6B.7 Assessing the Climate Footprint of Tropical Cyclones: Pertinent Players or Irrelevant Pawns?

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1. Introduction

Despite the uncertainties in future projections of TC activity, significant deficiencies still remain in reconciling the significance of TCs within the climate. Recent prior research has suggested that TCs not only stabilize the environment in the area along the TC track (Schenkel and Hart 2011), but also potentially across entire basins as well (Sobel and Camargo 2005). Moreover, in addition to potentially altering meridional oceanic heat transport (e.g., Emanuel 2001), TCs have been found to modulate the atmospheric mid-latitude Rossby wave pattern (e.g., Riemer et al. 2008) and significantly reduce the hemispheric zonal available potential energy gradient through the transport of heat and moisture polewards (Cordeira 2010). Building upon previous work, the following study seeks to take the preliminary step in addressing the climate significance of TCs by examining the spatiotemporal response of the large scale environment to TC passage.

2. Data and Methods

In this study, four-dimensional storm-relative composites of raw anomalies and normalized anomalies are constructed from one month prior to one month after TC passage for all Saffir-Simpson category 3 to 5 (major) Western North Pacific (WPAC) TCs within the Best Track (Chu et al. 2002) from 1982 to 2009 (N=257 distinctly named TCs). The NCEP Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) is selected for use in this study due to previous work which has shown that the mean values of TC intensity and track within the CFSR are closest to those values in the Best Track compared to other members of the current generation of reanalyses (Schenkel and Hart 2012). A second set of composites of normalized mean sea level pressure anomalies filtered according to the methodology of Wheeler and Kiladis (1999) are constructed to quantify the role of convectively coupled equatorial waves in the generation of anomalies. These composites differ from the storm-relative composites in two ways: the domain is zonally periodic centered at the longitude at which the TC is located at and each gridpoint represents the average of all gridpoints within 5° meridionally of the equator at a given latitude.

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To attribute anomalies to physical processes, vertically integrated energy budgets are computed in the storm-relative composites according to the methodology of Trenberth (1997). For brevity, only the results for the sensible heat budgets are detailed in this study with the equation appearing as follows:

$$\frac{\partial}{\partial t}\frac{1}{g}\int_{p_t}^{p_s}(c_pT)dp = -\nabla\cdot\frac{1}{g}\int_{p_t}^{p_s}(\mathbf{v}c_pT)dp + \frac{1}{g}\int_{p_t}^{p_s}(\frac{c_pT\omega\kappa}{p})dp + Q_1 \qquad (1)$$

where c_p is the specific heat capacity of air at constant pressure, T is the temperature, p_s is the surface pressure, p_t is the pressure of the top model level (1 hPa), $\mathbf{v}$ is the horizontal velocity, ω is the vertical velocity, κ is $\frac{R}{c_p}$, R is the ideal gas constant for dry air, and Q_1 is the vertically integrated diabatic heating term. The diabatic heating term is composed of four subcomponents: the net downward radiative flux through the top of the atmosphere, the net downward radiative flux through the surface, the sensible heat flux through the surface, and the latent heat gain in the atmosphere due to precipitation.

3. Basin Scale Environmental Response within the Tropics to TC Passage

The composites exhibit a significant environmental response of 0.2σ to 0.4σ to TC passage in the normalized mean sea level pressure anomaly field at equatorial latitudes (Fig. 1) in spite of the fact that the composite TC did not directly pass through this region. These positive anomalies extend over a longitude band that is approximately 24% of the Earth's circumference. A vertical cross section of normalized temperature anomalies (Fig. 2a) reveals cold anomalies throughout most of the troposphere that are most significant at middle and upper levels with values between 0.2σ to 0.3σ. Further, a drying of the lower troposphere is found at southerly latitudes (not shown) coincident with the cold anomalies suggesting an anomalous stabilization of the equatorial environment following TC passage. Fig. 2b shows that these cold and dry anomalies are associated with anomalous subsidence at tropical latitudes.

The structure of the composited anomalies appears to be due two factors as seen in Fig. 3. First, there

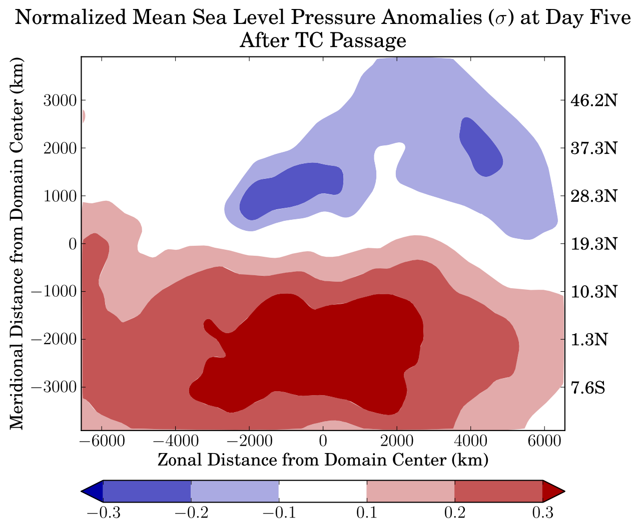

Fig. 1: Plan view of normalized mean sea level pressure anomalies (σ) in the composite domain at day five after major WPAC TC passage. Day five represents the time of peak environmental response to TC passage. The numbers near the right side of the figure represent the mean latitudes of the composite domain for major WPAC TCs.

is a suppression of precipitation due to the subsident secondary circulation outside the TC that likely yields substantial diabatic cooling anomalies (mean value of -23 W m^{-2}) particularly at middle and upper levels. Secondly, there is an anomalous low level horizontal flux divergence of heat and moisture yielding a cooling and drying of the lower troposphere (mean value of -37 W m^{-2}) as a result of the redirection of the monsoonal southwesterlies from the ITCZ into the TC. Although the pressure work term opposes these two terms due to anomalous subsidence, the horizontal flux divergence and diabatic heating terms yield a net cooling and drying of the troposphere over a 10° latitude band extending across the basin (not shown). These results suggest a local deceleration of the Hadley cell in response to the secondary circulation of the TC.

Filtering the composites in the wavenumber-frequency domain at the equator reveals that a convectively suppressed MJO event is partially responsible for the positive pressure anomalies helping to explain the length scales of the anomalies (Fig. 4). The timing of the anomalies relative to the TC together with the absence of a significant contribution from other equatorial waves suggests that TCs may be primarily responsible for the generation of the positive pressure anomalies especially given that the MJO, at most, comprises 36% of the maximum anomaly magnitude. Moreover, Fig. 4 also shows a convectively suppressed Kelvin wave emerging from the area of positive pressure anomalies following TC passage. This Kelvin wave is stronger, initiated farther to the east, and propagates farther eastwards than a second Kelvin wave found 35 days after the first wave during a subsequent convectively suppressed MJO event. The location, strength, and timing of the Kelvin wave relative to the TC suggest that the TC may either be responsible for *initiating* or *modulating* the Kelvin wave.

If TCs are responsible for the initiation of convectively suppressed Kelvin waves, then significant sensitivity in the atmospheric response may exist not only to TC structure, but also to the meridional location of the TC-induced cold and dry anomalies relative to the equator as suggested by previous

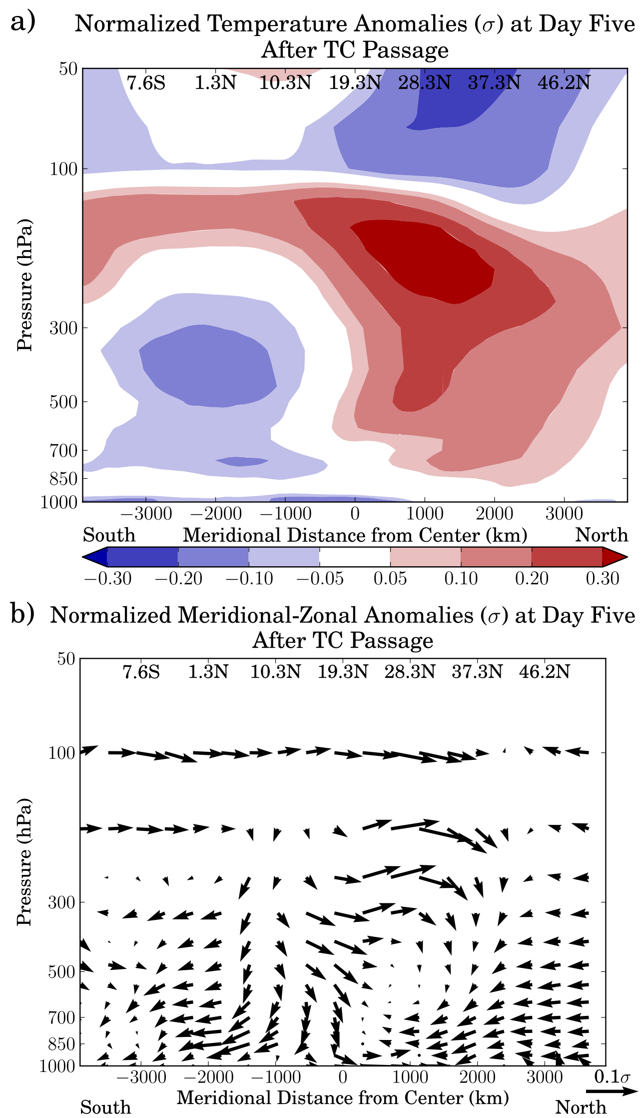

Fig. 2: Vertical cross section of (a) normalized temperature anomalies (σ) and (b) normalized meridional-vertical wind vector anomalies (σ) in the composite domain at day five after major WPAC TC passage. Each field is zonally averaged over the area enclosed by the 0.3σ mean sea level pressure contour found in Fig. 1. The vertical cross section is taken through the center of the composite domain from south to north.

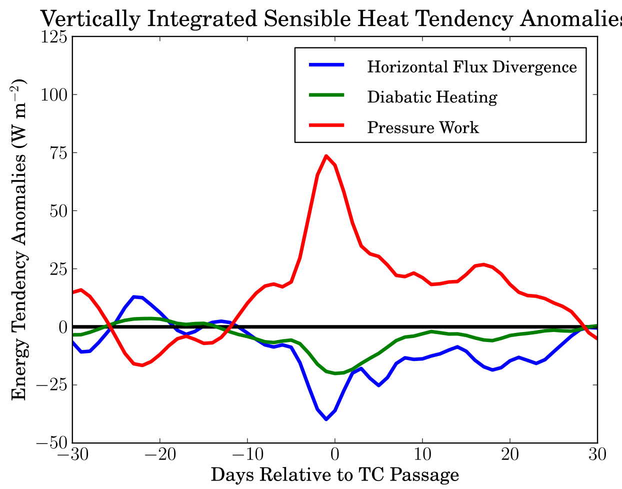

Fig. 3: Time series of raw vertically integrated sensible heat tendency anomalies (W m^{-2}) for the horizontal flux convergence of sensible heat term (blue), the diabatic heating term (green), and the pressure work term (red) areally averaged over the region enclosed by the 0.3σ mean sea level pressure contour found in Fig. 1. For reference, an anomalous heating tendency of 25 W m^{-2} corresponds to a heating rate of approximately 0.25 K m^{-2} day^{-1} throughout the entire troposphere.

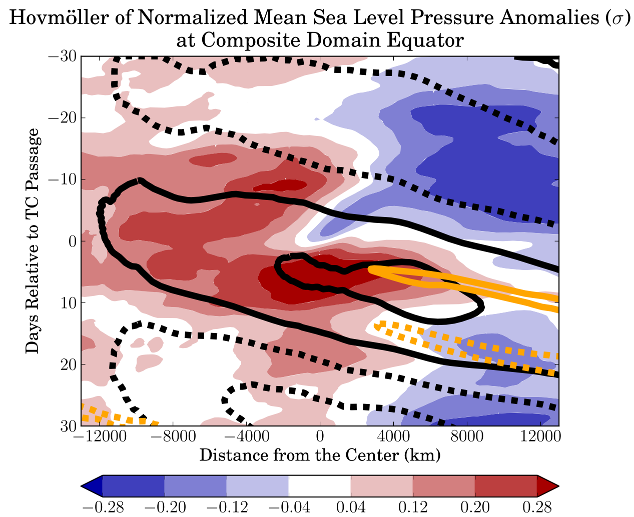

Fig. 4: Hovmöller of normalized mean sea level pressure anomalies (σ) in the composite domain for major WPAC TCs. Anomalies are averaged for all points within 500 km meridionally of the composite domain equator. The black (orange) contours denote the anomalies attributed to the MJO (Kelvin wave) wavenumber-frequency spectrum with dashed (solid) contours representing the convectively active (suppressed) phase for each equatorial wave.

work (e.g., symmetric versus antisymmetric diabatic cooling perturbations; Gill 1980). The generation of these waves may also suggest a mechanism whereby TCs inhibit the genesis of subsequent TCs potentially providing physical reasoning for why there is an observed preferential spacing of 1500 km to 1800 km between instances of multiple TCs within the Eastern North Pacific (EPAC), North Atlantic (NATL), and WPAC. The preferred spacing between TCs occurs in spite of the differences that are found between these three basins (e.g., genesis mechanisms, TC size). Lastly, the large scale response to TC passage in the WPAC differs from that in the EPAC and NATL possibly suggesting that the role of TCs varies among basins.

4. Broader Implications of TC Passage

The climate implications of TC passage also extend beyond the tropics given that the anomalous aggregation of heat and moisture by the TC is eventually transported out of the Hadley cell for 51% of major WPAC TCs. The concomitant increase in mean sea level pressure at the equator and the reduction in mean sea level pressure anomalies at poleward latitudes yields a significant decrease of 23% in the meridional pressure gradient of the WPAC, and potentially the strength of the Hadley cell, in the two weeks following TC passage. Further, the increase in the meridional pressure gradient of the WPAC by 9% in the two weeks prior to TC passage may suggest that TCs serve as an efficient mechanism for redistributing energy polewards once the meridional energy gradient has become too strong. Given that approximately 9 major TCs and 27 total TCs occur in the WPAC per year, questions remain concerning how the magnitude of the environmental response scales with the occurrence of multiple TCs given the preference for TC activity to cluster in time.

Instead of solely examining the impact of TCs upon the mid-latitudes or tropics, the results of this study argue for a more holistic view for the role of TCs within the climate as summarized in Fig. 5. Specifically, the triggering of convectively coupled equatorial waves by TCs may suggest a mechanism for ENSO modulation as a result of the westerly wind anomalies associated with TC-induced atmospheric Kelvin waves. Moreover, the composites also exhibit a significant Rossby wave response downstream of the TC at poleward latitudes as demonstrated by the significant negative normalized pressure anomalies located to the northeast of the domain center in Fig. 1. Furthermore, the polar jet is also displaced northward while the tropical easterly jet accelerates and broadens following TC passage. Lastly, the long residence time and substantial spatial scales of TC-induced sea surface temperature anomalies (e.g., Schenkel and Hart 2010) may, on the aggregate, imply that TCs serve as an efficient mechanism for regulating the temperature of the tropical oceans with impacts potentially extending into the subsequent winter. In their totality, these results strongly suggest that TCs are not just irrelevant pawns, but are instead pertinent players within the climate.

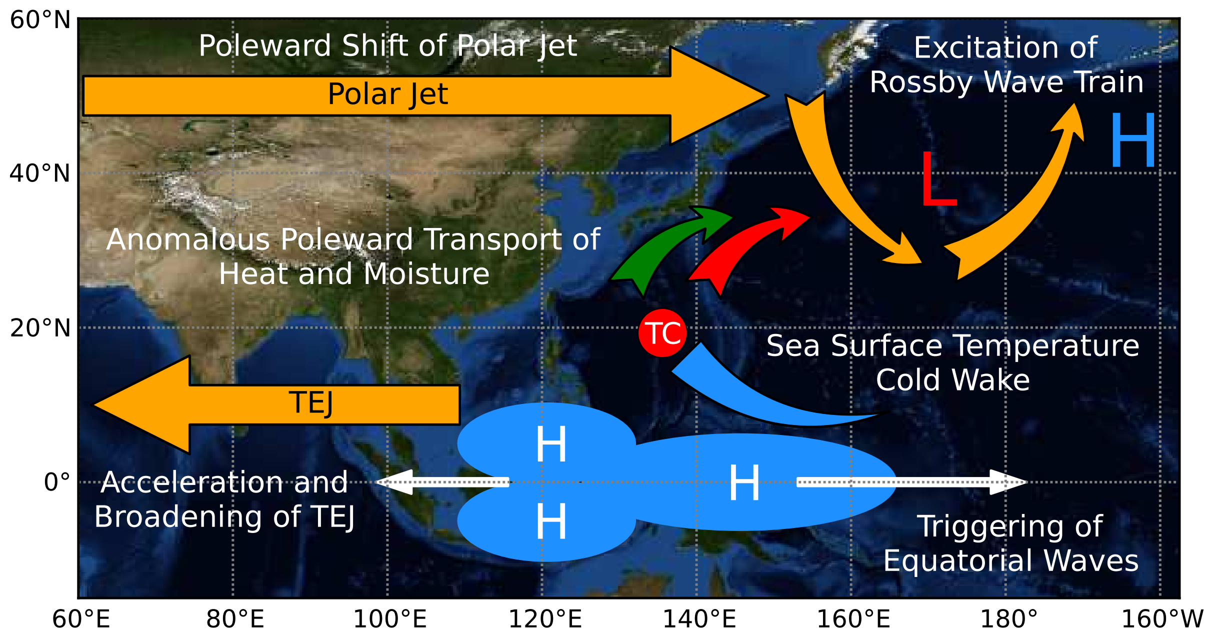

Fig. 5: Conceptual model depicting the impacts of TCs upon their large scale environment.

Acknowledgments

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