COMMENTARY

Observational evidence supports the role of tropical cyclones in regulating climate

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Tropical cyclones are relatively rare weather events, yet they consistently rank among the world's deadliest and costliest natural hazards. In the United States, tropical cyclones account for nearly $10 billion annually in economic damages (1), and damages from Hurricane Sandy (2012) are estimated to be over $50 billion. Understanding the role of these events within Earth's climate system is of paramount importance to improving climate change projections and for constructing sound hazard assessments and adaptation strategies (2).

The relationship between tropical cyclone activity and global warming is a controversial topic. Observational evidence suggests variability in sea surface temperature is linked to changes in tropical cyclone activity (3–5). However, questions about the effect of global warming on tropical cyclones are not fully answered, and projections of the response of tropical cyclones to future climate change have significant uncertainties (6–9). Mounting evidence indicates that tropical cyclones are not passive players in Earth's climate system. Rather, the storms actively contribute to the dynamics of the global ocean (10–12) and atmosphere (13). Quantifying the role of tropical cyclones in the Earth system may improve our understanding of the nature of climate change and reduce uncertainty in climate projections. In PNAS, Mei et al. (14) help to fill this gap by providing valuable information about the effect of tropical cyclones on long-term warming of the global ocean. The authors employ innovative techniques using satellite altimetry to quantify changes in sea surface height in storm-affected regions during the months following tropical cyclones. Changes in sea surface height are closely linked to changes in ocean heat content (e.g., thermal expansion), thus these results enable direct estimates of the vertically integrated changes in ocean temperatures caused by tropical cyclones. Results shed much-needed light on the interactions between tropical cyclones, ocean mixing, and ocean heat uptake.

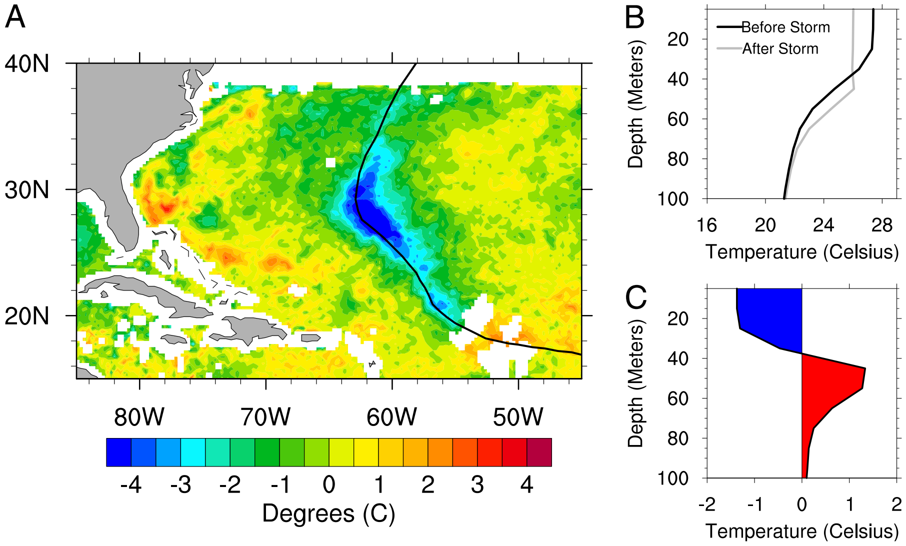

Fig. 1. Upper ocean response to Hurricane Gert, 1999. (*A*) Observed surface temperature anomaly showing cooling along the storm track primarily as a result of vertical ocean mixing [data from National Aeronautics and Space Administration (NASA)'s Tropical Rainfall Measuring Mission (TRMM) Microwave Imager]. (*B*) Vertical ocean temperature profiles averaged over Hurricane Gert's track before (black curve) and after (gray curve) the storm (analyzed using NASA ocean reanalysis ECCO2). (*C*) Difference between temperature profiles shown in *B*, highlighting the cool anomaly (above 40 m) and warm anomaly (below 40 m) following storm passage because of vertical ocean mixing.

The ocean plays a central role in determining the Earth's climate because it can accumulate enormous amounts of heat from the atmosphere and release it over long time periods. Mechanical ocean mixing provides an important source of energy that controls global circulation patterns and rates of ocean heat uptake (15). We currently lack a complete description of the physical processes responsible for this mixing. Identifying sources of mixing, as well as constraining mixing rates, is a major scientific challenge.

Although tropical cyclones are highly localized and relatively short-lived weather events, they produce vigorous bursts of ocean mixing. This mixing can disrupt the usually well-stratified tropical ocean conditions, redistributing ocean heat vertically in regions affected by the storms. The signature response of tropical cyclone-induced mixing is surface cooling along the storm paths, accompanied by warming within the ocean interior (Fig. 1). The vertical and horizontal extent of the mixing depends on the intensity, size, and translational speed of the storm, as well as the background ocean conditions (16).

Past studies have indicated that, when aggregated globally, tropical cyclones significantly contribute to global ocean mixing and energy budgets. The implications are that tropical cyclones can potentially contribute to ocean heat uptake and transport by pumping heat into the ocean interior (10–12). Because tropical cyclone activity is sensitive to ocean temperature, feedbacks may exist in the climate system between tropical cyclones, ocean mixing, and ocean heat content that are not captured in the current generation of climate models. This feedback may be important for understanding past and potential future changes in the Earth's climate system (17–19).

Previous efforts to quantify ocean heat pumping by tropical cyclones were limited by

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lack of information about subsurface ocean conditions, and they largely relied on the surface temperature response to tropical cyclones (Fig. 1*A*) to estimate changes in vertically integrated ocean heat content. The results of Mei et al. (14) significantly advance our understanding of the magnitude of tropical cyclone heat pumping by using satellite altimetry to estimate ocean heat content changes in the regions affected by the storms. The authors' techniques can detect small increases and decreases in sea surface height, which are closely linked to the thermal expansion and contraction of ocean water, thus providing a direct estimation of the changes in vertically integrated ocean heat content caused by tropical cyclone mixing and surface fluxes. The authors' techniques are unique in that they can directly monitor ocean heat content changes for months following storms. This method enables the authors to sort out the effect of tropical cyclones from seasonal changes in sea surface height and other background variability.

The authors find that tropical cyclones warm the ocean at a rate of ∼0.3 PW (1 PW = 1e15 Watts) during the period 1993–2010, which is more than 20-times the observed background warming rate within the equatorial regions and comparable to roughly 15% of the peak global poleward ocean heat fluxes. Results provide fresh evidence using comprehensive observational products to support the importance of tropical cyclones on global ocean dynamics by contributing to ocean mixing, heat budgets, and transports. Furthermore, Mei et al. (14) find that the magnitude of this heat pumping increases with tropical cyclone intensity.

Many recent theoretical and modeling assessments point toward an increase in tropical cyclone intensity with global warming, and these results support the possibility of a positive climate feedback. Under future warming, the number of intense tropical cyclones could increase, which would in turn potentially increase the rate of ocean warming. Because ocean temperature is closely linked to the maximum potential intensity of a tropical cyclone, the fraction of intense events could increase further, causing additional ocean warming and thus closing the feedback loop. The existence of such a feedback is somewhat speculative, but it has been proposed as an explanation for sustaining past warm climate conditions (17, 18) and warrants further examination in the context of current and future climate change.

Mei et al. significantly advance our understanding of the magnitude of tropical cyclone heat pumping.

The findings of Mei et al. (14) are not without limitations. For example, the upper-ocean response to tropical cyclones is largely controlled by the background conditions (e.g., stratification), which can vary by region and time of year (16). Because the authors use a composite method that aggregates the storms over all regions and time periods, it is not clear how the ocean response may differ based on the timing or location of the storms. The impact of these regional differences on basin-scale ocean dynamics requires further examination.

Additionally, seawater density depends not only on temperature, but also salinity. Tropical cyclones produce an enormous amount of rain, which can reduce salinity and potentially increase water volume along storm tracks. Any reduction in salinity because of the addition of freshwater from rain could mimic the effect of additional ocean heat on sea surface height, and perhaps bias estimates of changes in ocean heat content.

Regardless of the limitations, Mei et al. (14) support important links between tropical cyclones and climate. Whether the extra ocean heat induced by tropical cyclones remains in the tropical oceans, gets carried poleward by ocean currents, or is released back to the atmosphere in the following winter (20), these results provide definitive and unique evidence that tropical cyclones are important contributors to the climate system with implications on the dynamics of the global ocean (10–12, 16–19) and atmosphere (13, 19). Considering these effects—as well as possible feedbacks—in our theoretical and numerical models of Earth's climate system may improve our understanding of past climate changes and reduce uncertainty in future climate projections.

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