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The sensitivity of hurricane frequency to ITCZ changes and radiatively forced warming in aquaplanet simulations

Timothy M. Merlis,[1,2] Ming Zhao,[3] and Isaac M. Held[4]

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[1] The response of hurricane frequency to climate changes in an aquaplanet configuration of a 50-km resolution atmospheric general circulation model is examined. The lower boundary condition is an energetically consistent slab ocean with a prescribed cross-equatorial ocean heat flux, which breaks the hemispheric symmetry and moves the Intertropical Convergence Zone (ITCZ) off the equator. In this idealized configuration, hurricane frequency increases in response to radiatively forced warming. The ITCZ shifts poleward when the model is warmed with fixed cross-equatorial ocean heat flux, and it is argued that the increase in hurricane frequency results from this poleward shift. Varying the imposed cross-equatorial ocean heat flux amplitude with fixed radiative forcing can isolate the effect of ITCZ shifts. If an increase in radiative forcing is accompanied by a reduction in the ocean heat flux amplitude such that the position of the ITCZ is unchanged, the simulated hurricane frequency decreases under warmed conditions. **Citation:** Merlis, T. M., M. Zhao, and I. M. Held (2013), The sensitivity of hurricane frequency to ITCZ changes and radiatively forced warming in aquaplanet simulations, *Geophys. Res. Lett.*, *40*, 4109–4114, doi:10.1002/grl.50680.

1. Introduction

[2] A variety of studies project a decrease in global tropical cyclone frequency in response to global warming, though there is uncertainty in the sign of changes in individual basins and sensitivity to the projected pattern of sea surface temperature (SST) changes [*Sugi et al.*, 2002; *Emanuel et al.*, 2008; *Zhao et al.*, 2009; *Knutson et al.*, 2010; *Murakami et al.*, 2012]. These projections are based on simulations with global models and downscaling techniques, and some mechanistic interpretations have been proposed [*Sugi et al.*, 2002; *Bengtsson et al.*, 2007; *Emanuel et al.*, 2008; *Held and Zhao*, 2011]. To make further progress in understanding the sensitivity of global tropical cyclone frequency to climate changes, it may be helpful to use idealized model configurations.

[3] Here we perform 50-km horizontal resolution global atmospheric general circulation model (GCM) simulations with an energetically consistent aquaplanet slab-ocean lower boundary condition. The symmetry between the hemispheres is broken by a cross-equatorial ocean heat flux [*Kang et al.*, 2008]. We then perturb the climate with an increase in solar constant or carbon dioxide concentration. This perturbation results in a latitudinal shift of the model's Intertropical Convergence Zone (ITCZ). To the extent that the region of cyclone formation in this zonally symmetric climate moves with the ITCZ, this shift might be anticipated to have a strong effect on cyclogenesis by modifying the ambient vorticity seen by incipient storms.

[4] We also anticipate that the shift of the ITCZ in such aquaplanet warming simulations can be model dependent due to differences in cloud feedbacks [*Kang et al.*, 2008; *Zhang et al.*, 2010; *Frierson and Hwang*, 2012]. To the extent that the tropical cyclone response depends strongly on the ITCZ shift, one might expect a large spread in the tropical cyclone frequency response if this calculation is repeated with other models. It may also be possible to attribute part of the spread in future projections of tropical cyclone frequency to the differences in this aspect of the simulated change in mean climate.

[5] We therefore examine whether the number of tropical cyclones N in this model, varying the radiative forcing $\mathcal{F}$ and the cross-equatorial ocean heat flux O, can be summarized in the form

$$N = n(\mathcal{F}, O) = n[\phi_I(\mathcal{F}, O), \mathrm{T}(\mathcal{F})], \tag{1}$$

where ϕ_I is the ITCZ latitude and T is the tropical-mean SST. Both the radiative forcing and the ocean heat flux affect the ITCZ latitude, while the radiative forcing modifies the mean SST. By varying O, we can isolate the dependence of N on the ITCZ latitude. By choosing a value of O that results in the same ITCZ shift as a change in $\mathcal{F}$, we can isolate the effect of $\mathcal{F}$ on N that is not accounted for by the shift of the ITCZ. It is interesting to ask if the latter is consistent with the results from comprehensive projections [*Knutson et al.*, 2010].

[6] We note that the function $n(\phi_I, \mathrm{T})$ posits that the variations in hurricane number in these aquaplanet simulations that are not accounted for by the change in the ITCZ latitude are related to mean SST; however, the mean SST should be thought of as standing in for aspects of the tropical environment that are strongly linked to the mean SST and more directly control the frequency of cyclogenesis, such as the saturation moisture deficit in the free troposphere or the total tropical deep convective mass flux [e.g., *Emanuel et al.*, 2008; *Held and Zhao*, 2011].

2. GCM Description

[7] We use the Geophysical Fluid Dynamics Laboratory High-Resolution Atmospheric Model (HiRAM) with about

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[1] Princeton University and Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA.

[2] Now at McGill University, Montreal, Quebec, Canada.

[3] UCAR/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA.

[4] NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA.

Corresponding author: T. M. Merlis, McGill University, 805 Sherbrooke Street West, Montreal, QC H3A 2K6, Canada (timothy.merlis@mcgill.ca)

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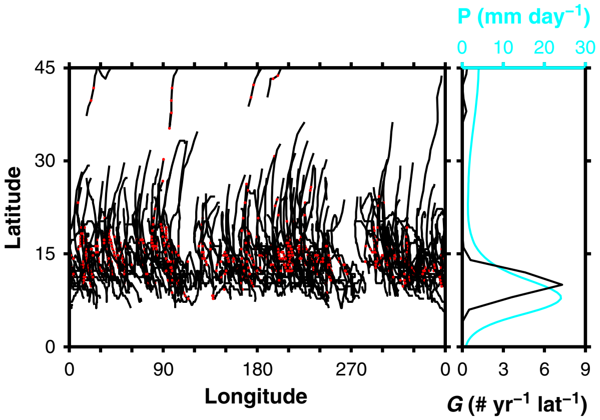

Figure 1. (left) Hurricane tracks for 5 years of the reference simulation with hurricane-strength wind-speed indicated in red. (right) Time- and zonal-mean hurricane genesis frequency (black) and precipitation (cyan) for the reference simulation.

50-km horizontal resolution (C180 cubed sphere), 32 vertical levels, and an aquaplanet slab-ocean lower boundary condition. HiRAM generates a seasonal cycle of tropical cyclone number in individual ocean basins that compares well to observations in comprehensive simulations using observed SSTs [*Zhao et al.*, 2009]. In addition, HiRAM captures many aspects of interannual and decadal variability in Atlantic hurricanes over the last 30 years [*Zhao et al.*, 2009].

[8] The slab-ocean boundary condition allows the surface temperature to evolve in response to turbulent surface fluxes and radiative fluxes in an energetically consistent manner. We use a 20-m slab depth, which allows for a more rapid equilibration than larger, more realistic values. There is no seasonal cycle in these simulations, minimizing the slab depth's effect on the large-scale climate. Tropical cyclone statistics in slab-ocean GCMs are sensitive to the slab depth for small values of the depth because the turbulent surface fluxes in developing cyclones can cool the surface enough to lead to unfavorable conditions for deep convection and further development. Sensitivity studies to the slab depth will be discussed elsewhere, but this model's tropical cyclone frequency is not sensitive to the slab depth if it is comparable to or larger than 20 m. We present averages over 5 years following at least a 5-year spin-up from an Earth-like initial condition.

[9] We use a time-independent insolation distribution that is similar to the annual mean on Earth [rather than equinox conditions, as in the aquaplanet configuration described by *Neale and Hoskins*, 2000]; there is no sea ice, and the surface temperature is allowed to drop below freezing. The reference CO_2 concentration is 300 ppm, the ozone distribution is symmetric between the hemispheres, and there are no aerosols or non-CO_2 greenhouse gases. The Q-flux formulation, the distribution of the specified convergence and divergence of heat in the slab that is used to break the north-south symmetry and move the ITCZ off the equator follows that used by *Kang et al.* [2008]: the heat flux convergence is antisymmetric about the equator, a sinusoidal function of latitude between 40° and 90°, and identically zero between 40° and the equator. The maximum value of this flux convergence is referred to as Q_0. For our reference simulation, we use $Q_0 = 40$ W m^{-2}, which corresponds to a 2.35 PW northward ocean heat flux at the equator.

[10] Tropical cyclones are identified using the tracker described in *Zhao et al.* [2009]. We use the term "hurricanes" throughout to refer to tropical cyclones with $|\mathbf{v}_s| > 29.5$ m s^{-1}. The surface wind $\mathbf{v}_s$ is evaluated at 10 m and the wind-speed threshold for hurricane strength is reduced from its standard value of 33 m s^{-1} to account for the limited horizontal resolution following the recommendation of *Walsh et al.* [2007]. The parameter dependence of the results is similar if this adjustment is not made or if sub-hurricane intensity tropical cyclones are included, but the absolute number of tropical cyclones is sensitive to the choice of wind-speed threshold. This GCM does not simulate the full tropical cyclone intensity distribution, with few storms above 45 m s^{-1}, which is due in part to inadequate horizontal resolution.

2.1. Reference Climate

[11] The global-mean surface temperature of the reference climate is 284.0 K. The prescribed cross-equatorial ocean heat flux converges heat in the northern hemisphere extratropics and diverges heat from the southern hemisphere extratropics making the northern hemisphere warmer than the southern hemisphere (Figure 2a). The concomitant energetically direct cross-equatorial Hadley circulation moves the ITCZ to the northern hemisphere [cf. *Yoshimori and Broccoli*, 2008; *Kang et al.*, 2009; *Chiang and Friedman*, 2012]. The ITCZ, defined as the latitude of the maximum precipitation, is located at 8°N in the reference climate (Figure 1). Hurricane genesis primarily occurs (> 95% of the total) in the northern hemisphere tropics along the poleward flank of the ITCZ (Figure 1), and about 35 hurricanes form in the annual and global mean (Figure 3a). For comparison, HiRAM simulations with comprehensive boundary conditions have about 55 hurricanes globally [*Zhao et al.*, 2009]. In addition to genesis near the ITCZ, there are a few detected hurricanes (< 5% of the total) in the extratropics, and including these does not affect the parameter dependence of the results presented here. The global number of hurricanes is sensitive to both the cross-equatorial heat flux and the radiative forcing.

2.2. Global Radiative Forcing Simulations

[12] We perform simulations in which the solar constant S_0 is modified from a reference, Earth-like value of 1400 W m^{-2} to substantially higher 1500 W m^{-2} and substantially lower 1300 W m^{-2} values to generate large climate changes. In addition, we present simulations with $2 \times CO_2$ and $4 \times CO_2$ concentration (relative to the reference concentration of 300 ppm) to determine the extent to which our results are dependent on the type of radiative perturbation. All simulations in this series have maximum ocean heat flux convergence Q_0 of 40 W m^{-2}.

2.3. Perturbed Ocean Heat Flux Simulations

[13] Hurricane frequency is sensitive to the degree of hemispheric asymmetry in this GCM. The radiative perturbations may increase or decrease the hemispheric asymmetry through inhomogeneous radiative feedbacks, even with unchanged Q-flux amplitude. To manipulate the hemispheric asymmetry directly, we modify the Q-flux amplitude ($Q_0 = 20, 45, 50, 60$ W m^{-2}) with the reference solar constant and

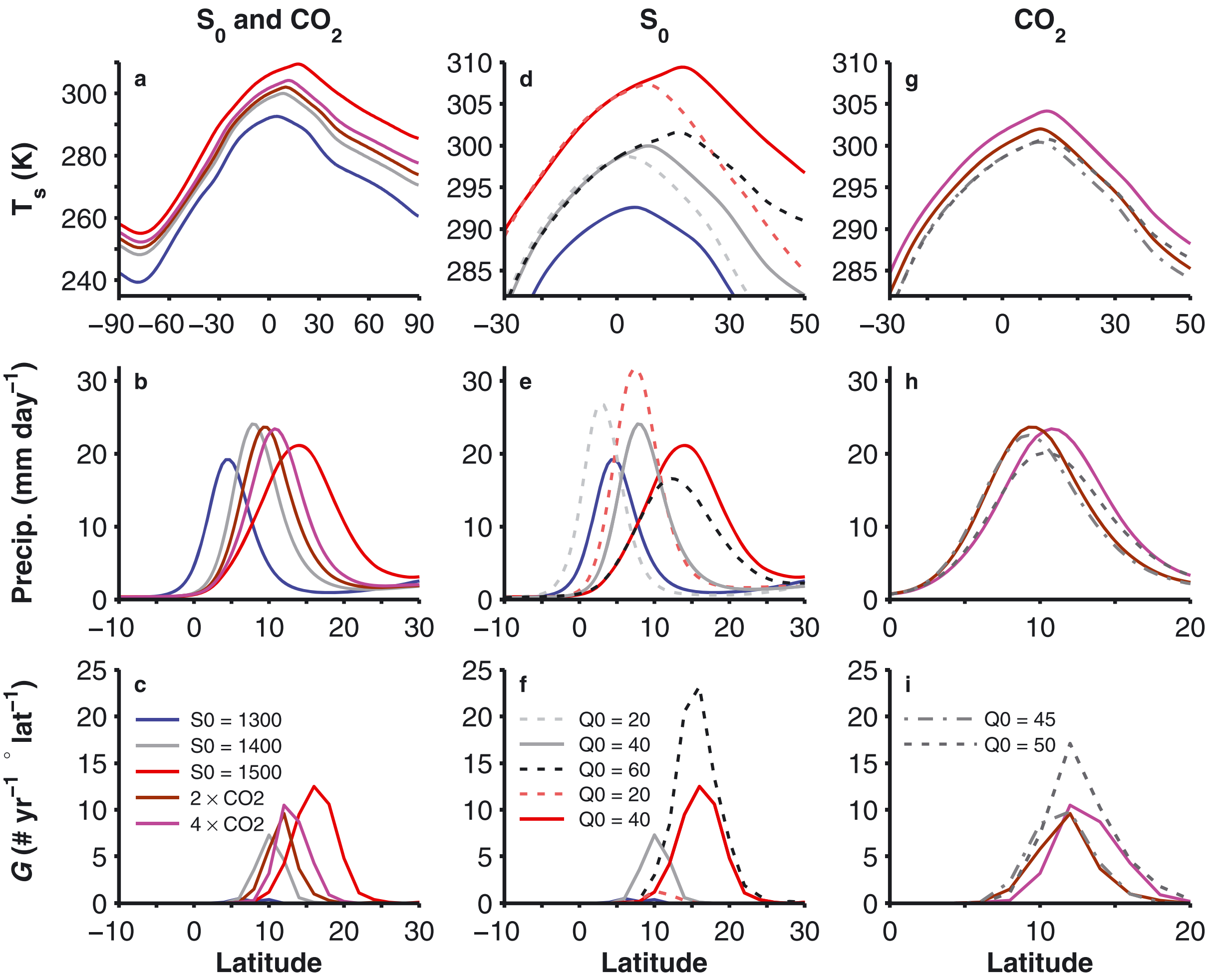

Figure 2. Time- and zonal-mean (a, d, and g) surface temperature, (b, e, and h) precipitation, and (c, f, and i) hurricane genesis frequency for (a, b, and c) radiative forcing simulations, (d, e, and f) solar constant-perturbation simulations and corresponding reference solar constant simulations with perturbed Q-flux amplitude, and (g, h, and i) CO_2-perturbation simulations and corresponding reference CO_2 simulations with perturbed Q-flux amplitude. Solid lines indicate reference Q-flux amplitude (40 W m^{-2}), and dashed lines indicate perturbed Q-flux amplitude, with lighter shades corresponding to lower Q-flux amplitude. Line colors correspond to radiative properties as indicated in the legend.

CO_2 concentration, which generates climate states with similar ITCZ latitude to those of the simulations with perturbed radiative agents. In addition, we have performed a high solar constant (S_0 = 1500 W m^{-2}) simulation with Q-flux amplitude of 20 W m^{-2}. These experiments are chosen to help isolate the effect of the ITCZ shifts on hurricane frequency.

3. Response to Global Radiative Forcing

[14] The global-mean surface temperature decreases by 6.8 K when the solar constant is reduced from 1400 W m^{-2} to 1300 W m^{-2} and increases by 10.0 K when the solar constant is increased from 1400 W m^{-2} to 1500 W m^{-2}, corresponding to sensitivities of 0.9 K and 1.4 K per percent change in insolation, respectively. The global-mean surface temperature increases by 2.2 K in the 2 × CO_2 simulation and by 4.4 K in the 4 × CO_2 simulation. The northern hemisphere tropical-mean surface temperature changes at a similar rate to the global-mean surface temperature. However, there is more warming in the northern hemisphere than in the southern hemisphere, and the surface temperature maximum shifts poleward with warming (Figure 2a).

[15] The precipitation increases globally and in the convergence zone with warming (Figure 2b). In addition to changes in the amount of precipitation, the latitude of the maximum precipitation shifts poleward with warming (Figure 2b); the maximum precipitation is close to the maximum ascending vertical velocity in all simulations. The ITCZ latitude is closest to the equator in the coldest simulation and is furthest from the equator in the warmest simulation. These simulations also feature a widening of the ITCZ with warming (Figure 2b).

[16] Hurricane genesis occurs on the poleward flank of the ITCZ in all climates and shifts poleward with warming (Figure 2c). In addition to changes in the genesis location, the frequency of genesis is higher for the warmer climates, when the ITCZ is further poleward (Figure 2c). Increases in hurricane frequency when the ITCZ is moved poleward also occur in fixed SST simulations with this model when the latitude of the maximum SST is moved to higher

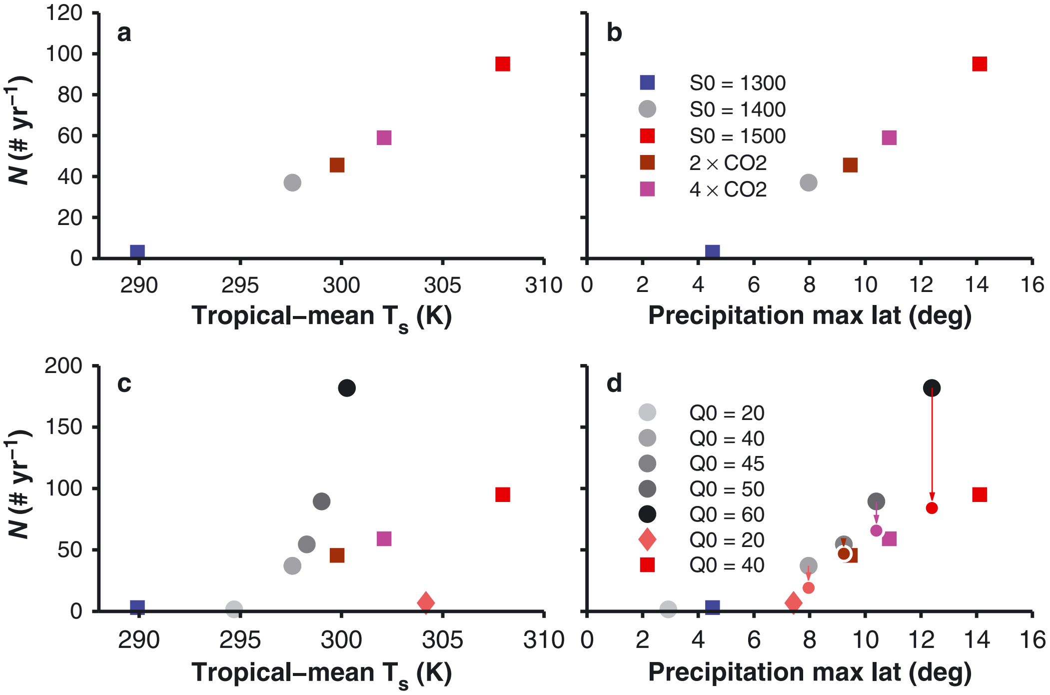

Figure 3. Global hurricane frequency versus (a and c) mean surface temperature of the northern hemisphere tropics (averaged from 0° to 30°N) or (b and d) latitude of maximum precipitation for (Figures 3a and 3b) global radiative forcing simulations and (Figures 3c and 3d) combined global radiative forcing and ocean heat flux amplitude simulations. The arrows and small circles in Figure 3d show the estimate (2) applied to the simulations with reference solar constant and CO_2 concentration. Simulations with reference to Q-flux amplitude and perturbed radiative forcing are denoted by squares, those with reference radiative forcing and perturbed Q-flux amplitude by circles, and the single simulation in which both are perturbed by a diamond.

latitudes, as described elsewhere [A. P. Ballinger 2012, personal communication].

[17] Figures 3a and 3b summarize the results for hurricane frequency in these perturbed solar constant and CO_2 concentration simulations by plotting the global hurricane frequency versus the mean SST of the northern hemisphere tropics and versus ITCZ latitude. The hurricane frequency increases with mean SST roughly linearly in the series of simulations with perturbed radiative parameters (Figure 3a). There is also a similarly clear relationship between the hurricane frequency and ITCZ latitude: hurricanes are more frequent when the ITCZ is further from the equator (Figure 3b), which occurs in response to warming radiative perturbations (Figure 2b). To decompose the changes in hurricane frequency into a part associated with the ITCZ shifts and a part related to changes in the thermodynamic environment associated with the warming itself, we examine the results of simulations with perturbed Q-flux amplitude.

4. Response to Global Radiative Forcing and Changes in Cross-Equatorial Ocean Heat Flux Amplitude

[18] The combined radiative forcing and Q-flux amplitude simulations give five pairs of climates with similar ITCZ latitude (Figures 2e and 2h), but different mean surface temperatures (Figures 2d and 2g). Note that the ITCZ width varies together with the ITCZ latitude over the range of simulations (Figures 2e and 2h), so we cannot distinguish the effect of ITCZ width on hurricane frequency from the effect of ITCZ latitude. When the ITCZ latitude is approximately unchanged (through changing the Q-flux amplitude) but the climate is warmer, there is a general reduction in hurricane genesis (Figures 2f, 2i and 3d). In contrast, if one solely examines the relationship between the number of hurricanes and the mean SST in the combined set of simulations, no clear relationship emerges (Figure 3c).

[19] Prescribed SST HiRAM simulations with uniform SST warming and increased CO_2 concentration have a reduction of tropical cyclone frequency of about 10% per kelvin of warming [*Held and Zhao*, 2011]. This provides an estimate for the number of hurricanes in the warmed climates with similar ITCZ latitude $\tilde{N}$, given the number of hurricanes in the reference climate and the change in SST: $\tilde{N} = (1 - 0.10\delta T)N_{\mathrm{ref}}$. The estimate is slightly better if we assume a linear relationship between $\log(N)$ and δT rather than between N and δT given the large temperature perturbations generated here:

$$\tilde{N} = N_{\mathrm{ref}} \exp(-0.10\delta T). \qquad (2)$$

[20] Figure 3d shows this estimate with small circles for simulation pairs with similar ITCZ latitude. The changes estimated using (2) are comparable to the number of hurricanes in the warmer climates explicitly simulated by the GCM when climates with similar ITCZ latitude are compared. The discrepancies are presumably due to minor mismatches in the ITCZ latitude and factors beyond the surface temperature change and ITCZ latitude that determine

hurricane frequency. Also, this dependence would not capture the effect of a threshold ITCZ latitude, with no hurricanes produced when the ITCZ is sufficiently close to the equator. The simulation results appear to have such a threshold, however, we note that the lack of hurricanes in the simulations with the ITCZ close to the equator is related, in part, to differences in the intensity distribution. For example, the low solar constant simulation with the ITCZ at 4.5°N has some tropical cyclones, but almost none achieve hurricane-strength surface winds.

[21] We can summarize these results using the notation in (1). For small perturbations, the sensitivity of hurricane frequency to a given shift in the ITCZ, holding radiative forcing fixed, is roughly

$$\frac{1}{n}\frac{\partial n}{\partial \phi_I} \approx +40\%\,(^\circ\mathrm{lat})^{-1}, \tag{3}$$

while the sensitivity to a change in temperature holding ITCZ latitude fixed is

$$\frac{1}{n}\frac{\partial n}{\partial \mathrm{T}} \approx -10\%\,\mathrm{K}^{-1}. \tag{4}$$

The sensitivity of the ITCZ latitude to warming in this idealized configuration of HiRAM is somewhat more than half a degree latitude per kelvin of warming:

$$\frac{\partial \phi_I}{\partial \mathrm{T}} \approx +0.6^\circ\mathrm{lat}\,\mathrm{K}^{-1}, \tag{5}$$

so that, the sensitivity of hurricane frequency to a radiatively forced temperature change is

$$\frac{1}{N}\frac{\partial N}{\partial \mathrm{T}} \approx \frac{1}{n}\frac{\partial n}{\partial \phi_I}\frac{\partial \phi_I}{\partial \mathrm{T}} + \frac{1}{n}\frac{\partial n}{\partial \mathrm{T}} \approx +14\%\,\mathrm{K}^{-1}. \tag{6}$$

[22] It is clear that (at least) two parameters are necessary to capture the sensitivity of hurricane frequency to climate perturbations in these simulations: the surface temperature change (or something that covaries with the temperature) *and* the ITCZ latitude. The simulation results are consistent with reduced global tropical cyclone frequency in warmer climates *if* the ITCZ latitude does not change. Note that additional factors beyond the two sensitivities elucidated here must be considered when comprehensive boundary conditions and the associated zonal asymmetries are included.

5. Conclusions

[23] Global tropical cyclone frequency is sensitive to the magnitude of off-equatorial thermal forcing in 50-km aquaplanet GCM simulations. In the model examined, this sensitivity is important in interpreting simulations with perturbed greenhouse gas concentrations or solar constant because the intertropical convergence zone (ITCZ) shifts poleward with increasing CO_2 concentration or solar constant.

[24] The effect of the changes in ITCZ latitude on hurricane frequency can be isolated by manipulating the amplitude of the imposed cross-equatorial ocean heat flux in the idealized slab-ocean aquaplanet configuration. If we manipulate the ITCZ latitude of a warmed climate so that it is similar to that of a reference climate, the sensitivity of tropical cyclone frequency is consistent with the reduced global frequency found in most projections for the 21st century [*Knutson et al.*, 2010].

[25] The results of these simulations can be approximately summarized by considering the sensitivity of hurricane frequency to the tropical-mean SST change with unchanged ITCZ latitude, $-10\%\,\mathrm{K}^{-1}$, and the sensitivity of hurricane frequency to shifts in the ITCZ latitude with unchanged radiative forcing, $+40\%\,(^\circ\mathrm{lat})^{-1}$.

[26] The latitude of the ITCZ in the simulations presented here is sensitive to increases in radiative forcing, with poleward shift of more than half a degree latitude per kelvin of warming. Our extraction of the separate sensitivities of hurricane frequency to warming and to a shift in ITCZ latitude suggests that the increase due to poleward shift of the ITCZ would be larger than the reduction due to warming in isolation if the ITCZ shift were larger than $\sim +0.25^\circ\mathrm{lat}\,\mathrm{K}^{-1}$. Therefore, the hurricane frequency increases in response to warming radiative perturbations in this model, when this particular reference state is perturbed. The resulting sensitivity of hurricane frequency does not differ substantially between the simulations with increased CO_2 concentration and the simulations with increased solar constant.

[27] However, the sensitivity of ITCZ latitude to radiative perturbations is model dependent. *Frierson and Hwang* [2012] find both equatorward and poleward shifts in comprehensive slab-ocean simulations of the annual-mean precipitation response to $2 \times CO_2$ and relate these changes to interhemispheric differences in radiative feedbacks. The ITCZ latitude in a set of simulations similar to those presented here, but with a gray radiation GCM forced by varying longwave optical depth [as in *O'Gorman and Schneider*, 2008], is about a factor of 5 less sensitive per kelvin warming than found here; this highlights the importance of cloud and water vapor feedbacks in determining changes in the ITCZ latitude. Note that it is the summer-season ITCZ position which is relevant for hurricane genesis, and that the seasonal ITCZ latitude may change differently from the annual mean. Some models feature poleward shifts and others equatorward shifts in summertime precipitation in the CMIP3 simulations of the A2 scenario [*Chou et al.*, 2009]. While there is uncertainty in the sign of greenhouse gas-forced ITCZ shifts, other radiative forcing agents such as sulfate aerosols have spatial structure in their emissions that should affect the ITCZ latitude in a more robust manner [*Yoshimori and Broccoli*, 2008].

[28] Adding uniform SST perturbations to atmospheric GCMs forced with prescribed SSTs minimizes shifts in the mean tropical circulation. These circulation changes may be important in determining hurricane frequency changes in comprehensive models and in nature, as they are in these simulations. In particular, changes in the ocean circulation, such as variability or trends in the Atlantic Meridional Overturning Circulation, should lead to changes in the ITCZ latitude and, therefore, hurricane frequency.

[29] One may be able to concisely summarize the changes in hurricane frequency in these simulations in terms of functions of one or more of the characteristics of the SST changes. However, simulations with this GCM forced by prescribed SSTs with an off-equatorial maximum appear to be characterized by fairly complex relationships between the SST distribution and the tropical cyclone frequency [A. P. Ballinger 2012, personal communication]. The changes in the cross-equatorial Hadley circulation are central to the results described here, and there are reasons why one should not expect a simple relationship

between surface temperature and the cross-equatorial Hadley circulation [*Lindzen and Hou*, 1988; *Kang and Held*, 2012; *Merlis et al.*, 2013].

[30] We have presented the simulation results in terms of the ITCZ latitude, but we cannot distinguish this latitude effect from the meridional scale of the ITCZ because the more poleward convergence zones are always wider in these simulations (Figures 2e and 2h). However, environmental vorticity is a standard component of proposed genesis indices for tropical cyclones [e.g., *Emanuel and Nolan*, 2004; *McGauley and Nolan*, 2011; *Tippett et al.*, 2011, some of which have thresholds rather than a continuous dependence on vorticity], so an increase in hurricane frequency with poleward shift of the ITCZ is to be expected. A dynamical theory for this dependence does not yet exist in our view.

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References

Bengtsson, L., K. I. Hodges, M. Esch, N. Keenlyside, L. Kornblueh, J.-J. Lou, and T. Yamagata (2007), How may tropical cyclones change in a warmer climate? *Tellus*, *59A*, 539–561.

Chiang, J. C. H., and A. R. Friedman (2012), Extratropical cooling, interhemispheric thermal gradients, and tropical climate change, *Annu. Rev. Earth Planet. Sci.*, *40*, 383–412.

Chou, C., J. D. Neelin, C.-A. Chen, and J.-Y. Tu (2009), Evaluating the "rich-get-richer" mechanism in tropical precipitation change under global warming, *J. Clim.*, *22*, 1982–2005.

Emanuel, K., R. Sundararajan, and J. Williams (2008), Hurricanes and global warming: Results from downscaling IPCC AR4 simulations, *Bull. Am. Meteor. Soc.*, *89*, 347–367.

Emanuel, K. A., and D. S. Nolan (2004), Tropical cyclone activity and the global climate system, in *Preprints, 26th Conf. on Hurricanes and Tropical Meteorology,* vol. 10, Amer. Meteor. Soc. A, Miami, FL.

Frierson, D. M. W., and Y.-T. Hwang (2012), Extratropical influence on ITCZ shifts in slab ocean simulations of global warming, *J. Clim.*, *25*, 720–733.

Held, I. M., and M. Zhao (2011), The response of tropical cyclone statistics to an increase in CO_2 with fixed sea surface temperatures, *J. Clim.*, *24*, 5353–5364.

Kang, S. M., and I. M. Held (2012), Tropical precipitation, SSTs and the surface energy budget: A zonally symmetric perspective, *Clim. Dyn.*, *38*, 1917–1924, doi:10.1007/s00382-011-1048-7.

Kang, S. M., I. M. Held, D. M. W. Frierson, and M. Zhao (2008), The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM, *J. Clim.*, *21*, 3521–3532.

Kang, S. M., D. M. W. Frierson, and I. M. Held (2009), The tropical response to extratropical thermal forcing in an idealized GCM: The importance of radiative feedbacks and convective parameterization, *J. Atmos. Sci.*, *66*, 2812–2827.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. Kossin, A. K. Srivastava, and M. Sugi (2010), Tropical cyclones and climate change, *Nat. Geosci.*, *3*, 157–163.

Lindzen, R. S., and A. Y. Hou (1988), Hadley circulations for zonally averaged heating centered off the equator, *J. Atmos. Sci.*, *45*, 2416–2427.

McGauley, M. G., and D. S. Nolan (2011), Measuring environmental favorability for tropical cyclogenesis by statistical analysis of threshold parameters, *J. Clim.*, *24*, 5968–5997.

Merlis, T. M., T. Schneider, S. Bordoni, and I. Eisenman (2013), Hadley circulation response to orbital precession. Part I: Aquaplanets, *J. Clim.*, *26*, 740–753.

Murakami, H., R. Mizuta, and E. Shindo (2012), Future changes in tropical cyclone activity projected by multi-physics and multi-SST ensemble experiments using the 60-km-mesh MRI-AGCM, *Clim. Dyn.*, *39*, 2569–2584.

Neale, R. B., and B. J. Hoskins (2000), A standard test for AGCMs including their physical parametrizations: I: The proposal, *Atmos. Sci. Lett.*, *1*, 101–107.

O'Gorman, P. A., and T. Schneider (2008), The hydrological cycle over a wide range of climates simulated with an idealized GCM, *J. Clim.*, *21*, 3815–3832.

Sugi, M., A. Noda, and N. Sato (2002), Influence of the global warming on tropical cyclone climatology: An experiment with the JMA global model., *J. Meteorol. Soc. Japan*, *80*, 249–272.

Tippett, M. K., S. J. Camargo, and A. H. Sobel (2011), A Poisson regression index for tropical cyclone genesis and the role of large-scale vorticity in genesis, *J. Clim.*, *24*, 2335–2357.

Walsh, K. J. E., M. Fiorino, C. W. Landsea, and K. L. McInnes (2007), Objectively determined resolution-dependent threshold criteria for the detection of tropical cyclones in climate models and reanalyses, *J. Clim.*, *20*, 2307–2314.

Yoshimori, M., and A. J. Broccoli (2008), Equilibrium response of an atmosphere-mixed layer ocean model to different radiative forcing agents: Global and zonal mean response, *J. Clim.*, *21*, 4399–4423.

Zhang, R., S. M. Kang, and I. M. Held (2010), Sensitivity of climate change induced by the weakening of the Atlantic meridional overturning circulation to cloud feedback, *J. Clim.*, *23*, 378–389.

Zhao, M., I. M. Held, S. J. Lin, and G. A. Vecchi (2009), Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM, *J. Clim.*, *22*, 6653–6678.