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ANALYZING TROPICAL CYCLONE–CLIMATE INTERACTIONS USING THE HIGH-RESOLUTION COMMUNITY EARTH SYSTEM MODEL

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EXECUTIVE SUMMARY

This research aims to advance the understanding about the interactions between tropical cyclones (TCs) and climate using the high-resolution Community Earth System Model (CESM). The high-resolution CESM can generate TCs within the modeled climate, providing a valuable platform for TC–climate research. In this work, we performed a suite of CESM simulations using various model configurations including fully coupled, atmosphere-only, and ocean-only. We used the fully coupled simulation as the control and performed an atmosphere-only simulation to examine the sensitivity of modeled TCs to ocean coupling, concluding that ocean coupling is essential to capturing realistic TC intensity and intensification. We then investigated the impact of TCs on the global ocean using a set of ocean-only simulations with and without TC forcing. We found that TCs can influence global ocean temperature patterns, ocean energetics, and ocean heat transport. These results help provide insights into the model behavior and the physical nature of the connection between TCs and climate.

RESEARCH CHALLENGE

Tropical cyclones (TCs) are one of the world's most destructive natural hazards. The 2017 hurricane season caused over $200 billion of damage. TC activity is closely linked to large-scale climate conditions [1], and the question of how TCs will change with the changing climate is drawing more and more attention. In addition, research has shown that TCs have the potential to actively contribute to the Earth's climate system through their interactions with the upper ocean [2,3]. Understanding these processes and feedbacks is of great importance to a better knowledge of the Earth's climate system and constraining uncertainty in climate projections.

The current generation of high-resolution Atmosphere General Circulation Models (AGCMs) with horizontal resolution finer than 25 km can generate realistic global TC activity and resolve the most intense TCs within the modeled climate [4,5], providing a unique platform for TC–climate research. The goals of this project are: (1) to characterize the model's self-generated TCs and analyze the sensitivity of the simulated TC characteristics to ocean coupling; and (2) to diagnose the impact of the model's self-generated TCs on the global ocean within the modeled climate.

METHODS & CODES

In this project, we analyzed the interactions between TCs and climate using various configurations of the high-resolution Community Earth System Model (CESM) [6]. We performed a 30-year fully coupled high-resolution simulation (CPL) in which the 0.25° (~25-km) resolution atmosphere component is coupled to the 1° (~110 km) ocean component. To analyze the sensitivity of the simulated TC activity to ocean coupling, we perform an atmosphere-only simulation (ATM) in which the atmospheric component is forced by sea surface temperature from the 30-year CPL. The impact of ocean coupling can then be diagnosed by comparing the simulation results between CPL and ATM. To analyze the impact of TCs on the global ocean, we performed two ocean-only simulations using the boundary conditions of the 30-year CPL in which TC effects at the ocean-atmosphere boundary were filtered out in one of the ocean simulations (OCN_FILT) while fully retained in the other (OCN_TC) in order to isolate the effect of the TCs on regional and global ocean variability across multiple time scales.

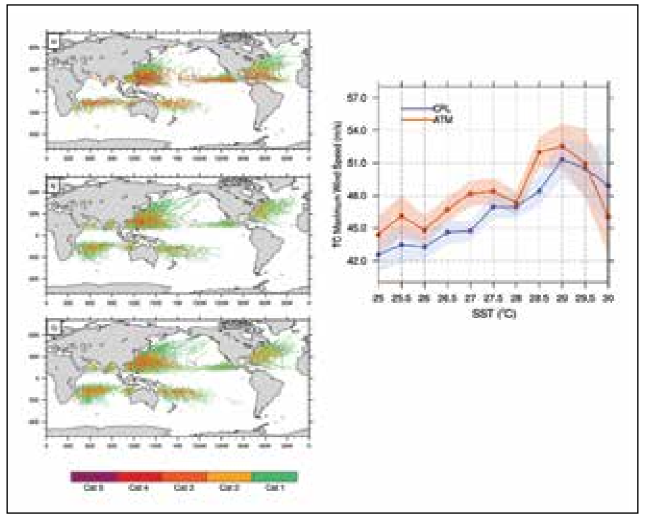

Figure 1: Thirty years of accumulated tropical cyclone (TC) tracks in the (a) observational best track during 1985–2014, (b) the coupled CESM simulation, and (c) the atmosphere-only simulation. (Right) Relationship between SST and maximum TC wind speed in the fully coupled simulation (blue) and the atmosphere-only simulation (salmon).

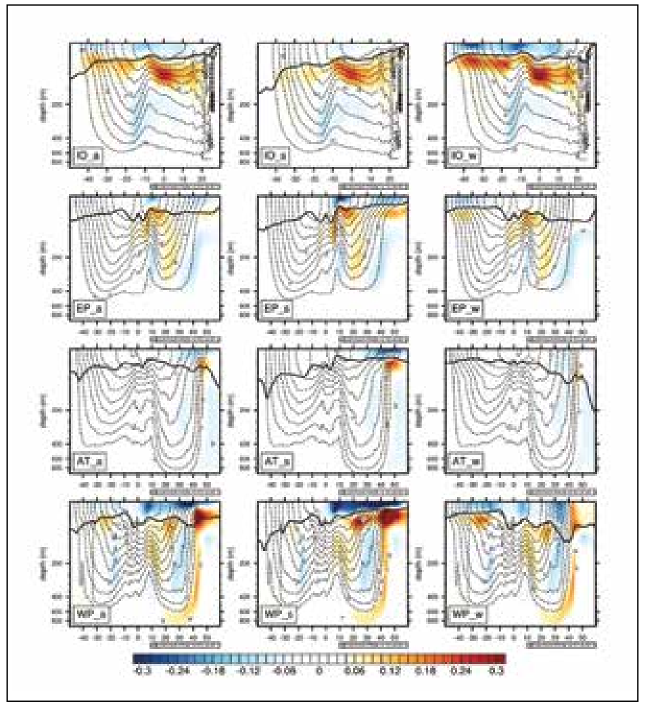

Figure 2: Meridional cross-section of long-term mean subsurface temperature differences between the OCN_TC run and OCN_FILT in the (top to bottom) Indian Ocean, eastern Pacific, Atlantic, and western Pacific for (left to right) annual, summer (June–November), and winter (December–May).

RESULTS & IMPACT

Results from the ATM simulation reveal that ocean coupling can influence the simulated annual TC number, spatial distribution, and storm intensity (Fig. 1). Despite using the same SST boundary forcing, ATM simulates more TCs globally than CPL, particularly for intense TCs stronger than Category 3. The differences are mainly attributable to the active air–sea coupling under TCs that accounts for the ocean's feedback: TC-induced SST cooling can restrain TC intensification, and this negative feedback mechanism can only be captured in a fully coupled model configuration.

For the ocean-only simulations, we found that the modeled TCs could induce changes in surface and subsurface ocean temperature patterns and seasonality (Fig. 2). On annual average, we observed SST cooling (up to 0.5°C) in major TC basins and SST warming (~0.1°C) at the higher latitudes. The surface warming occurs in the winter season, which is due to the reemergence of subsurface heat anomalies associated with the seasonal variations of the mixed-layer depth. This wintertime SST warming results in an anomalous SST gradient at the location critical for the midlatitude winter storm track. At the ocean subsurface, TC-induced heat anomalies generally travel along the isotherms following the ocean overturning cells, with a tendency to converge back to the near-equator upwelling zone. Moreover, we found that TCs can strengthen ocean gyre circulations and meridional overturning circulations, though the changes are small. The maximum overturning in the subtropical cell was enhanced by 3% on global average and 1% in the Atlantic. In addition, we found that the modeled TCs can influence ocean meridional heat transport (MHT). In general, TCs amplify the background MHT patterns, featuring enhanced poleward heat transport and cross-equator northward transport. However, the contribution of TC-induced anomalies to the background total MHT is not significant, accounting for ~2.5% of the background peak transport.

These results help to better understand the relationship between TCs and climate within the state-of-the-art TC-resolving Earth System Model. Results reveal how the choice of model configuration can influence the model's self-generated TC activity and how the model's self-generated TCs can influence the model-simulated global ocean in various aspects and across different time-scales. This has provided insights into the effect of resolved transient extreme weather events on the simulated mean climate within the high-resolution Earth System Models.

WHY BLUE WATERS

TC–climate research falls at the interface between weather and climate modeling, requiring high-resolution grid spacing to resolve weather-scale TC features, as well as global-scale coverage and decades of integration time. Blue Waters has the unique capability 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 & 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.

Li, H., and R.L. Sriver, Tropical cyclone activity in the high-resolution community earth system model and the impact of ocean coupling. *Journal of Advances in Modeling Earth Systems*, 10 (2018), DOI:10.1002/ 2017MS001199.

Li, H., and R.L. Sriver, Impact of Tropical Cyclones on the Global Ocean: Results from Multi-decadal Global Ocean Simulations Isolating Tropical Cyclone Forcing. *Journal of Climate*, in review (2018).