IMPACT OF OCEAN COUPLING ON SIMULATED TROPICAL CYCLONE ACTIVITY IN THE HIGH-RESOLUTION COMMUNITY EARTH SYSTEM MODE

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EXECUTIVE SUMMARY

This research seeks to advance our understanding of 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, or CESM. In this report, we highlight results from a set of 30-year simulations in which the high-resolution (25 km) atmosphere component is configured with three different levels of ocean coupling: prescribed sea surface temperature (SST), mixed-layer ocean, and full three-dimensional dynamic ocean with nominal 1-degree horizontal resolution. We find that the inclusion of ocean coupling significantly affects simulated TC characteristics, including storm frequency, geographic distribution, maximum wind, and storm intensification. Key differences in storm numbers and distributions can be attributed to variations in the modeled large-scale climate mean state and variability that arise from the combined effect of intrinsic model biases and air–sea interactions. This work addresses the importance of storm-induced ocean–atmosphere feedbacks in Earth's coupled climate system, which can help improve our understanding of how TC activity may change in the future.

RESEARCH CHALLENGE

TCs are among the world's deadliest natural hazards. How TC activity will vary with the changing climate is a topic of great interest. Recent research has shown that Atmosphere General Circulation Models (AGCMs) are capable of generating TC-like vortices, and the representation generally improves with increasing horizontal resolution [1]. The current generation of high-resolution (less than 50 km) AGCMs have been shown to capture realistic global TC activity and can resolve the most intense Category 5 TCs [2-4].

Correct representation of air–sea interactions under TCs is important for simulating realistic storm intensities and track durations. Local feedbacks due to ocean mixing and surface fluxes can inhibit storm develop and intensification as well as influence larger-scale ocean and atmospheric circulations. These feedbacks can influence TC characteristics and statistics in a global coupled Earth system model, and they can also contribute to the tropical mean state and variability on interseasonal to interdecadal timescales. AGCMs with prescribed surface ocean conditions do not capture these feedbacks and are thus missing important physical processes that can influence climate variability.

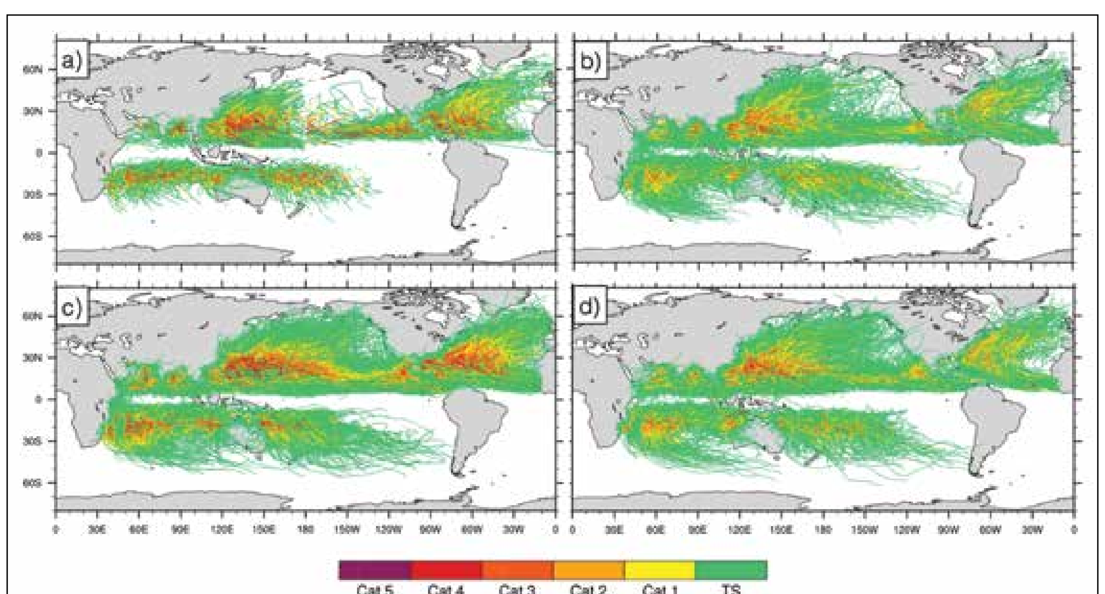

Figure 1: Global TC tracks accumulated over 30 years in the (a) observational best-track (1985–2014), (b) fully-coupled simulation, (c) atmosphere-only simulation, and (d) partially-coupled simulation.

METHODS & CODES

In this project, we assess the impact of ocean coupling on simulated TC activity using a high-resolution configuration of the CESM with a 25-km resolution atmosphere [5]. We performed three, 30-year simulations in which the atmosphere model is configured with three different levels of ocean coupling: (1) prescribed monthly-varying sea surface temperature based on the observed climatology; (2) a mixed-layer ocean model that allows thermodynamic exchanges between the atmosphere and the ocean mixed layer but does not account for ocean dynamics; and (3) a 1-degree ocean general circulation model with full dynamics and ocean–atmosphere fluxes. The models are configured with increased air–sea coupling frequency, modified surface wind drag law, and high frequency of history file output, in order to focus on ocean–atmosphere interactions associated with TCs. Each simulation is run for 30 years under the preindustrial climate conditions and with an active carbon–nitrogen cycle.

RESULTS & IMPACT

We find that TC number, geographical distributions, and intensity are sensitive to ocean coupling (Figs. 1 and 2). Differences in TC characteristics are mainly attributed to model differences in local air–sea flux exchanges and large-scale climate conditions. The fully coupled model with dynamic ocean simulates the most realistic annual TC number in the northwestern Pacific, though an expanded Indo-Pacific warm pool is likely contributing to more TCs forming in the central Pacific and Indian Ocean. The coupled model underestimates TC activity in the north Atlantic and northeastern Pacific, which is mainly due to biases in sea surface temperature and vertical wind shear, as well as the southward shift of the Inter-Tropical Convergence Zone. The partially coupled simulation with a mixed-layer ocean exhibits key features of TC distributions similar to the fully coupled simulation, including the cold surface ocean temperature bias and the underactive TCs in the north Atlantic. By design, ocean heat transport in the mixed-layer ocean model is specified based on the modeled estimates from the fully coupled model, thus biases in ocean heat transport in the coupled model are likely propagated to the partially coupled simulation. The uncoupled atmosphere-only simulation appears to perform better in the north Atlantic than the coupled model. However, the model exhibits an asymmetric bias in TC activity across the Pacific Ocean, including an overestimation of TC number in the eastern Pacific and underestimation of TC number in the northwestern Pacific. Our results show that this asymmetric pattern can be related to a weakened tropical zonal atmospheric overturning circulation (Walker Circulation) and associated biases in large-scale vertical motion.

This research addresses longstanding scientific questions about the relationship between tropical cyclones and ocean–atmosphere dynamics and variability on multiple spatial and temporal scales. It enables fundamental advancement of our mechanistic understanding about important physical processes related to TC dynamics, ocean mixing, ocean heat storage and transport, and global ocean–atmosphere circulations. It paves the way for more comprehensive coupled climate model experiments capable of linking extreme weather events with large-scale climate. Future work includes investigating the relationship between TC activity and climate variability on intraseasonal to interannual scales, as well as characterizing model uncertainties that may affect TC projections in the future climate with enhanced CO_2 forcing.

WHY BLUE WATERS

Given the substantial computational expense of high-resolution Earth system models, it is difficult to apply these models to study tropical cyclones because of the necessary grid resolution (¼ degree), integration length (multiple decades), and high frequency output (sub-daily). Blue Waters provides the unique capabilities to handle the computational demand associated with running the model at ultra-high resolutions, including scalability to over 15,000 cores, high-frequency input and output, and post-processing and visualization of model results.

PUBLICATIONS AND DATA SETS

Li, H., and R. L. Sriver, 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 (2016), DOI: 10.1002/2016JC011951.

Huang, A., et al., Regional variations in the ocean response to tropical cyclones: Ocean mixing versus low cloud suppression. *Geophysical Research Letters*, 44:4 (2017), DOI: 10.1002/2016GL072023.

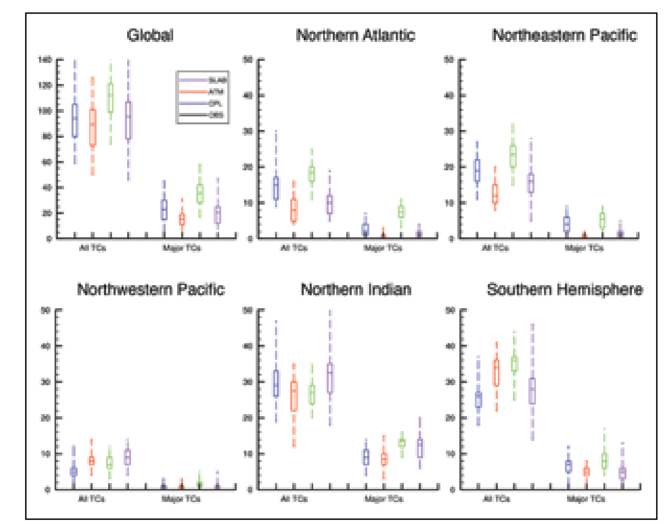

Figure 2: Global and basin-scale annual average TC number in observational best-track (blue), fully coupled simulation (red), atmosphere-only simulation (green), and partially coupled simulation (purple). In each panel, the left side accounts for the total storm number and the right side accounts for strong TCs with intensity higher than Category 3.