the performance of six dynamically downscaled decadal historical simulations with a 12 km resolution for a large domain (7200 km × 6180 km) covering most of North America. This study is based on high-spatial-resolution (12 km) RCM simulations using one numerical model to evaluate the model performance and the uncertainties coming from different boundary conditions and different model setups. The initial and boundary conditions are taken from three separate GCMs and one from reanalysis data. Figure 3 shows the initial findings for changes in seasonal and annual precipitation using CCSM4 boundary conditions with the RCM 8.5 scenario for 2085-2094 [4]. The hatched areas on the figures are statistically significant changes in seasonal precipitation for this decade. While this figure focuses on seasonal averages, further analysis will be needed to help identify regional and local climate extremes for using different GCMs as boundary conditions.

CWRF Uncertainty Analyses: We have continued using the regional CWRF model [5] in an MPE configuration at 30 km grid spacing over the United States to examine uncertainties in the treatment of cloud, aerosol, and radiative processes. When driven by the ECMWF-Interim Reanalysis (ERI), the CWRF ensemble mean exhibits higher prediction skills than the ERI. The variabilities of almost all ensemble members are closer to the normalized standard deviation of the observations than that of the ERI data. This is physically meaningful because the CWRF has a higher resolution and can simulate the spatial variability more realistically.

WHY BLUE WATERS

In climate modeling it is necessary to (a) quantify model characteristics/sensitivity, (b) produce a sufficiently long control, and (c) simulate historical and future mitigation scenarios. Based on the number of simulated model years at high resolution, very large allocations are required that are not attainable without systems like Blue Waters. For example, the computing requirements for simulations using the high-resolution ocean model (0.1°) have increased four-fold over the coupled model with a 1.0° ocean.

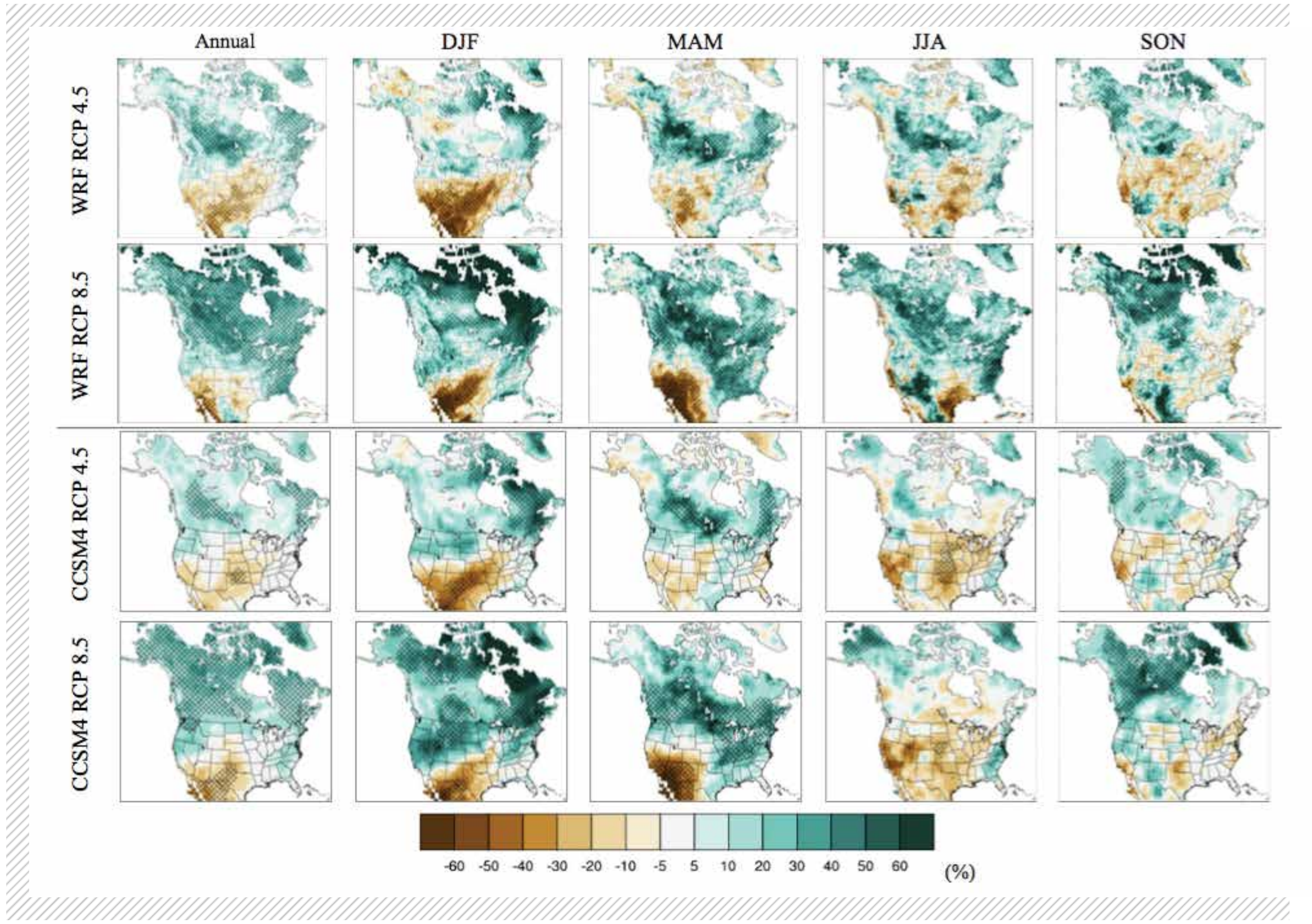


FIGURE 3: Difference in yearly and seasonal rainfall between 2085-2094 and 1995-2004 [4]. WRF simulations were driven by CCSM4 boundary conditions using bias correction for both decades. Hatched areas represent locations that experience statistically significant changes.

NEXT GENERATION WORK

The next generation systems will be required to achieve even higher resolution for the atmosphere model, eventually to represent small-scale processes without parameterizations, nested grids to study regional impacts, and more complex biogeochemistry. Striving for a 6 km horizontal resolution should enhance understanding of tropical cyclones and more accurately account for sophisticated land-ice processes (i.e., melting ice contribution to sea level rise). The 6km horizontal resolution translates to approximately 100 times more computation.

PUBLICATIONS AND DATA SETS

Zarzycki, C. M., et al., Impact of surface coupling grids on tropical cyclone extremes in high-resolution atmospheric simulations. *Geosci. Mod. Dev.*, 9:2 (2016), pp. 779-788.