A Simplified Climate Model for Understanding Tropical Cyclones and Ocean Heat Transport

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Abstract

Tropical cyclones (TCs) are perhaps the most powerful example of air-sea interaction. Although TC-induced energy exchange has been hypothesized to be a signicant agent of ocean heat transport under past and current climates, the margin of uncertainty in both observation and TC-permitting conventional climate models confounds these evaluations. In this study, we introduce a novel approach using simpler climate models, where land geometry is represented by a single strip of pole-to-pole continent, known as the Ridge conguration in previous work. This idealized design is known to represent the large-scale features of atmosphere-ocean general circulation and energy transport, serving to facilitate the physical interpretation of TC-induced energy exchange in the ocean, and its potential role in ocean heat transport. Under the framework of the Community Earth System Model, we congure an idealized, fully coupled Ridge model using Community Atmosphere Model version 4 (CAM4) and Modular Ocean Model version 6 (MOM6) at low horizontal resolutions. After obtaining a quasi-equilibrium climate, we then use the climatological sea surface temperature for forcing a CAM4-only, decadal simulation at TC-permitting resolution. Preliminary results indicate that the formation of a warm pool on the western side of the bounded ocean basin creates a more favorable environment for TC genesis than the cooler eastern side, analogous to observed TC climatology in the Pacic. By comparing ocean-only simulations with and without TCs in the atmospheric forcing, we evaluate the signicance of ocean heat transport attributable to TCs in the idealized atmosphere-ocean climate system. The insights gained through the process-based investigation of TC-induced air-sea interaction in this simpler model framework contribute to an improved understanding of the energetics of TCs, and their role in the climate system.

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Motivation

- Tropical cyclones (TCs) may impact ocean heat transport (cf. Mei et al., 2013; Li and Sriver, 2018).
- Studies using observation or conventional, realistic climate modeling at TC-permitting resolutions (Fig. 1, left column) are limited by large uncertainties.
- Can simplified, or idealized, climate models help us learn more?

Result: Large-Scale Climate

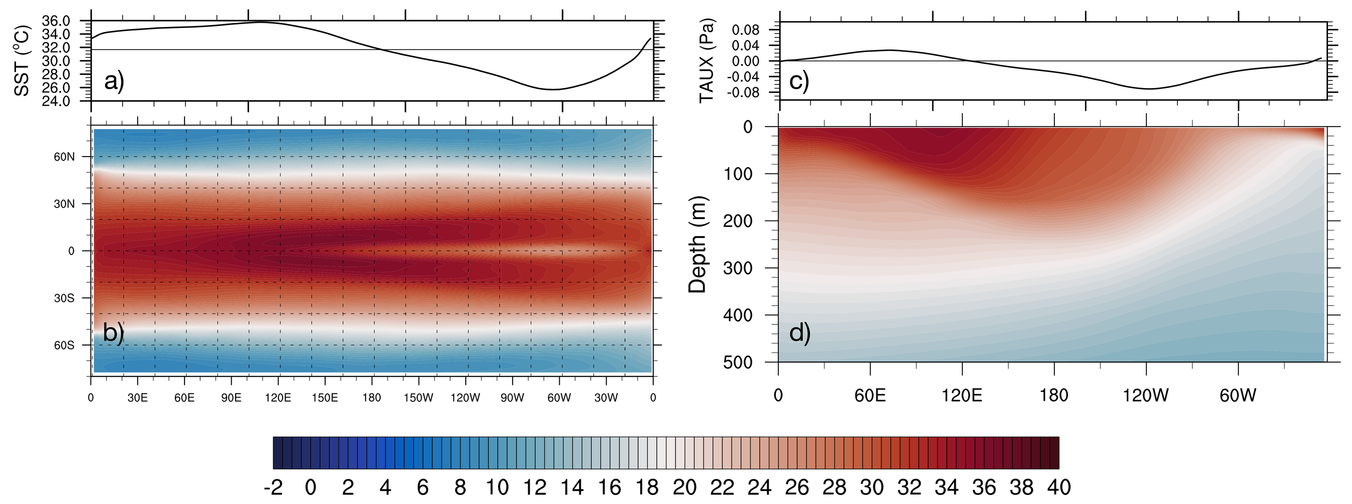

Fig. 3. Ocean climatology (Year 380-400) of CESM Ridge: (a) Equatorial SST (°C); (b) SST pattern (°C); (c) Zonal wind stress along the equator; (d) Equatorial transect of potential temperature (°C). The figures are aligned in longitude, with the ridge continent on the 0° meridian.

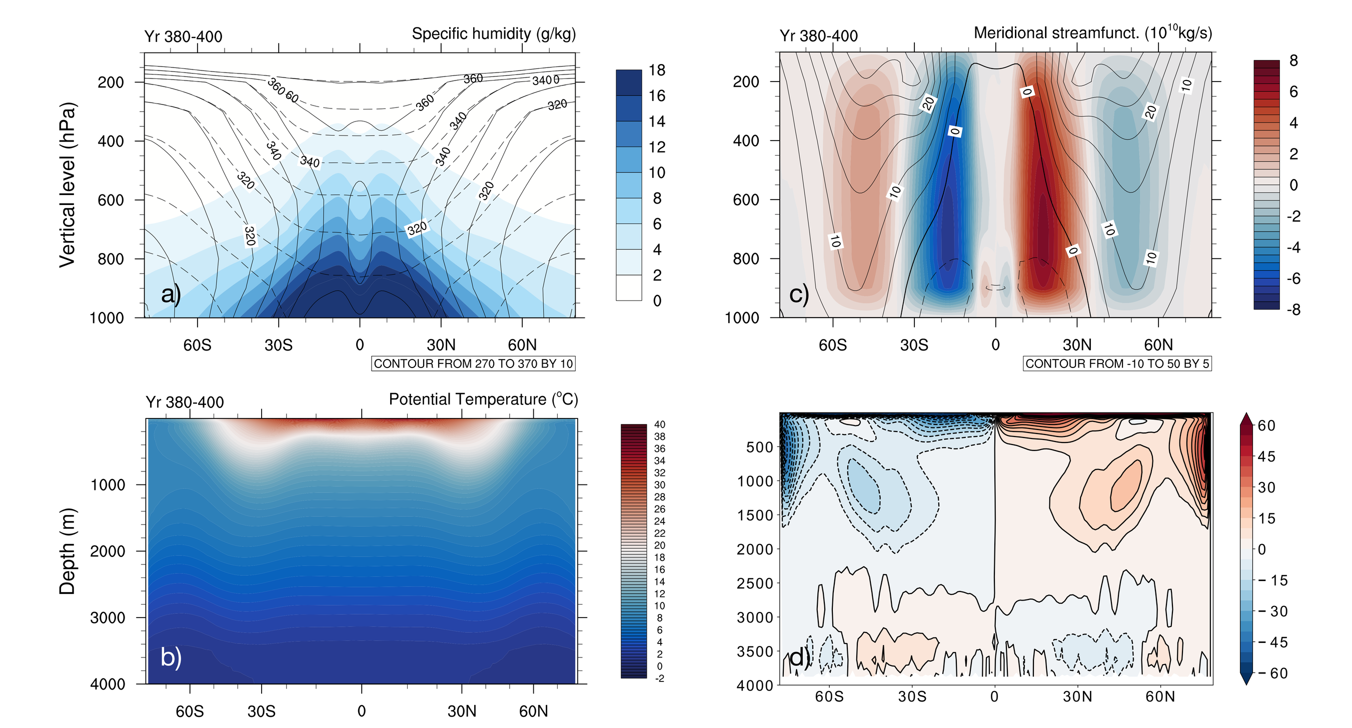

Fig. 4. Zonal mean climatology: (a) Atmospheric moisture (shaded), moist (K, solid) and dry (K, dashed) potential temperature; (b) Ocean potential temperature; (c) Atmospheric meridional overturning streamfunction (shaded) and zonal wind (contour lines); (d) Ocean meridional residual overturning streamfunction (Sv).

Data and Method

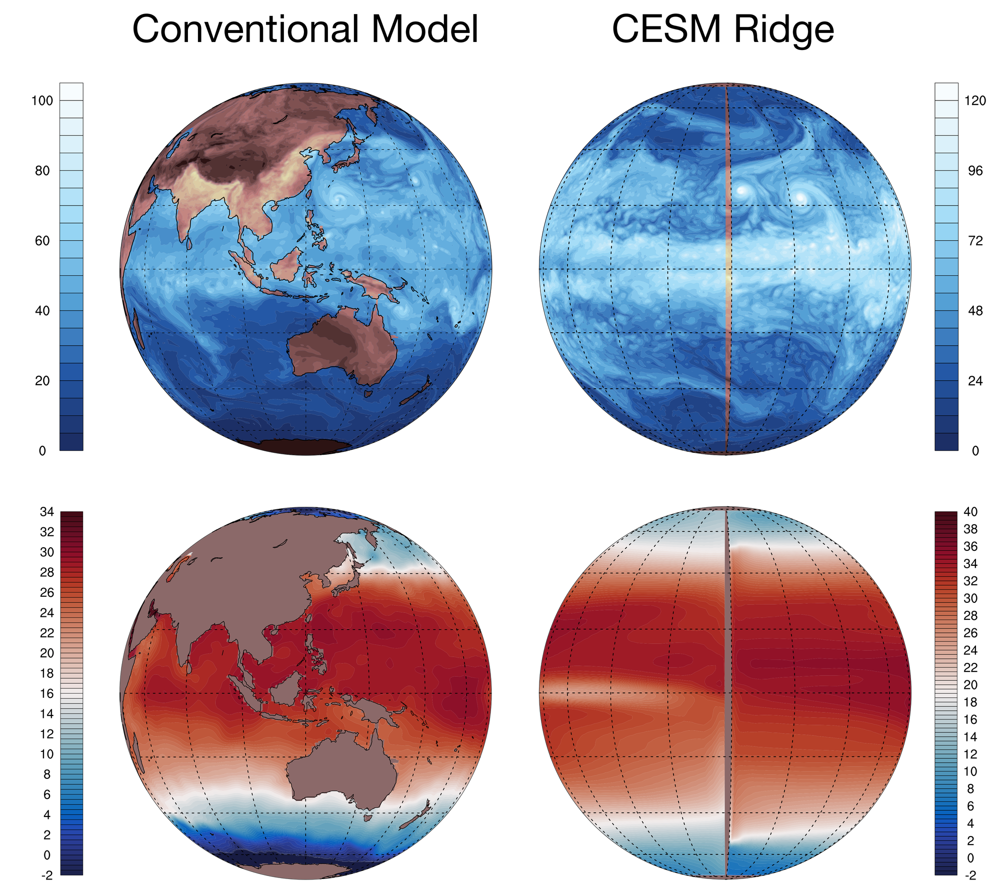

Fig. 1. Proof-of-concept for the simplified modeling framework. Top row: snapshots of simulated TCs, as seen in total precipitable water (kg/m²), using conventional (left) and idealized (right) models at 0.25° horizontal resolution; bottom row: the corresponding sea surface temperature (SST, °C) forcing, from observation (left) and the idealized, dynamical ocean component (right).

- A fully coupled climate model is configured with simplified land geometry. Known as the Ridge configuration in Enderton and Marshall (2009), an ocean basin is bounded by a single strip of pole-to-pole continent (Fig. 1, right column).
- Using the Community Earth System Model (CESM), the atmospheric component (CAM4) is at 1° horizontal resolution, and the ocean component (MOM6) is at nominal 2° horizontal resolution with equatorial refinement, and ocean maximum depth of 4000 m. The preliminary simulation is run for 400 years.

Result: Tropical Cyclone Genesis

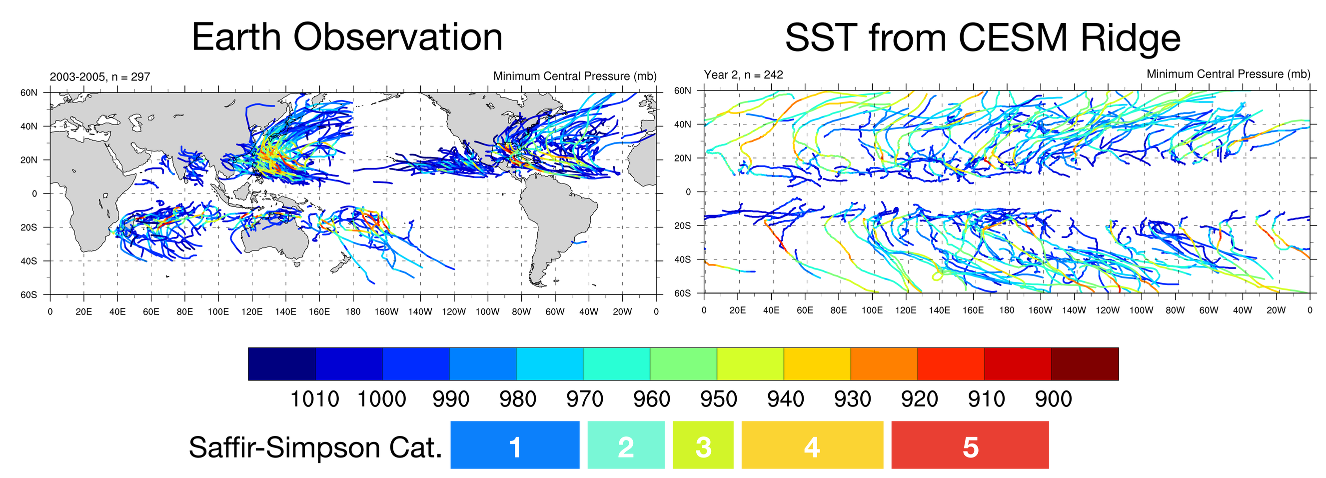

Fig. 5. TC tracks and intensity from: Left, three years of observation from the the International Best Track Archive for Climate Stewardship (IBTrACS, Knapp et al., 2010); Right, one year of atmosphere-only simulation at 0.25° horizontal resolution, forced by climatological SST from CESM Ridge (Fig. 3b).

Result: Top-of-Atmosphere Balance

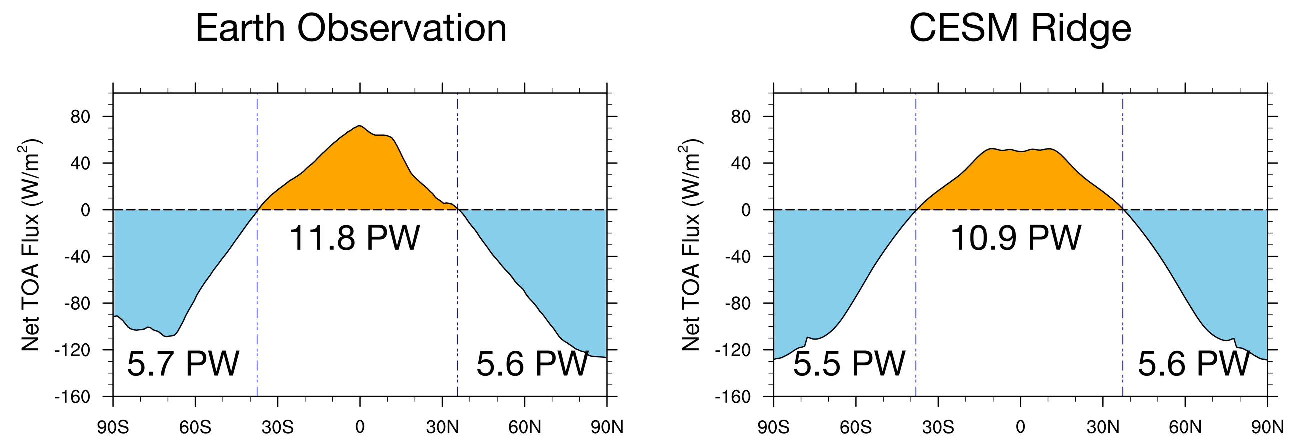

Fig. 2. Comparison between observed top-of-atmosphere fluxes (CERES EBAF-TOA 2005-2015 climatology, left) and CESM Ridge simulation, Year 380-400 (right). The CESM Ridge simulation is still equilibrating with a net imbalance of -0.25 W/m².

Discussion

- Simplified configurations, such as the Ridge, are promising tools for investigating the global ocean. The simplified configuration of the coupled model is planned to be released to the CESM community, potentially with other types of land geometries (see Appendix for Aqua).
- Understanding the SST pattern that affects TC genesis: What controls the location and intensity of the western warm pool?
- Next: Isolating the impact of TCs on ocean heat uptake and transport (Fig. 6).

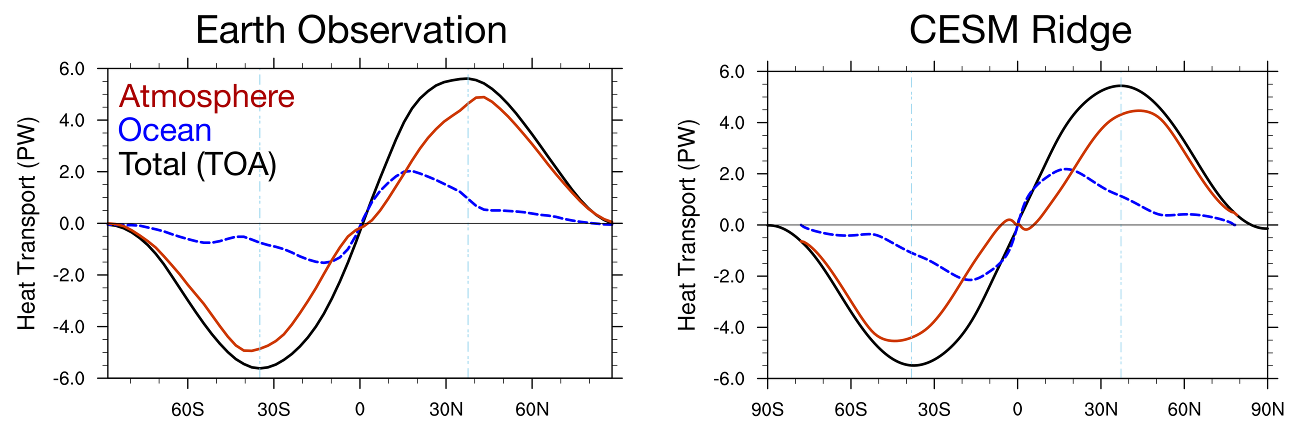

Fig. 6. Meridional heat transport by the atmosphere and the ocean. Left: Observation from Trenberth and Caron (2001); Right: CESM Ridge, where the equatorward heat transport by the atmosphere in the deep tropics is due to the equatorial upwelling that results in extensive cold surface waters (Fig. 3b).

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Appendix: CESM Coupled Aquaplanet

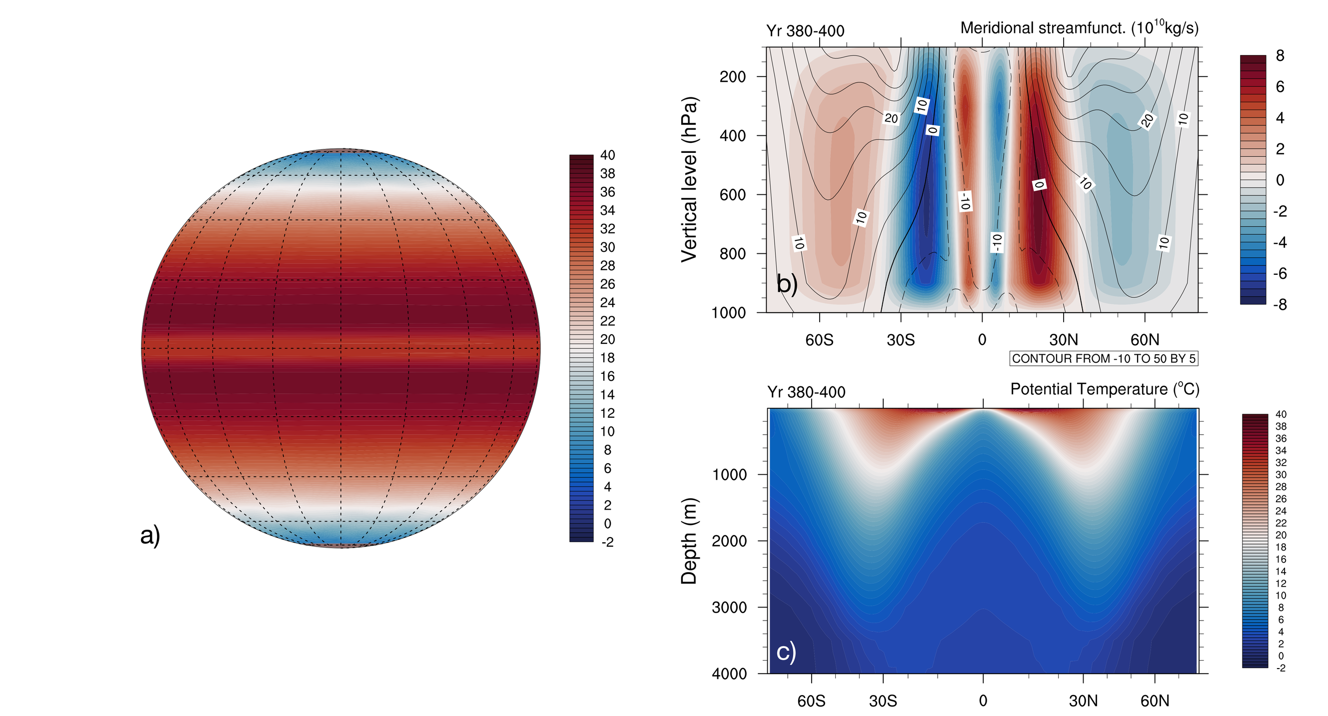

Fig. A1. CESM Aqua climatology (Year 380-400): (a) SST (°C, cf. Fig. 3b); (b) Atmospheric meridional overturning streamfunction (cf. Fig. 4c); (c) Zonal mean ocean potential temperature (cf. Fig. 4b).

- With a fully dynamical ocean, the coupled aquaplanet (Marshall et al., 2007; Farneti and Vallis, 2009) shows a drastically different climate from those of the atmosphere-only Aquaplanet Experiments (see Neale and Hoskins, 2001).
- Why is there a global cold "belt" of equatorial upwelling in the ocean?

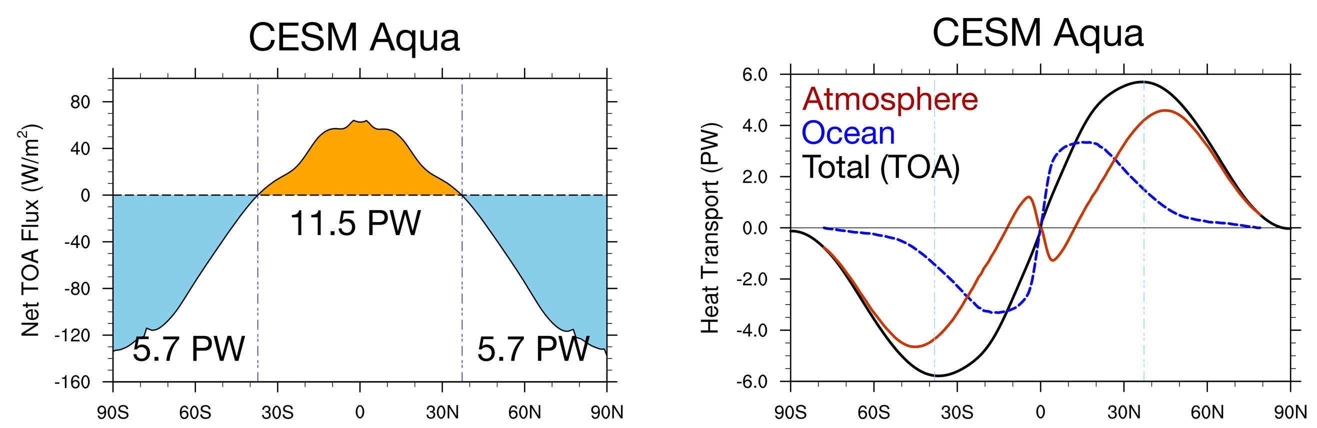

Fig. A2. CESM Aqua simulation (Year 380-400). Left: Top-of-atmosphere fluxes, equilibrating with a net imbalance of 0.20 W/m²; Right: Meridional heat transport. Note the equatorward heat transport by the atmosphere in the deep tropics, and the compensating increase in ocean heat transport compared to CESM Ridge (see Fig. 6, right).

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