ANALYZING TROPICAL CYCLONE-CLIMATE INTERACTIONS USING THE COMMUNITY EARTH SYSTEM MODEL (CESM)

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EXECUTIVE SUMMARY

Our research seeks to advance 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—CESM). Here, we highlight results from a series of ocean-only simulations, in which we analyze the effect of tropical cyclone wind forcing on the global ocean using three different horizontal ocean grid spacing (3˚, 1˚, and 0.1˚). Findings indicate that TCs significantly contribute to global ocean heat and energy budgets, pointing to important connections between TCs and ocean dynamics, which can influence seasonal to inter-annual climate variability (such as El Nino) and large-scale circulation patterns in the atmosphere and ocean. Furthermore, TCs' contribution to the climate system may have important implications for anthropogenic global warming through feedbacks in the coupled system, which is a scientific questions we seek to answer with our work.

INTRODUCTION

Tropical cyclones are among the world's most dangerous and destructive natural hazards. TC strength and frequency largely depends on the ambient environmental conditions and vary with changes in the earth's climate. TCs can also play an active role in the earth's climate system through complex ocean-atmosphere interactions. 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 tropical cyclones and climate may be fundamentally important to advancing our understanding of climate variability and constrain uncertainties for future climate change projections.

Tropical cyclones' potential influences on climate are mostly 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 particular, ocean model resolution largely affects the representation of small-scale oceanic features such as mesoscale ocean eddies, which are significant contributors to modulating upper ocean stratification and global ocean heat transport. Mesoscale eddies are explicitly resolved in the 0.1˚ ocean model, whereas they are partially (fully) parameterized in the 1˚ (3˚) model. The current work aims to investigate TCs' cumulative impacts on global ocean using the ocean-sea ice configuration of the Community Earth System Model (CESM) [1], and examine the sensitivity of these TC-related impacts to model horizontal grid spacing.

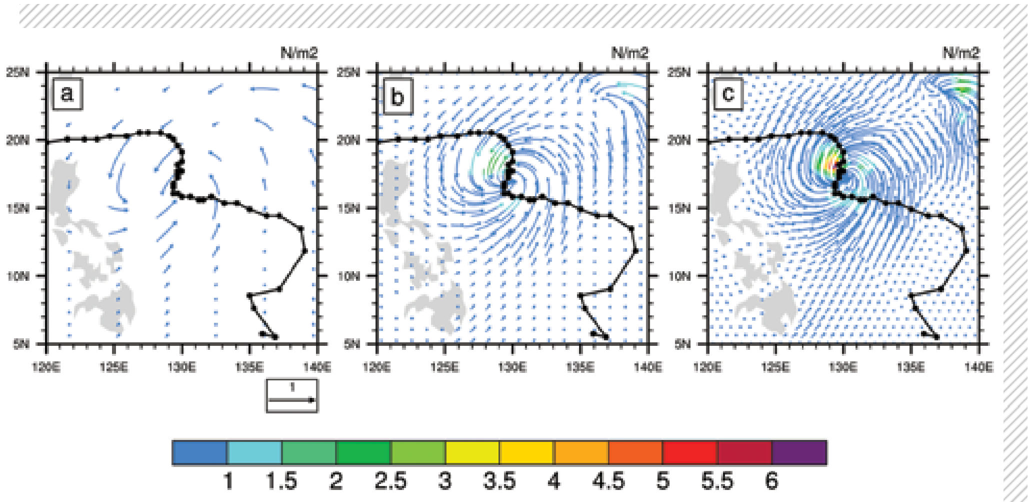

FIGURE 1: Tropical cyclone wind drag on the ocean surface as received in (a) 3°, (b) 1°, and (c) 0.1° ocean models.

METHODS & RESULTS

We conduct a suite of ocean-only simulations with varying ocean horizontal grid spacing (3˚, 1˚, and 0.1˚) using the Community Earth System Model (CESM). The ocean models are forced with identical atmospheric boundary conditions, in which we incorporate TC wind fields obtained from a high-resolution fully coupled CESM simulation [2] where TCs' geographical distribution, seasonal variation, and storm intensity are generally in agreement with the observational records. We also perform corresponding control simulations where the atmosphere contains no TC feature, to diagnose TCs' impact on the ocean properties.

Figure 1 shows an example of a TC event and the corresponding ocean surface wind drag perceived by the 3˚, 1˚ and 0.1˚ ocean models. Even though the models are forced with identical TC winds, the TC strength and wind patterns are different. The 0.1˚ model can preserve most of the TC characteristics, while its lower resolution counterparts underestimate the wind strength, which could lead to underestimated ocean vertical mixing and the subsequent heat uptake. Analysis reveals that the model simulates key characteristics of transient ocean responses to TCs, including mixing-induced sea surface cooling and sub-surface warming—responses that are sensitive to ocean grid resolution. Moreover, the 0.1˚ model better captures important dynamic processes such as ocean mixed layer deepening, eddy-induced vertical heat advection, and the zonal heat transport by equatorial waves.

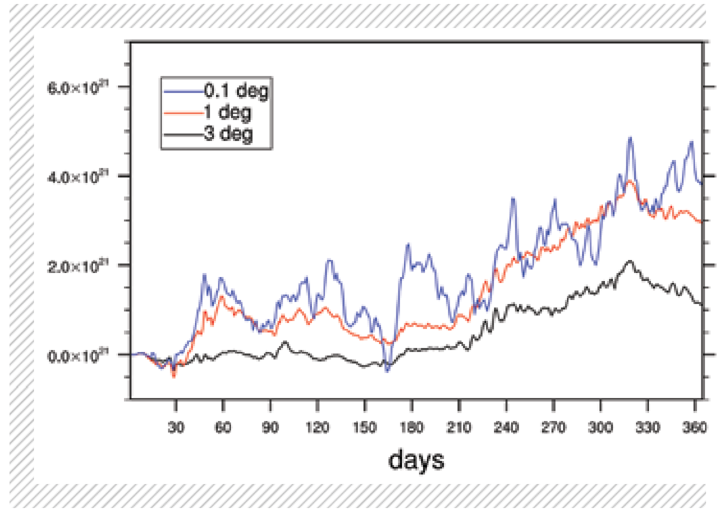

FIGURE 2: Time series of TC-induced ocean heat uptake in the 3° (black), 1° (red), and 0.1° (blue) ocean models. (Unit: J)

We estimate annually accumulated ocean heat gain injected irreversibly by TCs in the model cases. Figure 2 shows the time series of TC-induced ocean heat uptake over a one-year period. The value at the end of the year indicates the annually accumulated effect of TCs on the ocean heat anomalies. Results show that TCs could significantly contribute to global ocean heat and energy budgets, the magnitude of which depends on ocean grid resolution. The 0.1˚ model produces the most significant annual ocean heat uptake, amounting to 4e+21 Joules, or 0.13 petawatts in terms of annual heating rate. Differences between modeling scenarios suggest that enhanced ocean model resolution with resolved mesoscale eddies can greatly improve the representations of TCs' heating effect on global ocean.

WHY BLUE WATERS

A major challenge of high-resolution climate modeling studies is the heavy demand on computational resources. Our work involves a fully coupled CESM simulation with grid resolutions fine enough to capture realistic tropical cyclone circulations and ocean dynamics within a global framework. This effort represents the **cutting edge** of Earth system modeling, and it requires petascale computational power and a highly scalable platform. Blue Waters provides a unique opportunity to analyze tropical cyclone-climate connections using a state-of-the-art, comprehensive Earth system model. Results from this study will enable us to answer key science questions about tropical cyclones and climate that can fundamentally improve our understanding of climate variability and future changes.