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Impact of the latitudinal distribution of tropical cyclones on ocean heat transport

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[1] The heavy winds associated with tropical cyclones generate strong upper ocean mixing. Recent studies suggest that this enhanced mixing significantly contributes to the ocean poleward heat transport, mainly due to a strengthening of the subtropical cells. A general circulation model is used here to show that whether the poleward heat transport is actually increased depends crucially on the latitude band where mixing is enhanced. If upper ocean mixing is enhanced everywhere within 30° of the equator, poleward heat transport is increased. However, if mixing is enhanced solely in the subtropical bands, where tropical cyclones are observed, the poleward heat transport out of the deep tropics is decreased. **Citation:** Jansen, M., and R. Ferrari (2009), Impact of the latitudinal distribution of tropical cyclones on ocean heat transport, *Geophys. Res. Lett.*, *36*, L06604, doi:10.1029/2008GL036796.

1. Introduction

[2] The heat transport by the atmosphere-ocean system is crucial to maintaining the observed global climate. The ocean circulation dominates the heat transport in the northern hemispheric (NH) tropics and accounts for about half of the transport in the SH tropics. Poleward of about 20° the heat transport is dominated by the atmosphere [e.g., *Wunsch*, 2007]. The ocean heat transport (OHT) is understood to be primarily driven by subtropical wind-driven cells, with a smaller contribution by deeper overturning circulations [e.g., *Boccaletti et al.*, 2005].

[3] *Emanuel* [2001] suggested that the ocean mixing, driven by the strong surface winds in tropical cyclones (TCs) is an unappreciated contributor to the ocean circulation and heat transport in the tropics. The argument goes that TC-induced mixing events pump warm surface waters into the ocean interior which can propagate poleward and contribute to total OHT. *Emanuel* [2002] used a simple box model to show that the feedback of TC mixing on OHT could have an impact on the Earth's climate system and its variability. The TC-feedback allowed for multiple equilibrium states, with strong equator to pole temperature gradients, like today, and weak equator-to-pole temperature gradients, like in equable climates.

[4] *Emanuel* [2001] estimated the column integrated ocean heat uptake in the wake of TCs during the year 1996 to be 1.4 ± 0.7 PW. *Sriver and Huber* [2007] and *Sriver et al.* [2008] repeated the calculation, using a more extensive data set, but a somewhat cruder model, and found an averaged TC induced ocean heat uptake of about 0.48 PW for the years 1998–2005. If this heat was to be transported poleward, it would constitute 25–50% of the peak meridional OHT. However, the question of whether the heat pumped into the ocean by TCs is transported poleward, was not addressed in these studies.

[5] Analyzing the transient response of sudden mixing events in a GCM, *Pasquero and Emanuel* [2008] found that "the anomalous warm subsurface water in the perturbed area is advected toward lower latitudes over most of the ocean basins". This finding was, however, not further discussed in the context of the role of TC mixing on poleward OHT.

[6] *Korty et al.* [2008] studied the effect of TC induced mixing on the meridional OHT using a coarse resolution ocean general circulation model (OGCM). They showed that increased upper ocean mixing in the tropics and subtropics makes the poleward OHT larger, mainly due to a strengthening and deepening of the subtropical Ekman-cells. The pictures in their paper suggest that the increase in poleward OHT is less pronounced in simulations where mixing was not increased within ±4° of the equator. However the simulations with and without an equatorial gap are not directly comparable, and no explanation was given for this result. Our goal is to study the sensitivity of OHT to the latitude band where mixing is increased.

[7] The relationship between upper ocean mixing and OHT is best illustrated in terms of the vertically and zonally integrated ocean heat budget, in steady state,

$$\frac{1}{a}\frac{\partial}{\partial\phi}OHT \equiv \frac{1}{a}\frac{\partial}{\partial\phi}\int_{-H}^{0}\overline{\rho c_p v\theta}dz = \overline{Q}_s(\phi). \qquad (1)$$

Here a denotes the Earth's radius, ϕ is the latitude, the overbar denotes a zonal and temporal average, and Q_s is the surface heat flux. Equation (1) states that any OHT divergence is associated with a surface heat flux. Hence any increase in ocean heat uptake $\overline{Q}_s$ resulting from TC mixing, must drive an OHT out of the region spanned by TC activity. If TC mixing spans the whole tropics, then the additional heat flux can only go poleward. However, Figure 1 shows that TC power dissipation rapidly drops equatorwards of about 10°, suggesting that the additional ocean heat uptake due to TC mixing is confined to off-equatorial bands between 10°–30°. The heat uptake can therefore be compensated either by an increased OHT on the poleward side of these bands and/or by an increased OHT into the deep tropics (here defined as the equatorial band where TC induced mixing is absent). The latter would effectively result in a reduced poleward OHT out of the deep tropics. The fate of the heat pumped into the ocean is crucial to assessing the impact of TCs on Earth's climate,

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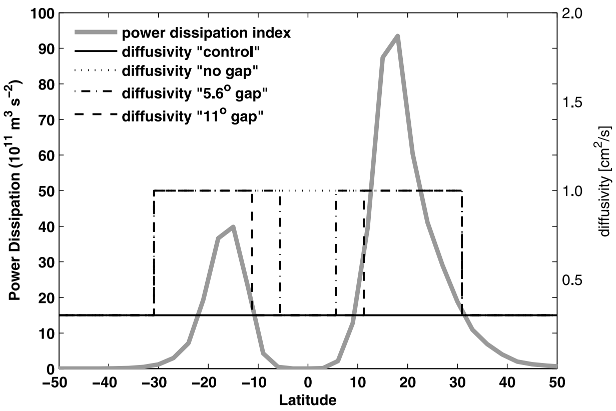

Figure 1. Latitudinal distribution of the tropical cyclone power dissipation index [*Emanuel*, 2005] integrated over the 1980–2007 time period. The tropical cyclone power dissipation does not exceed the background power dissipation for JAS, as calculated from the NCEP/NCAR reanalysis data, equatorward of about 10. The black lines show the latitudinal distribution of the upper ocean vertical diffusivity used in the four different model runs (see legend).

especially in the deep tropics where the OHT dominates over the atmospheric one. The question is here addressed by examining, with a numerical model, the sensitivity of the OHT to increased upper ocean mixing in different latitudinal bands.

2. Model

[8] We use the MIT OGCM with a horizontal resolution of 2.8° and 15 vertical levels [*Marshall et al.*, 1997]. Geostrophic eddies are parameterized with the *Gent and McWilliams* [1990] and *Redi* [1982] schemes, tapered as proposed by *Large et al.* [1997]. Convection is represented with an adjustment scheme [*Marshall et al.*, 1997], and diapycnal mixing is parameterized using a turbulent diffusivity. Due to the coarse vertical resolution, no explicit mixed layer parameterization is used. The surface heat and fresh water fluxes are each the sum of two terms: an imposed flux and a restoring term proportional to the difference between surface values and a monthly mean climatology [*Jiang et al.*, 1999]. The restoring timescales are 60 days for temperature and 90 days for salinity. This allows the surface fluxes to adjust to changes in SST resulting from TC-induced mixing. The model is initialized from Levitus climatology, forced with monthly mean climatological surface wind stresses [*Trenberth et al.*, 1990], and run to equilibrium for 8000 years. Statistics are computed from a 100 year interval once the model has achieved equilibrium.

[9] Four simulations are described in the paper. The "control" run uses a constant diapycnal diffusivity of $\kappa = 0.3 \times 10^{-4}$ m^2/s, a typical open ocean value [*Ledwell et al.*, 1998], and is here taken to represent a climate with no TCs. In the other three simulations, the mixing induced by TCs is represented by an increased diffusivity, $\kappa = 10^{-4} m^2/s$, in the upper 170m. The strength of the increased mixing is slightly higher than the diffusivity attributable to TCs in the present climate as estimated by *Liu et al.* [2008] and *Sriver et al.* [2008].The results below would change quantitatively, but not qualitatively, if the TC induced κ was somewhat reduced. The three simulations differ in the latitude intervals where κ is increased. In the "no gap" run, κ is increased equatorward of 31° latitude. In the "5.6° gap" run, κ is increased in the 31°S–5.6°S and 5.6°N–31°N bands, i.e., κ is not increased in a gap of 5.6° latitude around the equator. In the "11° gap" run, κ is increased in the 31°S–11.2°S and 11.2°N–31°N bands. The choice of the latitudinal bands where upper ocean mixing is enhanced is motivated by the latitudinal distribution of observed TC power dissipation (Figure 1).

3. Results

[10] Figure 2a shows the total northward OHT in the four model runs. While the simulated northward OHT is 30% lower than observed [e.g., *Wunsch*, 2007], which is a general problem in coarse resolution ocean-only models, the latitude where the OHT peaks and the overall pattern resemble that observed in the real ocean.

[11] In the "no gap" simulation OHT is increased, mainly in the subtropics, compared to the "control" run. The peak poleward heat transport increases by 0.15 PW and 0.24 PW in the northern and southern hemispheres, respectively. We also find a slight northward shift in OHT, due to an increased cross equatorial heat transport in the Pacific/

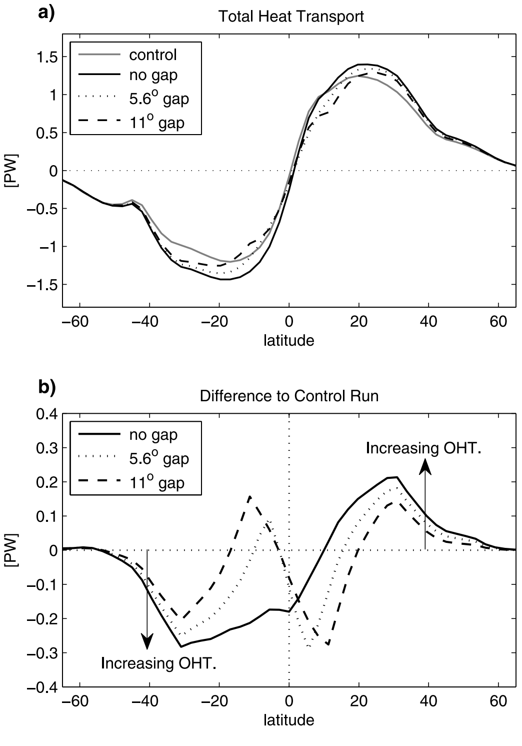

Figure 2. (a) Total northward OHT in the four model runs described in the text. (b) The OHT in the three model runs with increased upper ocean mixing minus the OHT in the control run. Positive values correspond to increased (reduced) poleward heat transport in the northern (southern) hemisphere while the signs are opposite for the southern hemisphere.

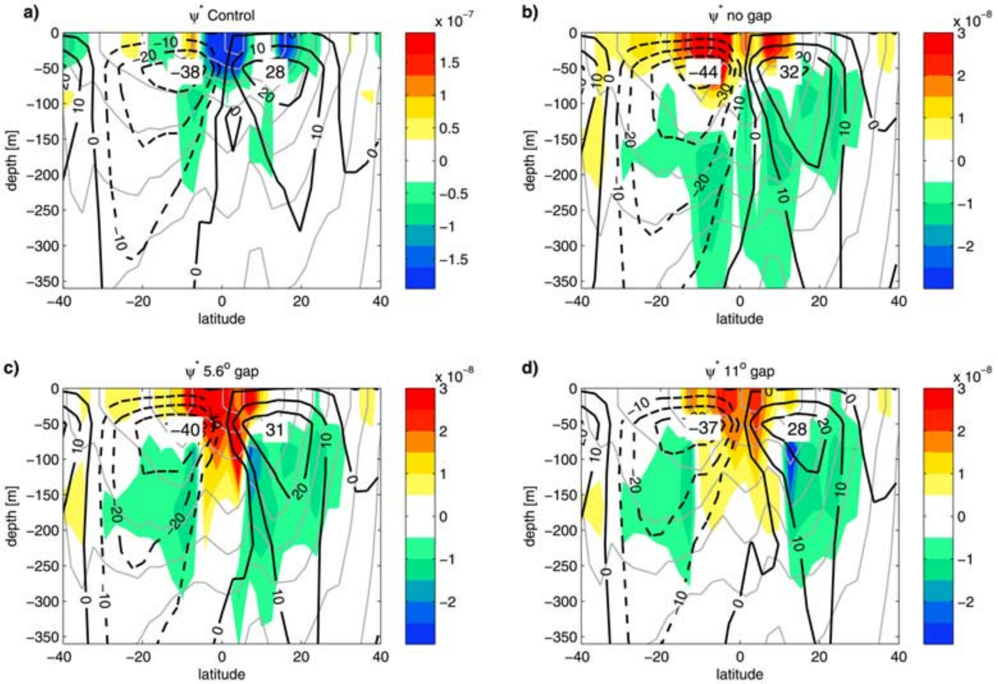

Figure 3. (a) The black contours show the meridional overturning streamfunction ψ^* including the contribution of the parameterized bolus velocity (in Sverdrup). Negative contours are dashed. The numbers shown in the center of the overturning cells are the maxima of ψ^*. The thin grey lines are isolines of zonally averaged potential temperature; the contour interval is 2K. The color shading indicates the convergence of the potential temperature advection ($\nabla \cdot \overline{\mathbf{uq}}$) in K/s. (b) Same as Figure 2a but for the "no gap" run. The color now shows the difference in the temperature advection between the "no gap" run and the "control" run. (c) Same as Figure 2b but for the"5.6° gap" run. (d) Same as Figure 2b but for the "11° gap" run.

Indian ocean, though this is likely an artifact of the ocean-only model in which the total cross-equatorial OHT is not coupled to the atmospheric one, as in the real world [e.g., *Enderton and Marshall*, 2008].

[12] In the simulations where mixing is not enhanced in a gap around the equator, the result is very different. The bulk response is a shift of the OHT curve towards higher latitudes. This results in a weakening of the OHT in the deep tropics and an increase further poleward, with a rather small change in peak heat transport, as shown in Figure 2b. To put these results in perspective, the 11° gap simulation shows an increased OHT of around 0.15 PW in the subtropics (only about 3% of the total ocean+atmosphere heat transport) and around 0.25 PW decrease in the deep tropics (about 10% of the total heat transport at that latitude).

[13] The surface heat flux (given by the slopes of the OHT shown in Figure 2b) increases over the regions of enhanced mixing as expected. Notice, however, that the increase in heat flux integrated over the areas of increased mixing is at least as big in the simulations with an equatorial gap as in the simulation with no gap. The poleward OHT in the simulations with an equatorial gap is thus not weaker because less heat is taken up in the (smaller) regions of enhanced mixing, but because the heat absorbed in the extratropics is brought back into the equatorial strip, and lost to the atmosphere there. The change in OHT is primarily the result of changes in the circulation pattern, and less the consequence of changes in ocean heat uptake.

[14] The change in OHT is mostly caused by a modification of the subtropical cells. As shown in Figure 3 the overturning is strengthened significantly in the "no gap" simulation compared to the "control" run. Note, particularly, the increased upwelling in the deep tropics, below the surface layer (see also Figure 4). In the "5.6° gap" case, the increase in the maximum overturning mass transport is only about half as strong then if mixing is increased with no gap. In the "11° gap" run there is hardly any change in the peak mass transport compared to the control run. It should be noted that the heat transport in the different simulations scales approximately with the strength of the overturning circulation at the respective latitude.

[15] The change in circulation and OHT among the four simulations can be explained as the superposition of a wind-driven subtropical cell (which does not change) and a diffusively-driven anomalous overturning, forced by the enhanced diffusivity. Figures 3 and 4 show that the increased subsurface diabatic heating due to enhanced κ is balanced by an increased diabatic upwelling of cold water on the equatorward side of the increased mixing bands. This upwelling branch is closed by sinking on the poleward flank of the subtropical cell in the "no gap" run (Figure 4) and reinforces the subtropical cell. In the "gap" simulations sinking occurs both on the poleward and equatorward flanks

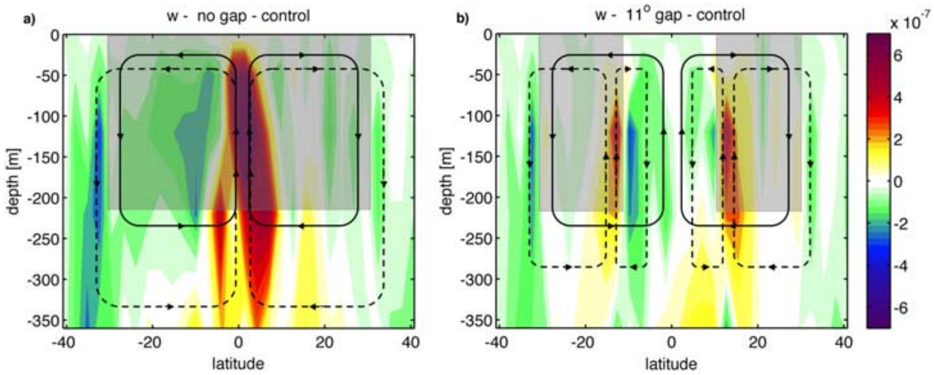

Figure 4. The color shows the vertical velocity difference in m/s between the indicated simulations and the "control" run. The shaded areas indicate the regions in which increased mixing was applied. The solid lines sketch the wind driven subtropical cells and the dashed lines sketch the change in the overturning induced by the increased mixing. (a) "no gap" case. (b) "11° gap" case.

of the band of increased mixing, generating two overturning cells (Figure 4). The cell equatorward of the mixing regions opposes the subtropical cell and acts to reduce the OHT.

4. Conclusions

[16] The results presented here confirm *Emanuel*'s [2001] surmise that TC induced mixing can significantly influence OHT. However, we find that most of the additional heat pumped into the ocean by TC mixing resurfaces in a narrow equatorial strip, resulting in a reduction of heat transport out of the deep tropics. The remaining heat that resurfaces on the poleward flanks of the increased mixing regions results in a minor increase of OHT at midlatitudes, while it is still somewhat increased in higher latitudes.

[17] The observed change in OHT due to increased upper ocean mixing is mostly due to a modification of the subtropical cells. If mixing is increased over the whole tropics, diapycnal upwelling in the deep tropics increases and with it the OHT by the subtropical cells. If, however, mixing is increased in a latitude band off the equator, upwelling increases in the bands of increased mixing while it is reduced in the deep tropics: such a circulation pattern decreases the poleward OHT out of the deep tropics, while it remains increased in higher latitudes.

[18] Since TCs rarely occur equatorwards of about 8° to 10°, the results presented here suggest that mixing triggered by TCs primarily induces an equatorward transport of heat and results in an overall decrease of poleward OHT out of the equatorial region. A significant increase in poleward OHT in present or past climates thus appears very unlikely. On the other hand, TC activity might be (or have been) able to modulate the equatorial warm water volume, which plays a key role in tropical climate variability, particularly in the Pacific.

[19] The purpose of this paper is to highlight the role of an equatorial gap in TC induced upper ocean mixing, using a simple model setup to illustrate the essential physics. If the work is to be made quantitative, several shortcomings must be addressed. First, we use a rather coarse resolution ocean-only model where the effect of TCs is represented as an increased diffusivity, following *Korty et al.* [2008]. This approach ignores aspects of the mixed-layer response to strong winds, like the excitation and radiation of inertial waves. Second, we do not have an atmospheric model and cannot account for changes in the atmospheric circulation in response to changes in OHT. Third, we do not consider the zonal dependence of TC activity, though *Scott and Marotzke* [2002] suggested that the buoyancy/mixing driven overturning circulation is also strongly sensitive to the zonal location of mixing.

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