Analyzing tropical cyclone-climate interactions using the Community Earth System Model (CESM)

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Executive summary

This project examines the relationship between tropical cyclones (TCs) and Earth's climate system using a high-resolution, state-of-the-art Earth system model (Community Earth System Model—CESM). We performed a suite of CESM simulations in which the high resolution atmosphere component (with 25 km horizontal resolution) is configured with three different levels of ocean coupling: prescribed sea surface temperature (SST), slab mixed layer ocean (no dynamics), and an ocean general circulation model with full dynamics and thermodynamics. We found that the inclusion of ocean coupling largely affects the simulated TC characteristics, including storm frequency, geographic distribution, maximum TC wind and storm intensification. Key differences in TC characteristics are attributed to the variations of the modeled large-scale circulations that arise from the combined effect of intrinsic model biases and air-sea interactions. These results provide new insights into the importance of coupled ocean-atmosphere interactions and feedbacks for understanding the connections between TCs and climate.

Description of research activities and results

Tropical cyclones (TCs) are among the world's most dangerous and destructive natural hazards. TC strength and frequency largely depend on the ambient environmental conditions and vary with changes in the Earth's climate. TCs can also play an active role in influencing the global climate system through complex ocean-atmosphere interactions and feedbacks on the large-scale atmospheric and oceanic circulations. Extreme TC winds cause vigorous vertical mixing in the upper ocean that disturbs stratification, resulting in anomalous heat gain in the ocean interior with the potential to alter ocean temperature distributions and influence large-scale circulations in the atmosphere and ocean. Understanding the connection between TCs and climate may be fundamentally important to advancing our understanding about climate variability and constrain uncertainties of future climate change projections.

TCs' potential influences on climate are largely missing from today's generation of climate models, in part due to the extreme computational costs associated with simulating the relevant small-scale physical processes and complex ocean-atmosphere interactions under TC conditions. In this research project, we explore the relationship between tropical cyclones and climate using a high-resolution state-of-the-art Earth system model (Community Earth System Model -- CESM), capable of simulating realistic tropical cyclone circulations and global cyclone activity metrics (number, intensity distribution, seasonality, etc.). Building on the results of an exploratory allocation analyzing the scalability of CESM on Blue Waters, we conducted a series of model experiments analyzing tropical cyclones in CESM on a global scale and explored potential feedbacks on global climate and weather patterns. We performed a 3-member ensemble of simulations spanning 30 years each, using three different CESM configurations: 1) uncoupled atmosphere model with 1/4 degree horizontal resolution (fixed surface conditions); 2) the 1/4 degree atmosphere model coupled to the slab ocean model (coupled thermodynamics but no ocean dynamics); and 3) 1/4 degree atmosphere model coupled to the dynamic ocean model with 1 degree horizontal resolution (full dynamics and thermodynamics).

This comprehensive modeling framework provides a useful testbed for analyzing tropical cyclone activity and variability for different levels of ocean-atmosphere coupling. The results are of broad interest to the TC, climate, and impacts communities, and these runs constitute one component in larger effort to understand the relationship between TCs and climate variability. The results have so far have been applied to analyzing model sensitivities related to ocean heat budgets (Li et al., 2016; Li and Sriver, 2016); TC variability (Li and Sriver, 2017), and tropical ocean-atmosphere interactions (Huang et al., 2017).

We have saved full ocean and atmosphere CESM output at 6-hourly intervals, as well as time mean monthly averaged fields, which are primarily in gridded NetCDF format with fully documented variables and global attributes (current total ~100 TB). We are also exploring advanced visualization tools, such as ParaView Parallel Visualization on Blue Waters, for creating animations of storm circulations and ocean-atmosphere interactions to be used for research purposes and educational outreach (in collaboration with NCSA researchers Rob Sisneros and David Bock as part of PI Sriver's NCSA Faculty Fellowship 2016-2017).

Analyzing connections between tropical cyclones and climate using Earth system models poses unique computational challenges, which makes this project well-suited for Blue Waters. The correct representation of storm characteristics and global cyclone activity metrics depends critically on: 1) model resolution, 2) atmosphere-ocean coupling, and 3) transfer of heat and momentum at the ocean-atmosphere interface. Given the large computational expense of high-resolution Earth system models, it is difficult to apply these models to study tropical cyclones because of the necessary integration length (e.g. multiple decades) and grid resolution (e.g. 1/4 degree). Blue Waters provides a unique opportunity to address these challenges in CESM, offering computational capabilities that exceed typical allocation resources from other available HPC systems (cf. Figure 1). For our benchmarked and load-balanced version of the model, the cost is roughly 6900 node hours per simulation year on Blue Waters.

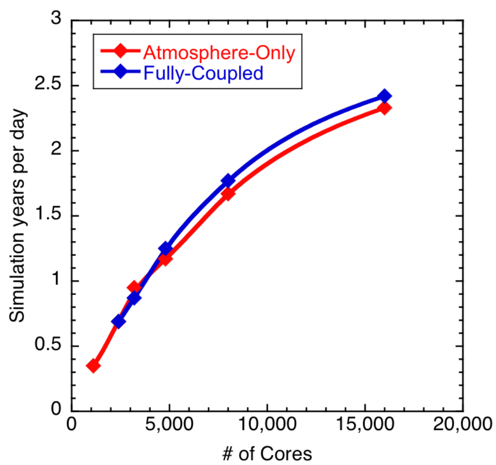

Figure 1. *Scaling results of CESM on Blue Waters for the atmosphere-only model (red curve) and the fully-coupled model (blue curve).*

In the next phase of the experiment, we plan to use the fully-coupled CESM to investigate the response of global tropical cyclone activity to changing greenhouse gas forcing (e.g. atmospheric carbon dioxide concentrations). This would expand the current sensitivity analysis into a more comprehensive climate change experiment. This work advances our mechanistic understanding about fundamental physical processes related to tropical cyclone dynamics, ocean-atmosphere interactions, feedbacks and implications for large-scale circulation. We are using comprehensive dynamic modeling techniques to link transient weather with large-scale climate, which can provide useful data products and resources for scientific analysis and impacts assessments.

Peer-Reviewed Publications Related to the Project:

Li, H., Sriver, R. L., and Goes, M. (2016), Modeled sensitivity of the Northwestern Pacific upper-ocean response to tropical cyclones in a fully-coupled climate model with varying ocean grid resolution, *Journal of Geophysical Research-Oceans,* 121, doi:10.1002/2015JC011226

* Ogura award recipient for best student paper (April, 2016)

Li, H. and Sriver, R. L. (2016), Effects of ocean grid resolution on tropical cyclone-induced upper ocean responses using a global ocean general circulation model, *Journal of Geophysical Research-Oceans*, 121, 8305-8319, doi:10.1002/2016JC011951.

** Paper selected as a Research Highlight by journal editor*

Huang, A., Li, H., Sriver, R. L., Fedorov, A. V., and Brierley, C. M. (2017), Regional variations in the ocean response to tropical cyclones: Ocean mixing versus low cloud suppression, *Geophysical Research Letters,* doi:10.1002/2016GL072023.

Li, H. and Sriver, R. L. (In Review), Impact of ocean coupling on simulated tropical cyclone activity in the High-resolution Community Earth System Model, Journal of Advances in Modeling Earth System.