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Modeled sensitivity of upper thermocline properties to tropical cyclone winds and possible feedbacks on the Hadley circulation

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Modeled sensitivity of upper thermocline properties to tropical cyclone winds and possible feedbacks on the Hadley circulation

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[1] The sensitivity of upper thermocline properties, and global climate, to tropical cyclone (TC) winds is examined using global ocean and atmosphere general circulation models. We combine seven years of global, satellite-based TC wind records with a standard surface wind input data set derived from reanalysis, and we apply idealized factors to TC winds in order to model the ocean's equilibrium response to increases in TC intensities. We find TC-induced vertical ocean mixing impacts upper thermocline properties, such as temperature and mixed layer depth, and the effects are amplified for increasing intensities. The model's ocean heat transport is also affected, but only when TC winds are increased substantially compared to present-day values. Atmospheric model simulations show altered ocean temperature can lead to changes in the mean Hadley circulation. Results suggest increased TC activity may affect global climate by altering the ocean's thermal structure, which could be important for large scale ocean-atmosphere feedbacks. **Citation:** Sriver, R. L., and M. Huber (2010), Modeled sensitivity of upper thermocline properties to tropical cyclone winds and possible feedbacks on the Hadley circulation, *Geophys. Res. Lett.*, *37*, L08704, doi:10.1029/2010GL042836.

1. Introduction

[2] Vertical ocean mixing is important to the climate system, because it contributes to maintaining the large scale ocean circulation. Sources of this mixing remain poorly understood, particularly in the tropics, where mixing rates vary by an order of magnitude between observed estimates [*Ledwell et al.*, 1993] and energy budget requirements [*Schneider and Bhatt*, 2000]. Currently, most ocean general circulation models are unable to reproduce realistic oceanic transports without prescribing "background" mixing. These background values account for a variety of potentially unrepresented mechanisms, such as boundary mixing and internal wave breaking.

[3] A previous hypothesis [*Emanuel*, 2001] suggests that vertical ocean mixing caused by tropical cyclone (TC) surface winds may be responsible for the majority of the present-day global ocean heat transport (OHT) (~1.4 PW, 1 PW = 10^{15} Watts). Since TC activity is potentially related to changes in surface temperature patterns [*Emanuel*, 2005], feedbacks may exist enabling TC-induced mixing to be a key contributor to transitions in equilibrium climate states [*Emanuel*, 2002].

[4] Several recent studies have attempted to test *Emanuel*'s [2001] hypothesis. *Sriver and Huber* [2007] used reanalyzed surface temperature records and climatological vertical temperature profiles to estimate the amount of ocean mixing globally by TC's. They estimated vertical ocean heat pumping by TC mixing to be ~0.26 PW, with peak values reaching ~0.5 PW. Subsequent work utilizing higher resolution satellite-based temperature records refined these global estimates to ~0.4 PW, with peak values near 0.6 PW [*Sriver et al.*, 2008]. These results indicated a considerably smaller TC influence on mixing and associated OHT compared to *Emanuel*'s [2001] estimate. However, a key finding of these studies suggested annual vertical mixing rates are on the order of 1 cm^2/s in regions with pronounced TC activity, which is the same order of magnitude as background values prescribed in many current ocean models. Independent research [*Liu et al.*, 2008] using a coupled hurricane-ocean model yielded similar results, finding diapycnal diffusivity by TC's may be as high as ~6 cm^2/s.

[5] From a modeling perspective, *Korty et al.* [2008] found that introducing a climate-sensitive vertical diffusivity parameterization based on TC potential intensity—a quantity calculated from sea surface temperature, along with atmospheric humidity and temperature profiles—into a coarse-resolution ocean general circulation model had a positive influence on poleward OHT. Additionally, *Jansen and Ferrari* [2009] found the latitudinal distribution of tropical ocean mixing is critical to the response in poleward OHT. Enhanced vertical mixing away from the equator, within latitudinal bands typically experiencing the highest levels of TC activity, led to decreased OHT out of the deep tropics due to modified subtropical overturning. A separate modeling study [*Hu and Meehl*, 2009] that prescribed North Atlantic hurricane winds and precipitation in a coupled climate model suggested TC winds have a positive influence on the strength of the Atlantic meridional overturning circulation and poleward OHT. However, storm precipitation effects limited this response through increased poleward freshwater transport, promoting stable stratification in the mid-to-high latitude Atlantic and inhibiting deepwater formation.

[6] Here we investigate the role of TC's within the climate system by testing the sensitivity of modeled upper ocean properties to global TC winds using an ocean general circulation model. TC winds are derived from NASA's Quick Scatterometer (QuikScat). We apply idealized factors (1x, 2x, 3x) to TC wind speeds and analyze the equilibrium response of upper ocean properties. In order to explore the

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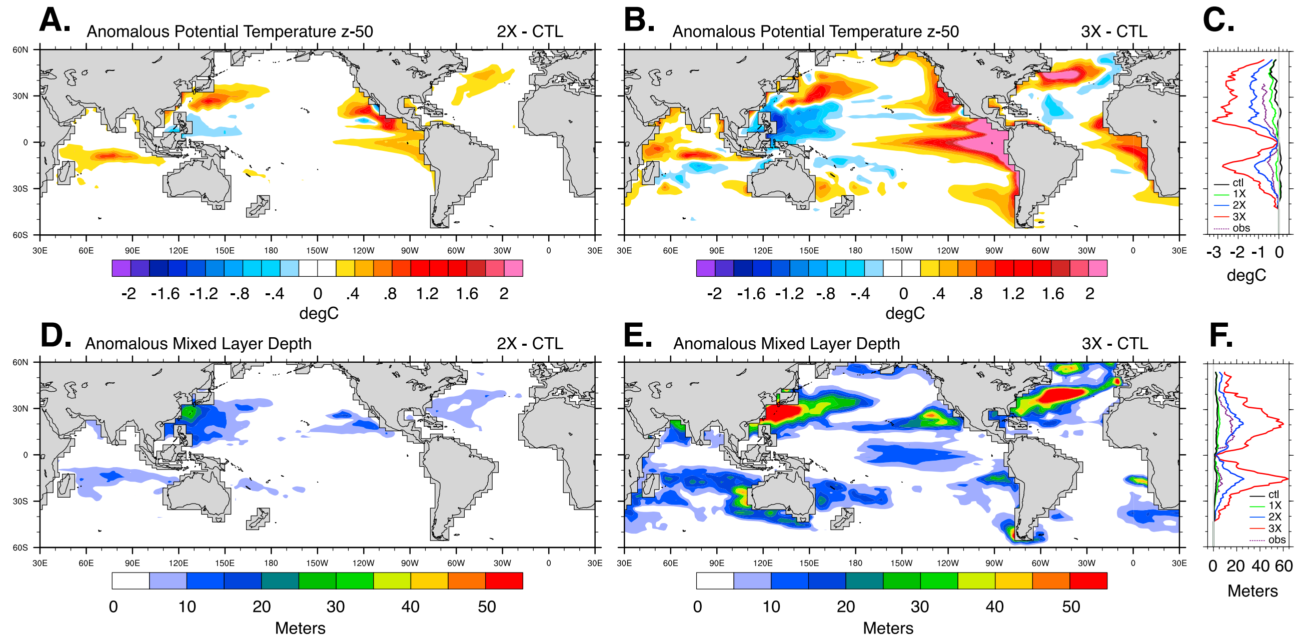

Figure 1. (a) Difference in mean ocean temperature at 50 meters depth between the 2X simulation and the control case. (b) Same as Figure 1a but for the 3X case. (c) Zonal average of the total mean annual anomalous sea surface temperature within storm wakes, calculated from the post-storm (7 days after passage) and pre-storm (3 days before passage) along-track temperature fields. Solid lines represent modeled response: black – CTL, green – 1X, blue – 2X, red – 3X. The dashed line represents anomalies derived from satellite-based temperature observations [*Sriver et al.*, 2008]. (d) Difference in mean mixed layer depth between the 2X simulation and the control. (e) Same as Figure 1d but for the 3X case. (f) Same as Figure 1c, but for anomalous mixed layer depth.

possibility of large scale ocean-atmosphere feedbacks caused by TC's, we use the resulting ocean thermal state as boundary conditions to atmosphere-only simulations. A primary goal of this work is to determine if the heat pumped vertically by TC mixing is transported poleward—a key assumption in several previous studies—using realistic TC wind fields. More generally, we aim to test the various separate predictions of the TC heat pump hypothesis by altering the model's input forcing. Crucially, we make no assumptions about how the energy is dissipated in the modeled ocean, i.e. we do not change the vertical mixing in the ocean. We also explore the large scale climatic impacts of this mixing.

2. Experimental Design

[7] We use components from the Community Climate System Model (CCSM3) [*Collins et al.*, 2006]. The ocean's grid contains 100 equally spaced and 116 variably spaced zonal and meridional grid points, respectively, and it contains 25 variably spaced vertical levels. The vertical level thickness increases monotonically with depth from 8 meters at the surface to 500 meters at the bottom. The atmosphere's grid is Gaussian and contains 128 zonal grid points, 64 meridional grid points (T42), and 26 vertical levels.

[8] Features of the ocean component include the Gent-McWilliams isopycnal transport parameterization, the K Profile Parameterization (KPP) for near-surface vertical mixing, and an anisotropic horizontal viscosity scheme [*Danabasoglu et al.*, 2006]. In addition, we use a new version of the model which includes a parameterization of diabatic mesoscale eddy fluxes along boundaries [*Ferrari et al.*, 2008], modified to apply only at the surface [*Danabasoglu et al.*, 2008]. Previous simulations using this parameterization have shown better modeled representation of upper OHT [*Danabasoglu et al.*, 2008].

[9] QuikScat winds were obtained from the Remote Sensing Systems (RSS), and we use the globally gridded wind fields (version 3) with spatial resolution 0.25° × 0.25°. Wind speeds are valid up to 50 m/s, signifying the limit to which the data exhibits good agreement with observations [*Brennan et al.*, 2009]. We created daily global wind fields consistent with the methods of *Sriver et al.* [2008]. TC wind footprints were sampled from these global fields using a 6° × 6° domain centered on Best Track locations for all storms globally from 2000–2006.

[10] Ocean model input is from the *Large and Yeager* [2004] bulk-forcing data sets, as part of the forcing for Common Ocean-Ice Reference Experiments (CORE) [*Griffies et al.*, 2008]. The atmospheric state combines reanalysis with satellite data, and surface fluxes are allowed to respond to evolving model sea surface temperature [*Large and Yeager*, 2004]. Precipitation fields are prescribed, and we apply weak salinity restoring to inhibit model drift [*Griffies et al.*, 2008]. We combined TC wind footprints derived from QuikScat with a 7 year interval of the interannual input winds. Simulations were carried out for 500 years, recycling the forcing fields corresponding to this 7 year interval.

[11] We performed 4 ocean-only simulations: 3 with TC wind forcing and a control. The "present day" TC simulation (1X) contains QuikScat-derived TC wind footprints combined with the standard wind input. The other two cases include enhanced TC winds with idealized factors (2x, 3x) applied to the global TC wind fields (cases 2X and 3X, respectively). As described below, the "1X" case underestimates

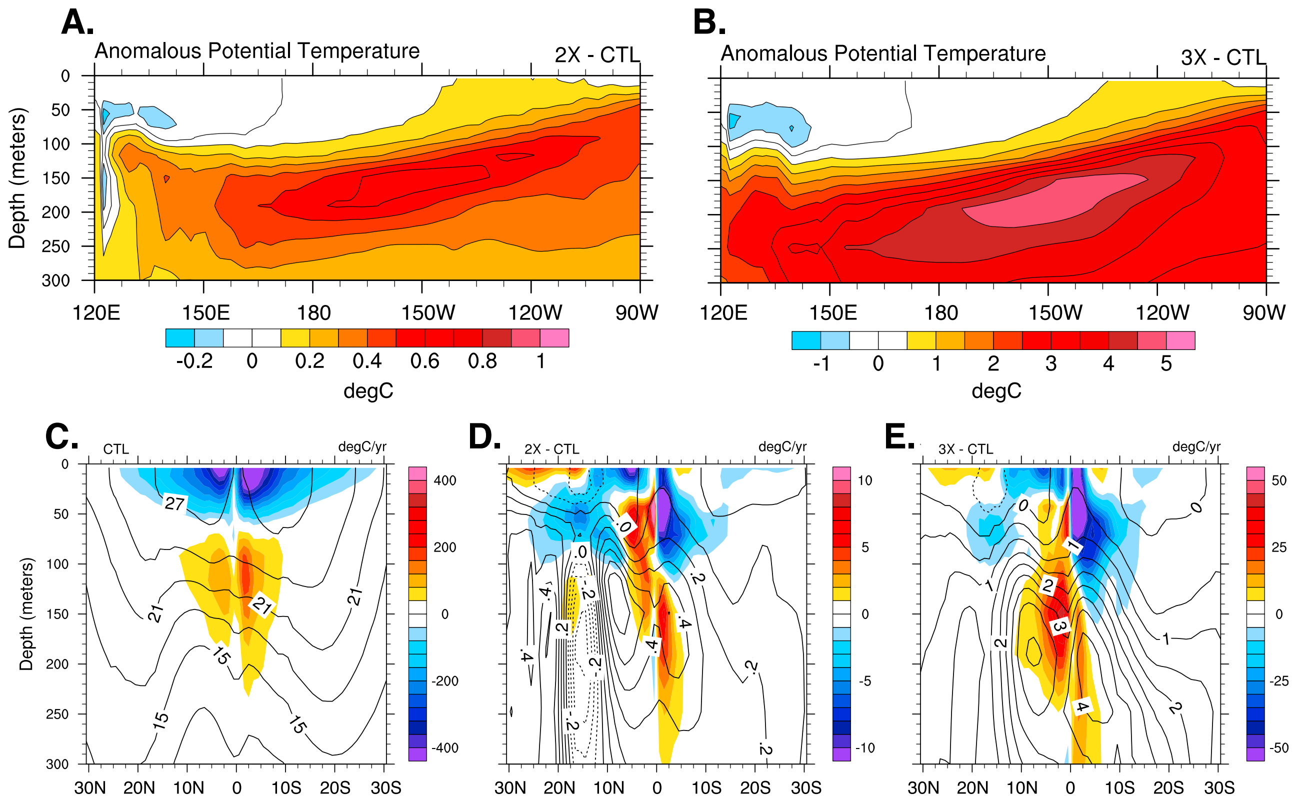

Figure 2. (a) Difference in mean equatorial Pacific temperature between the TC 2X simulation and the control case. (b) Same as Figure 2a but for the 3X case. (c) Equatorward heat convergence (color contour) in °C/yr averaged zonally across the Pacific basin for the CTL case. Black contours denote surfaces of constant potential temperature in °C. (d) Same quantities as in Figure 2c but for the difference between the 2X and CTL cases. (e) Same as Figure 2d but for the 3X case.

the true intensity of TC winds, so the nomenclature is only an approximate indicator of the changes in strength with respect to present-day values. The size, duration, and number of TC events are unchanged between runs. We performed 2 additional atmosphere-only simulations to explore the possibility of TC-induced feedbacks on the large scale atmospheric circulation. Boundary conditions were specified using the monthly mean 55-meter ocean temperatures from the 3X and control ocean simulations.

3. Results and Discussion

[12] We find modeled near-surface ocean temperature and mixed layer depth are sensitive to TC wind forcing, particularly for the cases with increased winds (Figure 1). Both of these responses are directly caused by enhanced vertical mixing associated with TC wind forcing. Figure 1 shows decreased surface temperatures accompanied by increased mixed layer depth in the regions experiencing the largest TC activity (see auxiliary material Figure S1), most notably in the northwestern Pacific region.[1] Here the heat pumping by TC's cools and deepens the mixed layer. Some of the heat pumped down into the ocean interior is advected poleward by the western boundary currents, evidenced by warmer midlatitude surface regions. The remainder of this heat remains in the tropics resulting in anomalously warm surface temperatures in the equatorial Pacific. This equatorial warming supports the idea that increased tropical ocean mixing may have contributed to maintaining permanent El Niño-like conditions during past warm climates, such as the early Pliocence (~5 to 3 million years ago) [*Brierley et al.*, 2009; *Fedorov et al.*, 2010].

[13] The model adequately simulates the transient response to TC wind forcing compared to global budgets of along-track surface cooling and mixed layer deepening [*Sriver et al.*, 2008] (Figures 1c and 1f). However, the 1X case under-represents TC effects compared to present-day estimates. The best general agreement occurs for the 2X case. There are several possible reasons for the lack of agreement between the 1X case and the satellite-based estimates. QuikScat is unable to retrieve reliable wind estimates greater than 50 m/s [*Brennan et al.*, 2009], thus the 1X case does not include TC wind conditions greater than category 2. Additionally, subsequent wind smoothing occurs during interpolation to the lower resolution necessary as input to the model. Specifically, our interpolation method is unable to retain the largest wind peaks or circulation structure of most events (which is also poorly resolved in globally gridded QuikScat winds). Finally, the model may be unable to accurately simulate vertical mixing in response to realistic TC surface wind forcing.

[14] Given these limitations in the QuikScat data and interpolation methods, the 1X winds are likely underestimates of the true TC winds speeds. Therefore, the 2X and 3X cases should not be regarded literally as increases in present-day TC intensity. Instead, these simulations are considered idealized scenarios representing systematic increases in global

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL042836.

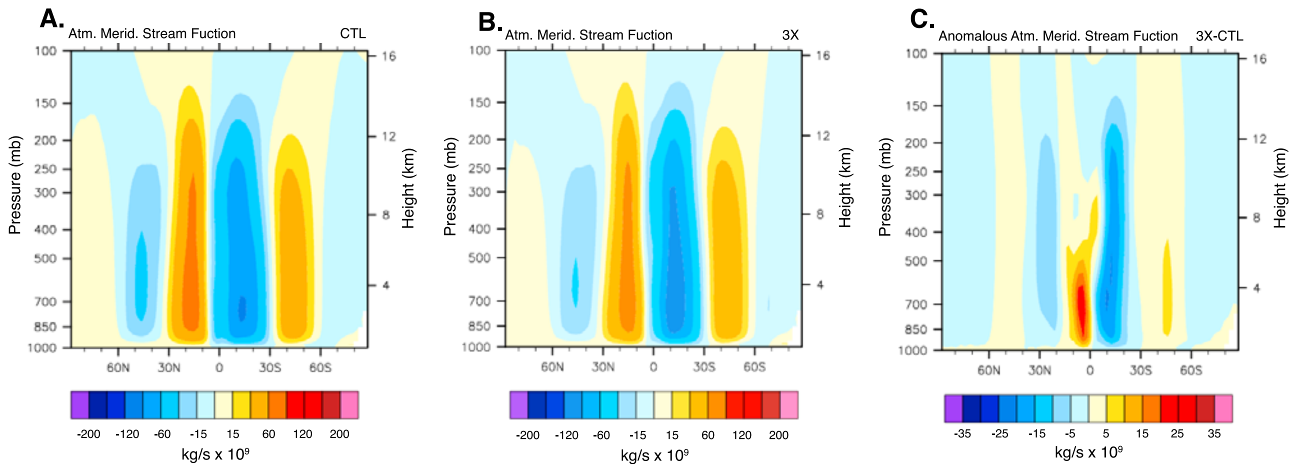

Figure 3. (a) Mean atmospheric meridional stream function for the CTL simulation. (b) Same as Figure 3a but for the simulation with input ocean temperature fields from the 3X case. (c) Atmospheric meridional stream function difference between the 3X and CTL cases.

TC intensities. This approach provides a useful framework for testing the modeled response to increased TC activity, and it is intended as a simple proof of concept.

[15] By adjusting the surface winds, we are capable of examining how much TC wind forcing is required to reproduce previous estimates of global mixing budgets. This approach differs significantly from previous modeling studies where TC mixing depths and magnitudes were simply prescribed. We find annual TC heat pumping to be 0.1, 0.3 and 0.8 PW for the 1X, 2X and 3X cases, respectively. The magnitude of the vertical heat pumping scales exponentially with TC wind speed. Earlier estimates derived from surface temperature measurements range from 0.3 to 0.4 PW [*Sriver and Huber*, 2007; *Sriver et al.*, 2008]. The 2X case most closely agrees with these previous estimates. This result, along with the global temperature and mixed layer depth budget analysis discussed previously, suggests the 2X scenario is likely the most realistic representation of the present-day TC contributions to the global ocean system.

[16] Since the upper boundary condition is not fully interactive, there is an implicit restoring effect by the prescribed atmosphere. While we cannot say with complete assurance whether the model's response for the 1X case is really smaller than reality, we are reasonably confident that TC impacts on heat convergence are under-represented in the model because the atmospheric restoring effect is important at longer temporal and larger spatial scales than used in these analyses [*Doney et al.*, 1998].

[17] We find modeled OHT to be sensitive to TC wind forcing, but only for cases with increased intensities (auxiliary material Figure S2). In general, modeled heat transport is consistent with the recent findings of *Jansen and Ferrari* [2009]. Specifically, TC's tend to inhibit transport out of the tropics, while they slightly increase poleward transport in the mid-latitudes. However, when TC winds are increased substantially (i.e. the 3X case), southern hemisphere poleward OHT is nearly doubled throughout most of the tropical latitudes, while northern hemisphere OHT is significantly decreased southward of 25°N. This effect primarily influences transport in the Pacific basin. Here the majority of heat transport in lower latitudes is achieved by the shallow, wind-driven subtropical overturning circulation. This circulation is less important in the Atlantic basin, where the deeper meridional overturning circulation is dominant.

[18] The shallow wind-driven circulation is an important contributor to meridional heat transport equatorward of 30°, particularly in the Pacific basin. These subtropical cells can be described by poleward Ekman transport at the surface and equatorward return flow at depth [*Klinger and Marotzke*, 2000]. Recent results suggest at least some of the heat mixed vertically by TC's may circulate equatorward via the return branch of the subtropical overturning cells [*Jansen and Ferrari*, 2009], thereby deceasing OHT out of the tropics. Our modeled near-surface temperatures exhibit an anomalously warm equatorial Pacific (Figures 2a and 2b) in the uppermost 300 meters, resulting from increased tropical heat convergence (Figures 2c–2e) in the return branch of the subtropical cell (and decreased divergence near the surface in the northern hemisphere).

[19] The El Niño-like temperature pattern is amplified for increasing TC intensity (Figures 1 and 2), and it is particularly sensitive to TC activity in the western Pacific. As heat in the upper ocean is mixed down into the thermocline by TC mixing in the northwestern Pacific, the excitation of equatorial Kelvin and Yanai waves contributes to transporting the anomalous heat into the equatorial undercurrent. It is eventually upwelled in the eastern equatorial Pacific, resulting in an anomalously warm "cold" tongue of the eastern Pacific with a diminished zonal temperature gradient along the equator.

[20] Increasing TC wind forcing significantly affects the dynamics of the subtropical overturning in the Pacific basin, thus altering the near-surface temperature patterns. Such changes would likely influence the large scale mean atmospheric state (e.g. the Hadley Circulation), since both the ocean's and atmosphere's meridional overturnings are largely controlled by the same surface wind forcing [*Held*, 2001]. Using CAM3, the atmospheric component of CCSM, we explore the possibility of TC-induced changes in the Hadley circulation by using the monthly near surface anomalous ocean temperatures from the 3X case as input to an atmosphere-only simulation. We find the TC-induced ocean temperature patterns enhance the Hadley circulation in the tropics, as shown in the atmospheric meridional

stream function (Figure 3). The response is particularly sensitive in the southern hemisphere, which is consistent with the ocean's heat transport response to increased TC winds (Figures 2c–2e and auxiliary material Figure S2).

[21] In general, we see a strengthening of the Hadley circulation in both hemispheres, accompanied by a slight equatorward shift of the northern hemisphere cell. There is no evidence of a poleward expansion of the overturning in either hemisphere, though we note the T42 atmosphere resolution may be incapable of capturing a modest expansion. Our findings contradict recent results [*Brierley et al.*, 2009] that suggest a decrease in the Hadley circulation strength, along with a poleward expansion, associated with an expanded warm pool in the tropical Pacific caused by enhanced vertical ocean mixing. While these atmosphere model results may be model-dependent, they reflect the potential implications that TC-induced changes of the upper ocean state may have on the mean atmospheric circulation in the tropics.

4. Conclusions

[22] Using an ocean general circulation model, it is shown that TC wind forcing is capable of altering upper thermocline properties via enhanced vertical ocean mixing. These effects have several important climatic consequences, including altered upper ocean thermal structure resulting in a permanent El Niño-like temperature pattern in the equatorial Pacific ocean. Additional results from an atmosphere general circulation model suggest the likelihood for large scale ocean-atmosphere feedbacks associated with increased TC intensities and ocean mixing. These feedbacks may be capable of increasing the mean atmospheric Hadley circulation in the tropics.

[23] Our methodology has several limitations, including a lack of fully interactive coupling between oceanic and atmospheric processes. Currently, it is still unclear how best to represent such interaction accurately and fully while still maintaining a system simple enough to be tractable. Future work is needed to better explore large scale ocean-atmosphere feedbacks associated with TC activity.

[24] **Acknowledgments.** The authors thank Gokhan Danabasoglu for supplying modified CCSM ocean model code containing the diabatic mesoscale flux parameterization, and Steven Yeager for providing guidance in implementing the *Large and Yeager* [2004] data sets. We also thank James C. McWilliams and Raffaelle Ferrari for constructive feedback. QuikScat data are produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team. QuikScat data are available at www.remss.com. This work was supported by grant NSF ATM 0741797 to M. Huber. R. Sriver's research was supported by the NOAA Climate and Global Change Postdoctoral Fellowship Program, administered by the University Corporation for Atmospheric Research. The authors acknowledge the use of the NCAR Command Language (NCL) in the data analysis and visualization herein.

References

Brennan, M. J., C. C. Hennon, and R. D. Knabb (2009), The operational use of QuikSCAT ocean surface vector winds at the National Hurricane Center, *Weather Forecast.*, *24*, doi:10.1175/2008WAF2222188.1.

Brierley, C. M., et al. (2009), Greatly expanded tropical warm pool and weakened Hadley circulation in the Early Pliocene, *Science*, *323*, doi:10.1126/science.1167625.

Collins, W. D., et al. (2006), The community climate system model version 3 (CCSM3), *J. Clim.*, *19*, 2122–2143, doi:10.1175/JCLI3761.1.

Danabasoglu, G., et al. (2006), Diurnal coupling in the tropical oceans of CCSM3, *J. Clim.*, *19*, 2347–2365, doi:10.1175/JCLI3739.1.

Danabasoglu, G., R. Ferrari, and J. C. McWilliams (2008), Sensitivity of an ocean general circulation model to a parameterization of near-surface eddy fluxes, *J. Clim.*, *21*, 1192–1208, doi:10.1175/2007JCLI1508.1.

Doney, S. C., W. G. Large, and F. O. Bryan (1998), Surface ocean fluxes and water-mass transformations rates in the coupled NCAR Climate System Model, *J. Clim.*, *11*, 1420–1441, doi:10.1175/1520-0442(1998)011<1420:SOFAWM>2.0.CO;2.

Emanuel, K. A. (2001), The contribution of tropical cyclones to the oceans' meridional heat transport, *J. Geophys. Res.*, *106*, 14,771–14,781, doi:10.1029/2000JD900641.

Emanuel, K. A. (2002), A simple model of multiple climate regimes, *J. Geophys. Res.*, *107*(D9), 4077, doi:10.1029/2001JD001002.

Emanuel, K. A. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686–688, doi:10.1038/nature03906.

Fedorov, A. V., C. M. Brierley, and K. Emanuel (2010), Tropical cyclones and permanent El Nino in the early Pliocene epoch, *Nature*, *463*, doi:10.1038/nature08831.

Ferrari, R., J. C. McWilliams, V. M. Canuto, and M. Dubovikov (2008), Parameterization of eddy fluxes near oceanic boundaries, *J. Clim.*, *21*, 2770–2789, doi:10.1175/2007JCLI1510.1.

Griffies, S. M., et al. (2008), Coordinated ocean-ice reference experiments (COREs), *Ocean Modell.*, *26*, 1–46, doi:10.1016/j.ocemod.2008.08.007.

Held, I. M. (2001), The partitioning of the poleward energy transport between the tropical ocean and atmosphere, *J. Atmos. Sci.*, *58*, 943–948, doi:10.1175/1520-0469(2001)058<0943:TPOTPE>2.0.CO;2.

Hu, A., and G. A. Meehl (2009), Effect of the Atlantic hurricanes on the oceanic meridional overturning circulation and heat transport, *Geophys. Res. Lett.*, *36*, L03702, doi:10.1029/2008GL036680.

Jansen, M., and R. Ferrari (2009), The impact of the latitudinal distribution of tropical cyclones on ocean heat transport, *Geophys. Res. Lett.*, *36*, L06604, doi:10.1029/2008GL036796.

Klinger, B. A., and J. Marotzke (2000), Meridional heat transport by the subtropical cell, *J. Phys. Oceanogr.*, *30*, 696–705, doi:10.1175/1520-0485(2000)030<0696:MHTBTS>2.0.CO;2.

Korty, R. L., K. A. Emanuel, and J. R. Scott (2008), Tropical cyclone-induced upper-ocean mixing and climate: Application to equable climates, *J. Clim.*, *21*, 638–654, doi:10.1175/2007JCLI1659.1.

Large, W. G., and S. G. Yeager (2004), Diurnal to decdal global forcing for ocean and sea-ice models: the data sets and flux climatologies, *NCAR Tech. Note NCAR/TN-460+STR*, 105 pp., Natl. Cent. for Atmos. Res., Boulder, Colo.

Ledwell, J. R., A. J. Watson, and C. S. Law (1993), Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment, *Nature*, *364*, 701–703, doi:10.1038/364701a0.

Liu, L. L., W. Wang, and R. X. Huang (2008), The mechanical energy input to the ocean induced by tropical cyclones, *J. Phys. Oceanogr.*, *38*, 1253–1266, doi:10.1175/2007JPO3786.1.

Schneider, E. K., and U. S. Bhatt (2000), A dissipation integral with application to ocean diffusivities and structure, *J. Phys. Oceanogr.*, *30*, 1158–1171, doi:10.1175/1520-0485(2000)030<1158:ADIWAT>2.0.CO;2.

Sriver, R. L., and M. Huber (2007), Observational evidence for an ocean heat pump induced by tropical cyclones, *Nature*, *447*, 577–580, doi:10.1038/nature05785.

Sriver, R. L., M. Huber, and J. Nusbaumer (2008), Investigating tropical cyclone-climate feedbacks using the TRMM Microwave Imager and the Quick Scatterometer, *Geochem. Geophys. Geosyst.*, *9*, Q09V11, doi:10.1029/2007GC001842.

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