Impacts of Atmospheric Temperature Changes on Tropical Cyclone Activity

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Abstract

Aspects of the impacts of tropical temperatures in the upper troposphere (UT) and the tropical tropopause layer (TTL) on tropical cyclone (TC) activity are explored. UT and lower TTL cooling both lead to an overall increase in potential intensity (PI), while temperatures 70hPa and higher have negligible effect. Idealized experiments with a high-resolution global model show that cooler temperatures in the UT are associated with increases in global and North Atlantic TC frequency, but TC frequency changes in this model are not significantly affected by TTL temperature changes and do not scale with PI. Large uncertainties exist in the historical (1980-2008) UT and TTL trends, and the estimated impact of this uncertainty on TC activity is comparable to observed TC changes, impacting our confidence in assessments of the connection between hurricanes and climate.

Future projections of hurricane activity have been made with models that simulate the recent upward Atlantic TC trends while either assuming or simulating very different tropical temperature trends. This situation is illustrated, on the one hand, by several regional TC downscaling systems that successfully simulate these Atlantic trends while imposing the very strong UT and TTL trends of the NCEP Reanalysis, an outlier among observational estimates, and, on the other hand, by a high-resolution global model that simulate upward Atlantic TC frequency trends with a more nearly moist-adiabatic warming profile. Therefore, understanding the character of and mechanisms behind changes in UT and TTL temperature is crucial to understanding past and projecting future TC activity changes.

(248 words, max 260)

1. Introduction:

Understanding and modeling the links between climate and tropical cyclones (TCs) is a topic of substantial scientific interest (*e.g.,* Knutson *et al.* 2010), motivated in large part by the societal and economic impact of hurricanes (*e.g.,* Pielke Jr. *et al.* 2008; Mendelsohn *et al.* 2012; Peduzzi *et al.* 2012). Statistical, dynamical and hybrid statistical-dynamical models have all proved useful in the development of understanding of and predictive capability for hurricane activity changes (*e.g.,* Gray 1984; Elsner and Jagger 2006; Oouchi *et al.* 2006; Camargo *et al.* 2007; Knutson *et al.* 2007, 2008; Emanuel *et al.* 2008; Gualdi *et al.* 2008; LaRow *et al.* 2008; Swanson 2008; Zhao *et al.* 2009, 2010; Bender *et al.* 2010; Chen and Lin 2010; Smith *et al.* 2010; Vecchi *et al.* 2011, 2012; Villarini *et al.* 2011, 2012; Villarini and Vecchi 2012; Zhao and Held 2012). Most of these studies, and others (*e.g.,* Emanuel 2005; Vecchi and Soden 2007; Ramsay and Sobel 2011), have focused attention on the role of SST changes in directly or indirectly controlling past and future hurricane changes. However, processes controlling hurricane statistics may be impacted by changes in the atmosphere that are not closely tied to sea surface temperature (SST) (*e.g.,* Sugi and Yoshimura 2004; Yoshimura and Sugi 2005; Emanuel 2010; Held and Zhao 2011); in particular, upper atmospheric temperature changes could impact TC activity (*e.g.,* Emanuel 2010; Emanuel *et al.* 2012).

The dynamical and statistical-dynamical modeling studies that have explored the impact of climate variability and change on hurricanes to date can be categorized into two broad categories: 1) global models that are either forced by estimates of SST (*e.g.,*Oouchi *et al.* 2006; LaRow *et al.* 2008; Zhao *et al.* 2009, 2010), or coupled to ocean models (*e.g.,* Gualdi *et al.* 2008; Smith *et al.* 2010); and 2) regional/limited-domain models that are forced by estimates of the large-scale 3D structure of the atmosphere, in addition to SST (*e.g.*, Knutson *et al.* 2007, 2008; Emanuel *et al.* 2008; Emanuel 2010). The changes to the 3D structure of the atmosphere in the SST-forced and coupled global models emerges from the dynamical response of the model system to the imposed boundary conditions and forcings (which usually include changes in atmospheric composition, *e.g.* CO_2 concentrations, O_3, volcanic aerosols); meanwhile, limited-domain models impose the evolution of the three-dimensional structure of the atmosphere. Thus, even though various global AGCMs may be forced with similar SSTs, their atmospheric temperature evolution need not be the same and may differ from those of observational estimates, including those used in limited domain models.

In particular, as was shown in Knutson *et al.* (2010), the observed history of Atlantic hurricane activity (including the multi-decadal trend) was recovered with comparable skill by the global SST-forced AGCM studies of Zhao *et al.* (2009,2010) and LaRow *et al.* (2008), and the limited-domain studies of Knutson *et al.* (2007) and Emanuel *et al.* (2008). This similarity in historical North Atlantic hurricane hindcast skill emerges even though these limited-domain models were forced with the NCEP-NCAR Reanalysis (Kalnay *et al.* 1996), which, as generally recognized and as we explore further below (*e.g.,* Figure 1), has atmospheric temperature trends in the tropics and Atlantic that differ considerably from the tropical-mean moist-adiabatic warming and stratospheric cooling exhibited by the global models. Also, the temperature trends in the NCEP data are outliers when compared to other reanalyses and homogenized radiosonde data (*e.g.,* Pawson and Fiorino 1998). Therefore, to the extent that atmospheric temperature changes have been important to hurricane activity, each limited-domain and global modeling system may have been achieving comparable hindcast skill for different reasons, and in response to large-scale changes that may have differed from those that occurred in the real climate system.

In this manuscript, specific attention is given to the possibility of an influence of temperatures in the tropical tropopause layer and lower stratosphere on hurricane intensity and trends (*e.g.,* Emanuel 2010; Emanuel *et al.* 2012). Temperatures in these layers can be influenced by trends in the strength of the stratospheric circulation and trends in radiatively active species such as ozone, both of which may be correlated with changes in the troposphere but cannot be understood in terms of changes of a moist adiabatic temperature profile in response to changes in SST (Fueglistaler *et al.*, 2009), which may not be captured by models that do not adequately resolve stratospheric dynamics and chemistry.

To what extent does the difference in the estimates of past tropical atmospheric temperature changes impact hurricane activity? And, at which pressure levels in the atmosphere are temperature/heating uncertainties/perturbations most influential? In the rest of the manuscript we attempt to address these questions. In Section 2 we describe our data sources and modeling framework. Section 3 focuses on the various estimates of the structure of atmospheric temperature change over the 1980-2008 period. Section 4 assesses the role of different estimates of past atmospheric temperature changes on hurricane potential intensity. In Section 5 we explore the impact of idealized atmospheric heating profiles on hurricane activity in an AGCM. In Section 6 we summarize our results, offer some discussion of their implications and highlight key steps forward.

2. Data and Methods:

a. Observational analyses:

We explore five different observationally-based estimates of the evolution of tropical atmospheric temperatures over the period 1980-2008. We use two products based entirely on homogenized radiosonde measurements of atmospheric temperature from select stations:

i) The United Kingdom's Meteorological Office's Hadley Centre Atmospheric Temperature (HadAT2) analysis (Thorne et al. 2005).

ii) Version 1.51 of the Radiosonde Innovation Composite Homogenization (RICH) made available at the University of Vienna (Haimberger *et al.* 2011) that is homogenized using information from neighboring radiosonde stations, and which provides an ensemble of 32 plausible records by varying parameters in the homogenization methodology.

The four other products used are observationally-constrained dynamical-model reanalyses:

i) The reanalysis produced by United States National Oceanic and Atmospheric Administration's National Center for Environmental Prediction (NCEP) and the United States National Center for Atmospheric Research (NCAR), referred to as the NCEP (Kalnay *et al.*, 1996). The data used are on a monthly, 2.5°x2.5° grid, and archived at 17 standard pressure levels.

ii) The interim reanalysis produced by the European Centre for Medium Range Weather Forecasting (ECMWF), referred to as ERA-Interim (Dee *et al.*, 2011). The data used are on a monthly, 1°x1° grid, and archived at 60 pressure levels between the surface and 0.1hPa.

iii) The Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker *et al.* 2010), produced by the United States National Aeronautics and Space Administration (NASA). The data used are on a monthly, 1.25°x1.25° longitude-latitude grid and 42 pressure levels between 1000 and 0.1 hPa.

iv) The NCEP Climate Forecast System Reanalysis (CFSR; Saha *et al.* 2010). The data used are on a monthly, 2.5°x2.5° longitude-latitude grid and archived at standard pressure levels with additional intermediate pressure levels.

b. Potential Intensity:

Potential intensity (PI) is a theoretical upper bound on the intensity a TC can attain, given its environment. From observational estimates and models we compute PI as estimated by Bister and Emanuel (1998, 2002) based on monthly-mean values of sea surface temperature (SST), sea level pressure, and profiles of atmospheric temperature and humidity, using the Fortran code available here: ftp://texmex.mit.edu/pub/emanuel/TCMAX/

c. Model: HiRAM

HiRAM is a global high resolution atmospheric model developed at GFDL with a goal of providing an improved simulation of the statistics of tropical storms. At about 50km horizontal grid size, HiRAM forced by the observed sea surface temperatures (HadiSST) is found to be able to reproduce many aspects of the observed hurricane frequency variability for the past few decades, for which reliable observations are available (Zhao *et al.* 2009). These include the geographical distribution of global hurricane tracks, the seasonal cycle, as well as the inter-annual variability and the decadal trend of hurricane frequency over multiple ocean basins. HiRAM has also been used to study hurricane seasonal forecasting in the N. Atlantic (Zhao *et al.* 2010; Vecchi *et al.* 2011) and the results support a view that the overall activity of the Atlantic hurricane season has substantial predictability, if one can predict ocean temperatures. The historical simulations used for this study are also the integrations (3-member ensemble) for GFDL's participation in the CMIP5 high resolution time-slice simulations (Held *et al.*, in preparation) and the US CLIVAR Hurricane Working Group.

3. Observed and Modeled Temperature Changes:

There are some common features present in past upper troposphere (UT) and tropical tropopause layer (TTL) temperature changes in all the observational estimates and the HiRAM AGCM, though there are also important differences between different estimates. Figure 1 compares the time-evolution and 1980-2008 linear trends of atmospheric temperatures averaged over the peak season of northern hemisphere hurricane activity (July-October) from the observational estimates and the three-member ensemble mean of the HiRAM AMIP experiment, focussing on the tropical-average (30°S-30°N). Because hurricane changes in the tropical Atlantic have been a topic of particular interest in AGCM and limited domain hindcasts, we also explore values at the data point nearest the San Juan, Puerto Rico radiosonde station (66°W,18°N). Both in the tropical-mean and at San Juan, all the observational estimates show long-term cooling in the lower stratosphere (50hPa) and upper TTL (70hPa), punctuated by a notable warming in response to the eruptions of Mts. El Chichón (1983) and Pinatubo (1991). The HiRAM model shows weaker 50-70hPa cooling than that of any of the observationally-based estimates, and it also shows reduced variability (HiRAM does not have a good representation of the quasi-biennial oscillation – QBO). In the lower TTL (100h-150hPa) HiRAM tends to track the non-NCEP observational relatively well, while NCEP is a considerable outlier.

The NCEP-NCAR Reanalysis stands out as an outlier among all the other observational estimates, by exhibiting very large cooling in the lower TTL and in the UT. In the lower TTL, the cooling in all products is smaller than in the lower stratosphere/upper TTL except NCEP, which shows a maximum cooling at 100hPa that is twice as large as the next largest cooling (CFSR). In the lower TTL the long-term cooling in HiRAM is smaller than that of most observational estimates (except ERA-Interim), and HiRAM shows no long-term change at 150hPa. The trends in HiRAM sit within the spread of the 32-member ensemble of trends from RICH between 850hPa and 150hPa (not shown). Meanwhile, the trends from NCEP are only within the RICH ensemble spread only at the 50hPa and 850hPa pressure levels (not shown).

In the UT there are also considerable differences across products. Most observational estimates have the sign of the long-term trend in temperature change from negative to positive between 150-200hPa, while that in NCEP has its zero crossing below 250hPa. The zero-crossing for HiRAM, at 150hPa, is higher than most observational estimates. In the upper and middle troposphere, the trends in HiRAM are within the range of the various observationally-constrained estimates. The NCEP and HadAT2 both show considerably less warming in the lower troposphere than do RICH, ERA-Interim, CFSR, MERRA or HiRAM: in NCEP and HadAT2 the 1980-2008 tropospheric warming trends do not increase with height.

The results are similar over San Juan and in the tropical mean, with the outlier nature of NCEP in the lower TTL and UT more notable than in the tropical mean. Over the entire atmospheric column, the temperature trends in NCEP are for more cooling/less warming than those in HiRAM. In the upper TTL the trends from the NCEP are at the cold end of the spectrum of the various observational estimates, while those from the HiRAM AGCM are at the warm end.

In the lower TTL and UT the NCEP is an extreme outlier among the other products in its estimate of trends and in the temporal evolution of temperature. In the lower TTL, the trends in the HiRAM model are deviate from the non-NCEP datasets in the opposite direction to those of NCEP. In the UT, the temperature trends in HiRAM are less of an outlier, relative to the population – while the NCEP trends depart from the population as a whole down to ~300hPa.

Two divergent views of the past evolution of tropical atmospheric temperatures (NCEP and HiRAM) have been used in assessments of the changes of hurricane activity since 1980: the ZETAC regional model (Knutson *et al.* 2007, 2008; Garner *et al.* 2009) and the statistical-dynamical methodology of Emanuel *et al.* (2008) use the NCEP to drive their hurricane downscaling methodologies, while the HiRAM evolution emerges from the AGCM used to explore hurricane activity in Zhao *et al.* (2009, 2010), Zhao and Held (2011) and Held and Zhao (2011). Therefore, it is important to understand the extent to which these differences in the multi-decadal trends in atmospheric temperatures influence simulated hurricane activity.

4. Atmospheric Temperature Changes and Potential Intensity:

In this section we explore the impact of the differences in the temperature evolution between the NCEP and HiRAM on the Bister and Emanuel (2002) TC Potential Intensity (PI). Overall, the differences in atmospheric temperature trends between NCEP and HiRAM in the Atlantic main development region (MDR; 80°W-20°W, 10°N-25°N) are of a similar character than those averaged over the tropics. In addition to differences in temperature trends, NCEP and HiRAM have large differences in their trends in PI across the tropics (Figure 2.a-.b). Trends in PI computed from NCEP are positive almost everywhere in the tropics, and exceed 2.5 $m \cdot s^{-1} \cdot decade^{-1}$ over large areas of the tropics. Meanwhile, trends in PI computed from HiRAM are positive in as many places as they are negative, and the increases are almost everywhere less than 2 $m \cdot s^{-1} \cdot decade^{-1}$. There are also differences across the two datasets in the relationship between trends in PI and relative SST (the difference in local SST to the tropical average, which has been found to be a good predictor of the response of PI across a range of models – *e.g.*, Vecchi and Soden 2007; Gualdi *et al.* 2007; Xie *et al.* 2010; Ramsay and Sobel 2011; Camargo *et al.* 2012). The patterns of PI trends exhibit some relationship to patterns of SST change in both datasets, but while in HiRAM the zero line of relative SST trends corresponds strongly to the zero line of PI trends, in the NCEP there are large areas with positive PI trends and negative relative SST trends (*e.g.*, the east Pacific).

The differences between the evolution of PI from the NCEP and HiRAM emerge clearly in their tropical-mean behavior (Figure 3.a), with the NCEP showing a clear increase but HiRAM no apparent change. The difference in PI trends emerges in the regional, seasonal PI as well; for example, Fig. 3.b shows time series of PI from the NCEP and HiRAM averaged over the Atlantic hurricane main development region (MDR; 80°W-20°W, 10°N-25°N) over the hurricane season (June-November). Both HiRAM and the NCEP exhibit increases in MDR PI over the 1980-2008 period – but the increase in NCEP is more than twice as large as that in HiRAM.

What drives these differences in regional and global trends in PI between HiRAM and the NCEP? PI depends on the surface enthalpy disequilibrium as well as the vertical profile of temperature in the atmosphere, with larger enthalpy disequilibrium or cooler UT/TTL temperatures leading to larger PI. Based on the differences in tropical temperature trends in the NCEP and HiRAM, which show less warming/more cooling aloft in the NCEP than in HiRAM, we hypothesize that a main source of the difference is the difference in the tropical-mean temperature trends. To test this hypothesis we recomputed PI from the NCEP data, after perturbing its temperature by replacing the NCEP tropical-mean temperature linear least-squares trend at each point with that from HiRAM. We scale the HiRAM temperature change by the SST trend in NCEP in order to isolate the impact of differences in the profile of tropical-mean temperature trend on PI. So, the modified temperature profile at each point is:

$$T^*(x,y,p,t) = T_N(x,y,p,t) - \mathcal{L}_{<T_N>}(p) \cdot t + \frac{\mathcal{L}_{<T_H>}(p) \cdot \mathcal{L}_{<S_N>}}{\mathcal{L}_{<S_H>}} \cdot t \qquad \text{(Eq. 1)}$$

where: T^* is the modified temperature structure evolution, T_N and S_N are the NCEP monthly atmospheric temperature and SST fields, respectively; T_H and S_H are the HiRAM monthly atmospheric temperature and SST fields, respectively; $\mathcal{L}_\xi$ is the slope of the linear least-squares trend of quantity ξ; and $<\cdot>$ is the tropical average of a quantity. Differences between the NCEP PI evolution and that computed using the modified temperature data reflect the impact of differences in the vertical structure of tropical-mean temperature trends between NCEP and HiRAM.

As can be seen in Figure 2.c, the PI trends over the globe are very similar between HiRAM and the modified NCEP, indicating that a large contribution to the regional differences in PI trend between the NCEP and HiRAM arise from differences in tropical-mean atmospheric temperature trends. There are still differences between the modified NCEP and HiRAM trends in certain regions: the modified NCEP has larger positive trends over the Indian Ocean; the modified NCEP has is largest Atlantic PI increase off the coast of South America, while in HiRAM it is off the coast of Africa. However, these regional differences are much smaller than the differences between the actual NCEP and HiRAM. It appears that the differences in regional PI trends between the modified NCEP and HiRAM are tied to differences in their relative SST trends; this HiRAM experiment is forced with the HadISSTv1 product (Rayner *et al.* 2003), while NCEP uses a different estimate of SST. For example, the relative warming of the Indian Ocean is more than twice as large in NCEP than in HadISSTv1 (used in HiRAM), and the relative warming of the Atlantic coincides with the location of the largest PI trends in each product. In fact, the zero line of the relative SST trend in NCEP corresponds very well with the zero line of PI trends in the modified NCEP, in contrast to that in the original NCEP (Fig. 2.a) but similar to HiRAM (Fig. 2.b).

The influence of the differences in tropical-mean temperature trends on PI can be seen through the blue lines in Figure 3, which show area averaged evolution and trends of PI computed from the modified NCEP temperature, which result in global and local trends that are much more similar between HiRAM and the modified NCEP – although the year-to-year values can still differ. This analysis indicates that the dominant contribution to differences in trends in PI between the NCEP and HiRAM is the difference in the profile of tropical-mean atmospheric temperature trends in these two datasets.

So, from which atmospheric levels do the differences between HiRAM and NCEP temperature trends contribute the most to their differences in PI trends? In order to isolate these sources, we perform additional partial perturbations to the temperature profile in the NCEP, where we substitute *T*(x,y,p,t)* at and above a certain pressure level only. The results from these partial perturbations are shown in Figure 4, focusing on the TTL (in blue), UT (dark orange) and rest of troposphere (light orange). More than half the difference between HiRAM and NCEP tropical-mean (and regional, not shown) PI trends is due to differences in temperature trends in the TTL, primarily from the large differences at 100hPa and 150hPa. Differences in temperature trends at and above 70hPa have a negligible impact on the differences in PI trends between NCEP and HiRAM. The differences in temperature trends in the troposphere also contribute a substantial amount to the differences in PI trends between the NCEP and HiRAM, with the NCEP cooling between 150hPa and 300hPa and HiRAM warming at those levels.

Therefore, to the extent that PI is an important control on hurricane intensity and, possibly, frequency as well, it is crucial to understand temperature trends that impact its evolution. We have found that differences between HiRAM and NCEP in their temperature trends at 70 hPa and higher up have little influence on trends in PI. However, temperature trends below that - roughly from 300 to 100hPa - have a substantial impact on trends in PI, and correspondingly the uncertainties in tropical UT and TTL temperature trends are also a source of major uncertainty in trends of PI.

5. Atmospheric Heating Influences on HiRAM:

Using the HiRAM AGCM we explore the impacts on TC activity of idealized heating anomalies that affect the mean tropical temperature profile and compare the model's response to those in PI computed from the model's temperature structure. We are encouraged to analyze HiRAM due to the quality of its simulation of TC genesis – climatology, variability, and trends (Zhao et al, 2009, 2010). In order to efficiently isolate the impact of atmospheric heating anomalies we build off of a control experiment forced with monthly climatological SST, with no interannual variability, computed from HadISST (Rayner *et al.* 2003) over 1981-2005. Four perturbation experiments were generated in which spatially uniform and time-invariant atmospheric cooling anomalies of different amplitudes were imposed over two different pressure ranges, one targeting the TTL and the other the UT, see Table 1.

The impact of the prescribed cooling anomalies on tropical-mean temperature, averaged over 20 years of model simulation, can be seen in the left panel of Figure 6. For reference, the right panel of Figure 5 shows the linear trends in tropical-mean temperature from NCEP, HiRAM-AMIP and their difference. All of the idealized heating experiments exhibit their largest temperature anomalies in the TTL, even when the heating was applied to the UT. The UT temperature anomalies in the experiments where the heating is applied to the TTL is considerably smaller than that in which the heating is applied to the UT. In this model, UT heating is has large impact on the TTL, but TTL heating does not efficiently impact the UT. The atmospheric cooling perturbations also drive increases in precipitation and convective mass flux averaged through the tropics.

We expect that the cooling perturbations should lead to an increase in hurricane activity. This can be explored more explicitly and quantitatively by tracking hurricane-like vortices in the AGCM. Figure 6 shows the response of two metrics of global and Atlantic TC activity: i) fractional change in the number of hurricanes[1], and ii) the change in the ratio of hurricanes to TCs (HU/TC ratio), which can be interpreted as a measure of storm intensity in this AGCM that is too coarse to capture the most intense TCs (*e.g.,* Zhao and Held 2010). In these HiRAM AGCM experiments, the amplitude of the cooling in the TTL is not a useful metric by which to discriminate the response of these TC metrics: the largest TTL cooling is in experiment B5, but it has the second weakest response in either hurricane measure, weaker than C1, which has the smallest cooling of the TTL. However, the mean cooling of the UT (150hPa-300hPa) is well correlated to the response of global and Atlantic frequency and HU/TC ratio (left panels Figure 6).

We also explore the relationship between PI changes and frequency changes in the right panels of Figure 6. PI changes in this set of experiments are well correlated with the change in HU/TC ratio (Fig. 6.f), showing a response of ~5% per ms^{-1}. However, for hurricane frequency PI does not provide a clean description of the response across the four experiments – it can discriminate between the frequency response of the TTL and UT cooling experiments, but it cannot explain the differences in frequency response

[1] The maximum 10-meter wind speed obtained during the storm lifetime is used to define a TC or hurricane. Following the recommendation of Walsh (2007) for a model of this resolution, we reduce the standard criteria (17 m/s for TCs and 33m/s for hurricanes), by 10%. This adjustment has very little effect on the fractional changes in storm counts in the model.

across them. For example, for hurricane frequency experiments B4 and C1 have a similar PI change, but B4 does not have a significant change in frequency but C1 has a ~50% increase. The HiRAM AGCM shows sensitivity of TC intensity, but not of frequency, to PI changes.

The blue horizontal and green vertical lines place the model-estimated sensitivity of the various TC activity metrics in the context of the observed activity changes in the Atlantic and the differences between NCEP and HiRAM. Based on the HiRAM AGCM's sensitivity of frequency to UT temperature changes, the differences in UT temperature trends between NCEP and HiRAM project onto fractional changes that are comparable compared to the observed changes. That is, the differences between HiRAM and NCEP trends appear to be a first order effect relative to the observed TC frequency trends in the Atlantic in this AGCM. For the HU/TC ratio changes, the observed trends have been much smaller (indistinguishable from zero, but nominally -5% / 29 years – other observations measures of intensity show a clearer increase over this period; *e.g.,* Elsner *et al.* 2008) so the discrepancies between NCEP and HiRAM trends in their PI and UT temperature trends are proportionately large.

6. Summary and Discussion:

We have explored uncertainties in multi-decadal changes in atmospheric temperature, and their influence on TC PI and frequency. Over the period 1980-2008 multiple observational estimates agree that the troposphere has warmed and the stratosphere has cooled, but disagree on the magnitude of the tropospheric warming and its vertical structure, and on the character of temperature changes in them upper troposphere (UT) and tropical tropopause layer (TTL). The large differences in temperature trends between different observational estimates, and their difference to the trend in the HiRAM AGCM, project onto uncertainties in TC metrics.

We have focused on the differences (and impacts) of the 1980-2008 trends in the NCEP-NCAR Reanalysis (NCEP) and of the SST-forced GFDL-HiRAM AGCM because the HiRAM model has been used to explore the sensitivity of hurricanes to climate (*e.g.,* Zhao *et al.* 2009, 2010) and the NCEP has been used as a forcing to limited-domain models used to understand the hurricane-climate connection (*e.g.,* Knutson *et al.* 2007, 2008; Emanuel *et al.* 2008, 2012; Emanuel 2010). The trends from the NCEP-NCAR Reanalysis (NCEP) product deviate most strongly from the rest of the estimates explored, and show much stronger cooling of the TTL and upper troposphere than any other estimate, with cooling extending from the stratosphere to 300hPa. Overall, the tropical-mean and Atlantic temperature atmospheric temperature trends in HiRAM tend to be within the spread of the various non-NCEP estimates, while the trend in NCEP between 300hPa and 100hPa is an extreme outlier among the various products explored (Figure 1).

Trends over 1980-2008 in Bister and Emanuel (1998, 2002) TC potential intensity (PI) also differ considerably between NCEP and GFDL-HiRAM (Section 4). The 1980-2008 trends in PI from GFDL-HiRAM closely follow relative SST (the difference between local and tropical-mean SST changes), in agreement with estimates of multi-year to centennial sensitivity of PI in coupled and atmospheric models (*e.g.,* Vecchi and Soden 2007; Gualdi *et al.* 2008; Xie *et al.* 2010; Ramsay and Sobel 2011; Camargo *et al.* 2012). Meanwhile, because of a large tropical-mean increase in PI in NCEP, the PI trends in the

NCEP do not follow relative SST as closely, with large regions showing PI increases with relative SST decreases.

The differences in 1980-2008 trends in large-scale PI in NCEP and GFDL-HiRAM arise primarily because of differences in tropical-mean atmospheric temperature trends in both products, with the NCEP showing less warming/more cooling throughout the entire atmosphere. The principal contributors to the NCEP to GFDL-HiRAM difference in PI are temperature trends in the lower TTL (150 and 100hPa) and upper troposphere (between 300 and 150hPa), with differences in the lower troposphere leading to a relatively smaller (<20%) part of the PI differences. Temperature trend differences at and above 70hPa have a negligible impact on the difference of PI in these two products. The tropical UT and TTL cooling in NCEP leads to an overall increase in PI, while HiRAM shows no tropical-mean PI change over 1980-2008. The strong TTL and UT cooling in NCEP make trends in PI deviate from the tight relationship to relative SST that has been noted in other studies (*e.g.,* Vecchi and Soden 2007; Gualdi *et al.* 2008; Xie *et al.* 2010; Ramsay and Sobel 2011; Camargo *et al.* 2012). The tendency for NCEP to have a large tropical-mean trend in PI that has been noted in the literature (*e.g.,* Emanuel 2007, 2010) arises primarily from the large cooling in the lower TTL and UT in NCEP (Figure 3), features that are outliers among other observationally-based products (Figure 1). NCEP and HiRAM also use SST products that have exhibited different trends in tropical-mean and in patterns of SST (Figure 2; Vecchi and Soden 2007); so beyond differences associated with tropical-mean atmospheric temperatures, these differences in the patterns of SST change lead to differences in trends of regional PI between GFDL-HiRAM and NCEP.

In the idealized heating experiments with GFDL-HiRAM, a measure of intensity (the ratio of the number of hurricanes to TCs) shows a strong relationship to PI (Figure 6.f). Intensity changes in this AGCM are more strongly connected to PI than are frequency changes. While this model is of insufficient resolution to represent the full spectrum of TC intensity, this ratio is reasonably well simulated in the model and so the model provides a crude estimate of intensity changes (Zhao and Held 2010).

Observational analyses have found a high correlation between SST changes in the tropical Atlantic and hurricane activity indices (*e.g.,* Elsner and Jagger 2006; Emanuel 2005). However, observational correlations as high or higher have been found between hurricane activity and the weighted difference between Atlantic and tropical-mean SSTs (the SST changes in the Atlantic relative to the tropics, or “Relative SST”) by other studies (*e.g.,* Swanson 2007, 2008; Vecchi *et al.* 2008; Villarini *et al.* 2010, 2011.a, 2012; Villarini and Vecchi 2012). The physical basis for exploring relative SST as a predictor of hurricane activity is based on the tendency of free tropospheric temperature changes to follow those of tropical-mean SST (Sobel *et al.* 2002) or SSTs in the Indo-Pacific region where the bulk of tropical convection resides (Chiang and Sobel 2002; Tang and Neelin 2004) as described by the Weak Temperature Gradient approximation (Sobel and Bretherton 2000). An Atlantic SST warming that is larger than that of the tropical average, with a tropospheric warming in the Atlantic that follows tropical-mean SST, would lead to a large-scale destabilization of the atmosphere in the Atlantic, to changes in the large-scale vorticity, shear and atmospheric humidity, as well as to increases in TC potential intensity (*e.g.,* Latif *et al.* 2007; Vecchi and Soden 2007; Gualdi *et al.* 2008; Sugi *et al.* 2009, 2012; Zhao *et al.* 2009; Xie *et al.* 2010; Zhao and Held 2011; Ramsay and Sobel 2011; Camargo *et al.* 2012). Supporting the notion of relative SST as a predictor for Atlantic hurricane activity, dynamical modeling studies have found that the threshold for TC genesis under projected climate changes over the 21st century increases along with the overall tropical warming (*e.g.* Knutson *et al.* 2008), and the interannual, decadal and climate change response of North Atlantic TC frequency simulated with a across a range of dynamical frameworks is well explained by relative SST (*e.g.,* Vecchi *et al.* 2008; Sugi *et al.* 2009, 2012; Zhao *et al.* 2009, 2010; Vecchi *et al.* 2011; Villarini *et al.* 2011.a; Knuston *et al.* 2012; Zhao and Held 2012). Changes of tropical atmospheric temperatures that are relatively horizontally uniform and larger in the upper troposphere than at the surface (approximating a “moist adiabatic” warming profile) are crucial to the “relative SST” interpretation of hurricane activity changes. Therefore, the strong departure from approximately moist adiabatic warming seen in NCEP leads to a different interpretation of the role of tropical-mean warming on hurricane activity, in which tropical-mean changes are less effective at balancing the impact of local SST changes.

The multi-decadal evolution of atmospheric temperature and TC PI in the hindcast experiments with HiRAM (Zhao *et al.* 2009, 2010) differs considerably from that of NCEP, which was used in ZETAC (Knutson *et al.* 2007, 2008) and the downscaling studies of Emanuel *et al.* (2008; E08) – yet these three studies reported comparable hindcast skill in tropical Atlantic hurricane activity. Historical hindcasts with HiRAM (Zhao *et al.* 2009) and ZETAC (Knutson *et al.* 2007) over 1980-2006 reported linear trends in hurricane counts that were comparable to those observed (the ZETAC trends were slightly larger than those observed), as did the statistical-dynamical methodology of E08. This suggests that the sensitivity of Atlantic hurricane activity to changes in atmospheric temperature in these three systems may differ. However, the response of future projections by these three systems shows comparable sensitivity to relative SST (Villarini *et al.* 2010; Knutson *et al.* 2012) – suggesting some level of commonality in their sensitivity to climate. Can these results be reconciled?

Analysis of an extended time series (1980-2008) of hurricane frequency from HiRAM and ZETAC suggests a path towards reconciling the sensitivities of those two systems. The year-to-year correlations of Atlantic hurricane frequency in HiRAM and ZETAC to observations are comparable to each other and comparable to the results described in the original papers (Zhao *et al.* 2009; Knutson *et al.* 2007) over a shorter record. In addition, the ensemble of linear trends in Atlantic hurricane from HiRAM compares well with observed over the longer 1980-2008 period, as did the shorter record in Zhao *et al.* (2009). However, the addition of 2007 and 2008 to the original ZETAC 1980-2006 time series leads to an Atlantic hurricane trend that goes from being somewhat larger than that observed to more than twice that observed (we note that the 2007 and 2008 integrations with ZETAC were not available at the time that Knutson *et al.* (2007, 2008) were written). The difference in the HiRAM and ZETAC trends over 1980-2008 are qualitatively consistent with the expectation from the differences in the atmospheric temperature trends present in both systems, assuming they have similar sensitivities to atmospheric temperature change. Therefore, Atlantic hurricanes in HiRAM and ZETAC need not have fundamentally different sensitivities to climate.

Reconciling the behavior of HiRAM and E08 is more problematic. The E08 methodology shows a strong sensitivity of hurricane frequency to temperature changes in the TTL (Emanuel *et al.* 2012); meanwhile, HiRAM shows strong sensitivity of global and Atlantic hurricane frequency to temperature changes in the UT, but not to TTL changes (Section 5). We speculate that this difference in sensitivity to TTL temperatures is related to a distinct sensitivity of frequency to PI: in the E08 methodology PI is a primary thermodynamic constraint on storm genesis; while in the GFDL-HiRAM model there is no consistent emergent relationship between PI and genesis. Since PI is impacted by TTL temperature changes (Figure 4), frequency in the E08 methodology is sensitive to TTL changes. The relationship that sometimes appears between PI and frequency in HiRAM reflects a connection of both PI and genesis to upper tropospheric temperature (Figure 6.d-.e) and to patterns of SST (Zhao *et al.* 2009, 2010; Vecchi *et al.* 2011, Held and Zhao 2011), rather than a direct connection of PI to genesis. In global atmospheric (*e.g.* Sugi *et al.* 2002, 2012; Held and Zhao 2011; Zhao and Held 2012) and coupled (*e.g.,* Gualdi *et al.* 2008) models hurricane frequency tends to scale with changes in large-scale ascent, for which tropospheric stability is of greater relevance than TTL temperatures. At this stage, it appears that HiRAM and the E08 downscaling technique have distinct sensitivity to climate; in fact, a downscale of the HiRAM model shown here using E08 technique does not recover the trends in Atlantic hurricane frequency that emerge in the HiRAM model (Emanuel *et al.* 2012). We speculate that the similar sensitivity to relative SST in future projections from HiRAM and E08 (*e.g.*, Villarini *et al.* 2010; Knutson *et al.* 2012) arises because GCM projections of the future have an approximately moist adiabatic warming of the troposphere, in which both large-scale stability and potential intensity tend to follow relative SST – so the differences in genesis sensitivity in HiRAM and E08 are masked. The differences in sensitivity of HiRAM and

E08 are only apparent when atmospheric temperature changes depart strongly from a moist adiabatic profile.

All of the observationally-based temperature products explored here, as well as HiRAM, show a cooling of the TTL across the tropics – though they disagree in its magnitude. If, as the E08 methodology indicates, TTL cooling acts to increase hurricane frequency, one would perhaps expect to have seen an increase in global mean frequency since 1980. However, the observed record shows a non-significant decrease in global hurricane frequency (Zhao *et al.* 2009; Maue 2011). Meanwhile, HiRAM (which does not show a sensitivity of frequency to TTL temperature) is able to recover the observed global-mean hurricane trends, along with the increases seen in the Atlantic and decreases seen in the East and West Pacific (Zhao *et al.* 2009). The observed history of global hurricanes may indicate that TTL temperature changes are not a robust influence on hurricane frequency.

A question arises from this comparison of HiRAM, ZETAC and E08: how can we discriminate between diverging sensitivities in models that perform comparably in hindcast mode? The good quantitative agreement between observed and modeled hurricane history was key to building confidence in each system's representation of the sensitivity of hurricanes to climate. However, given the different climate changes that drove hurricane changes that resemble observations in each system, it is no longer sufficient to explore hurricane hindcast skill in the Atlantic alone. A clear assessment of the plausibility of the different temperature trend profiles that either emerge from or are fed to these systems now becomes crucial.

Currently there is considerable uncertainty as to the character of past tropical atmospheric temperature trends, which does not allow the rejection of the hypotheses that tropical-mean UT temperatures have warmed at a reduced, equal or larger rate than tropical-mean SST since the late-1970s from direct temperature observations (Thorne *et al.* 2005, 2011; Sherwood *et al.* 2008; Santer *et al.* 2008). However, indirect evidence from observed changes to the structure of zonal-mean wind (Allen and Sherwood 2008) and the SST threshold for strong convection (Johnson and Xie 2010) suggests that the tropical troposphere may have warmed approximately moist-adiabatically. Since the trends in atmospheric temperature at and below 100hPa in HiRAM are within the spread of the non-NCEP reanalyses and the radiosonde-only products (and are largely within the 32-member spread of RICH). On the other hand, the large discrepancies in trends of lower TTL and UT temperature between NCEP and the rest of the estimates explored here (Figure 1) suggest to us that it is unlikely to be an accurate representation of the multi-decadal trends in tropical atmospheric temperature that appear so influential to hurricane activity.

These results highlight the need to understand the mechanisms behind the history of tropical atmospheric temperature changes. In particular, if the tropical-mean troposphere has not been warming like GCMs between 300 hPa and 100 hPa, there are implications to the evolution of TC potential and actual intensity. According to the GCM utilized here, if there are departures from the moist adiabat below 150hPa, this could influence TC frequency. Currently, most dynamical model projections of the 21st century show something resembling moist adiabatic warming in the tropics, but if the models are deficient in a process, or a key forcing has been neglected, the likely future evolution of

TC statistics may differ from these projections. If current models overestimate the warming of the upper troposphere and lower TTL in response to increasing CO_2, we would expect that current projections of 21st century hurricane activity underestimate the potential for increases in frequency and intensity of TCs. On the other hand, if the underestimate of TTL cooling of the was due to misrepresentation of the impact of stratospheric ozone decreases, which are expected to recover over the coming century (WMO 2011), we would expect that projections for the coming century may overestimate the potential increases of TC intensity by not allowing for a "rebound" from ozone recovery.

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Table 1: Perturbation experiments run with HiRAM-C180 to explore impact of atmospheric cooling on TC frequency.

Experiment Name	SST Forcing	Radiative Forcing	Cooling Location	Cooling Rate
AMIP	Monthly 1979-2008 HadISST	Time-varying CO_2, O_3, natural and anthropogenic aerosols	--NA--	--NA--
CTL	Monthly HadISST climatology	Climatological CO_2, O_3 and aerosols	--NA--	--NA--
B4	" "	" "	75-150hPa	0.25 $K \cdot day^{-1}$
B5	" "	" "	75-150hPa	0.5 $K \cdot day^{-1}$
C1	" "	" "	150-300hPa	0.5 $K \cdot day^{-1}$
C2	" "	" "	150-300hPa	2.0 $K \cdot day^{-1}$

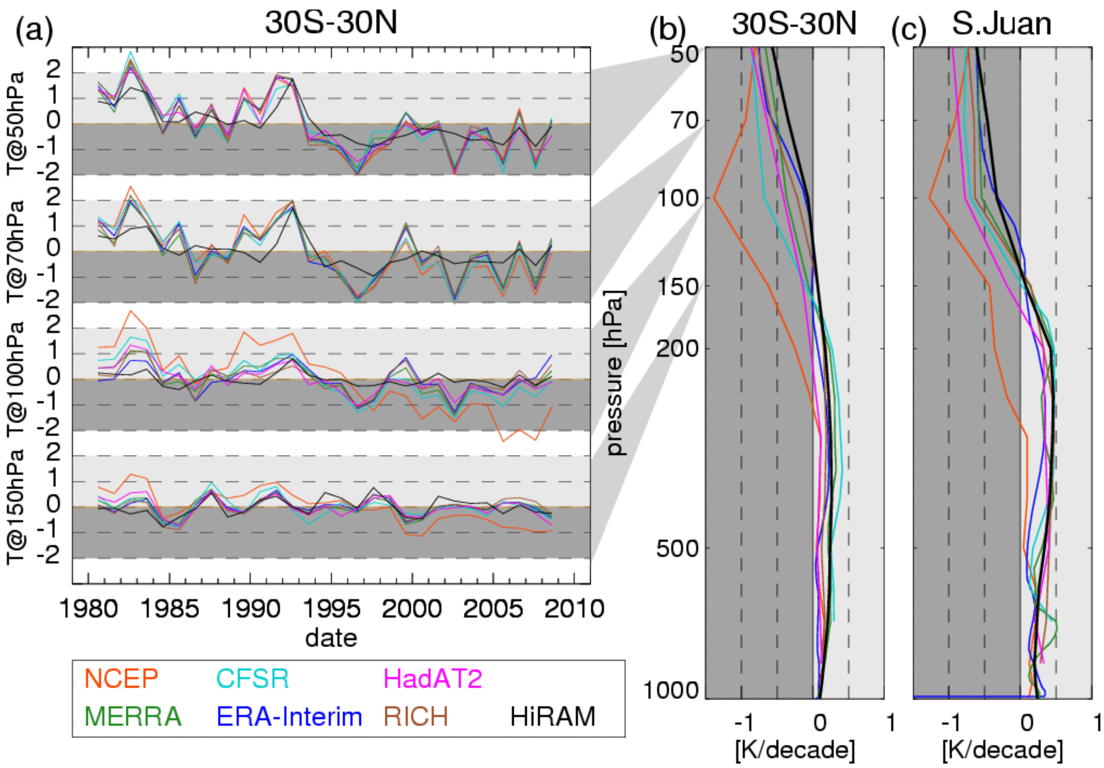

Figure 1: Estimates of 1980-2008 atmospheric temperature changes from six observationally-based products, including four assimilation products (NCEP/NCAR Reanalysis in red; NASA-MERRA in green, NOAA-CFSR in cyan, ECMWF-ERA-Interim in dark blue) and two radiosonde-only products (UKMO-HadAT2 in pink and the 32-member ensemble-mean RICH in brown), and from a three-member ensemble mean of the HiRAM-C180 AGCM. The left and center panels focus on tropical (30°S-30°N averages) and the right panel shows the data point nearest the radiosonde station at San Juan, Puerto Rico. Left time-series shows the evolution of annual-mean atmospheric temperature anomalies at three levels in the TTL (150hPa-70hPa) and one in the lower stratosphere. The center and right profiles show the linear least-squares trend of temperature over 1980-2008 for each product. Values in the time-series are in K, values of the trends are in K per decade.

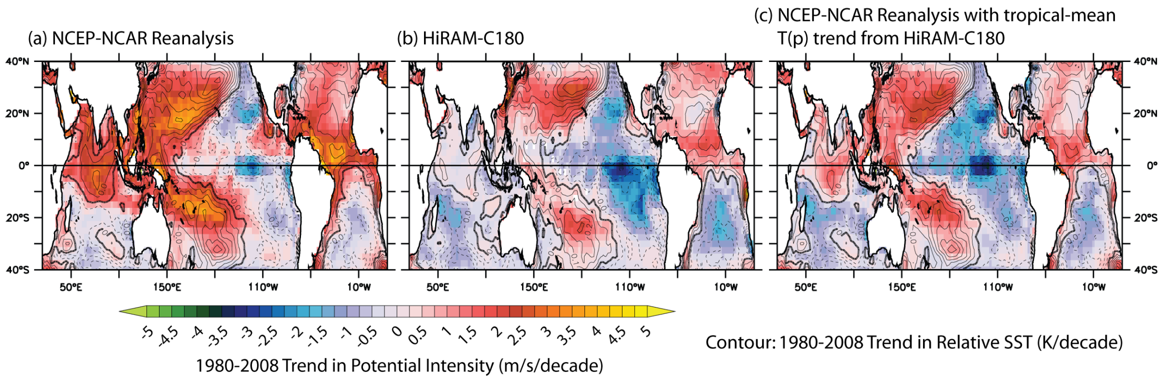

Figure 2: 1980-2008 linear-least-squares trends in monthly Bister and Emanuel (1998, 2002) PI (shaded) and relative SST (contour) computed from (a) NCEP-NCAR Reanalysis, (b) C180-HiRAM, and (c) adjusted NCEP-NCAR Reanalysis, in which the tropical-mean air temperature trend is replaced with that from C180-HiRAM (see Eq. 1). Relative SST is the difference between SST at a location and the tropical average (30°S-30°N), with units of K.

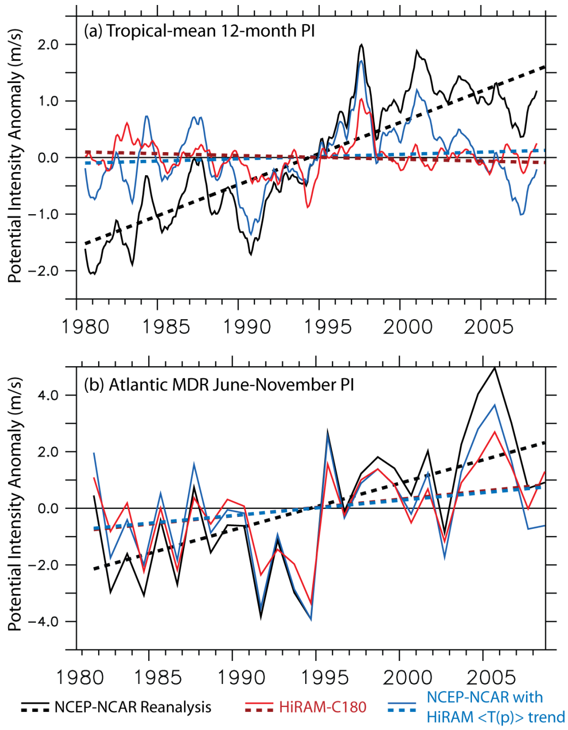

Figure 3: Time-series of Bister and Emanuel (1989) PI from NCEP (black), HiRAM-C180 (red) and the modified NCEP Reanalysis (blue), in which the tropical-mean atmospheric temperature trend is replaced with that from HiRAM-C180. Panel (a) shows the twelve-month running mean of tropical-mean (0°-360°, 30°S-30°N) PI; panel (b) shows the June-November average over the Atlantic hurricane main development region (MDR; 80°W-20°W, 10°N-25°N). Dashed lines show the 1980-2008 linear least-squares trends.

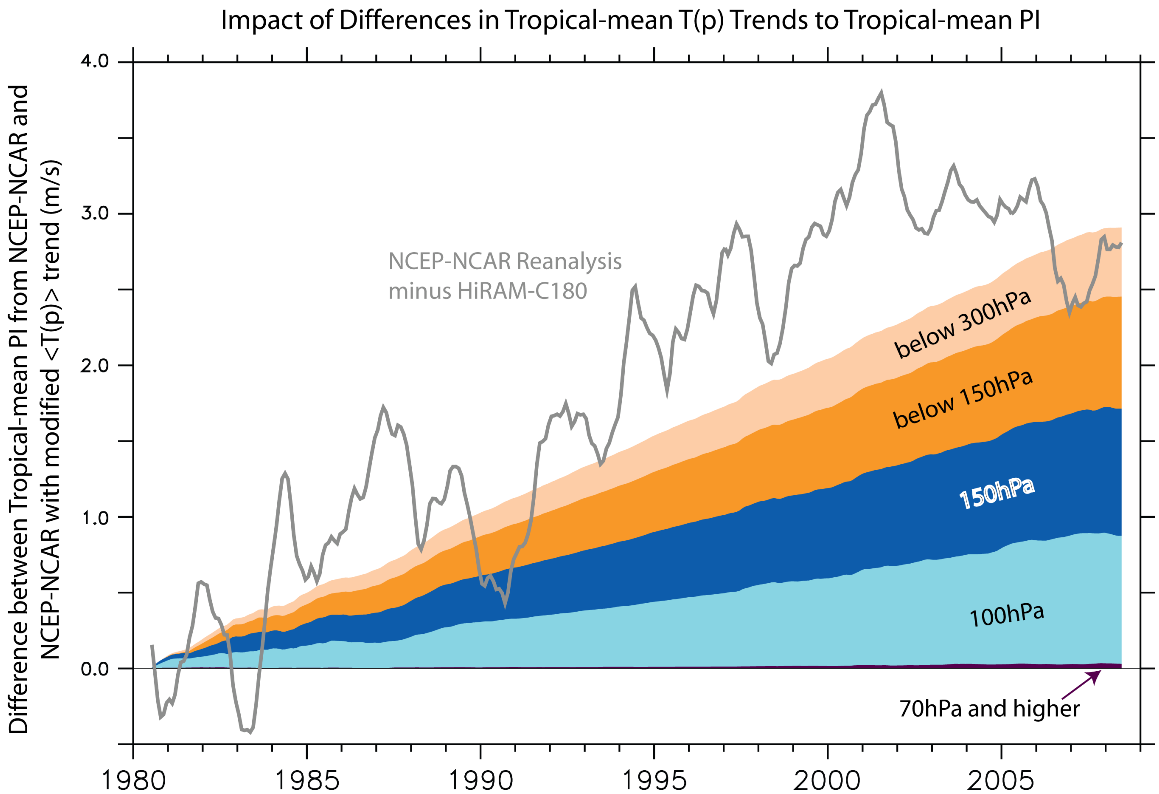

Figure 4: Contribution to PI differences between NCEP and HiRAM from different trends in tropical temperature at different atmospheric levels. The gray line shows the twelve-month running mean of the difference between tropical-mean PI in NCEP and HiRAM. The different wedges show the impact on tropical-mean PI of replacing the tropical-mean temperature trend in NCEP with that from HiRAM (see Section 4, Eq. 1).

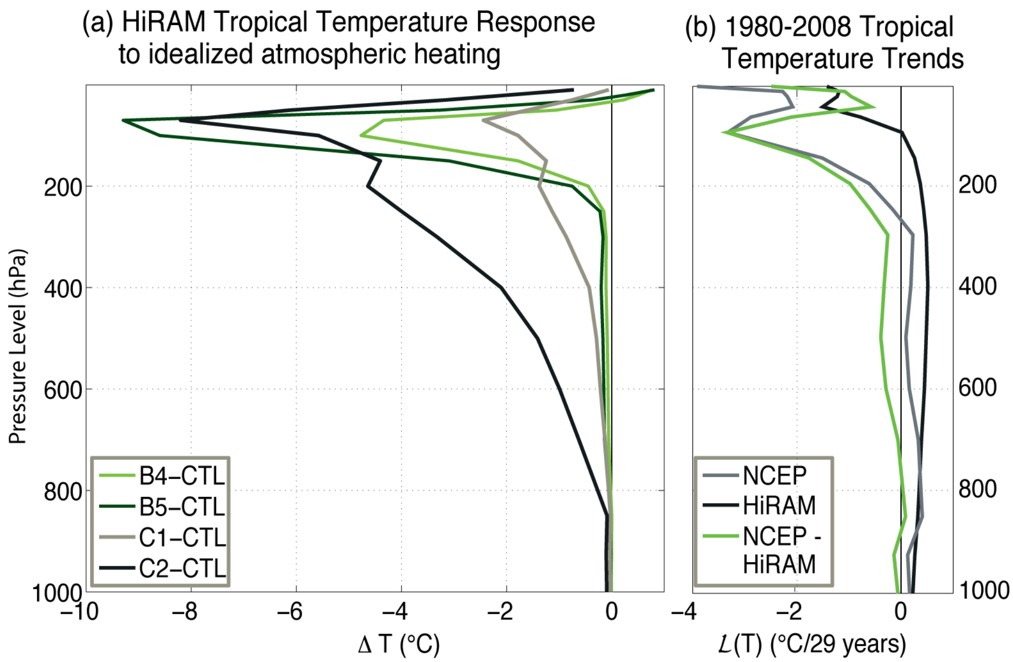

Figure 5: (a) Annual-mean tropical (30°S-30°N) atmospheric temperature response in HiRAM-C180 to the idealized tropospheric and TTL heating anomalies described in Table 1 and Section 5. (b) Tropical atmospheric temperature trends over 1980-2008 in NCEP (gray) and HiRAM AMIP (black); green line shows the difference between the NCEP and HiRAM AMIP trends.

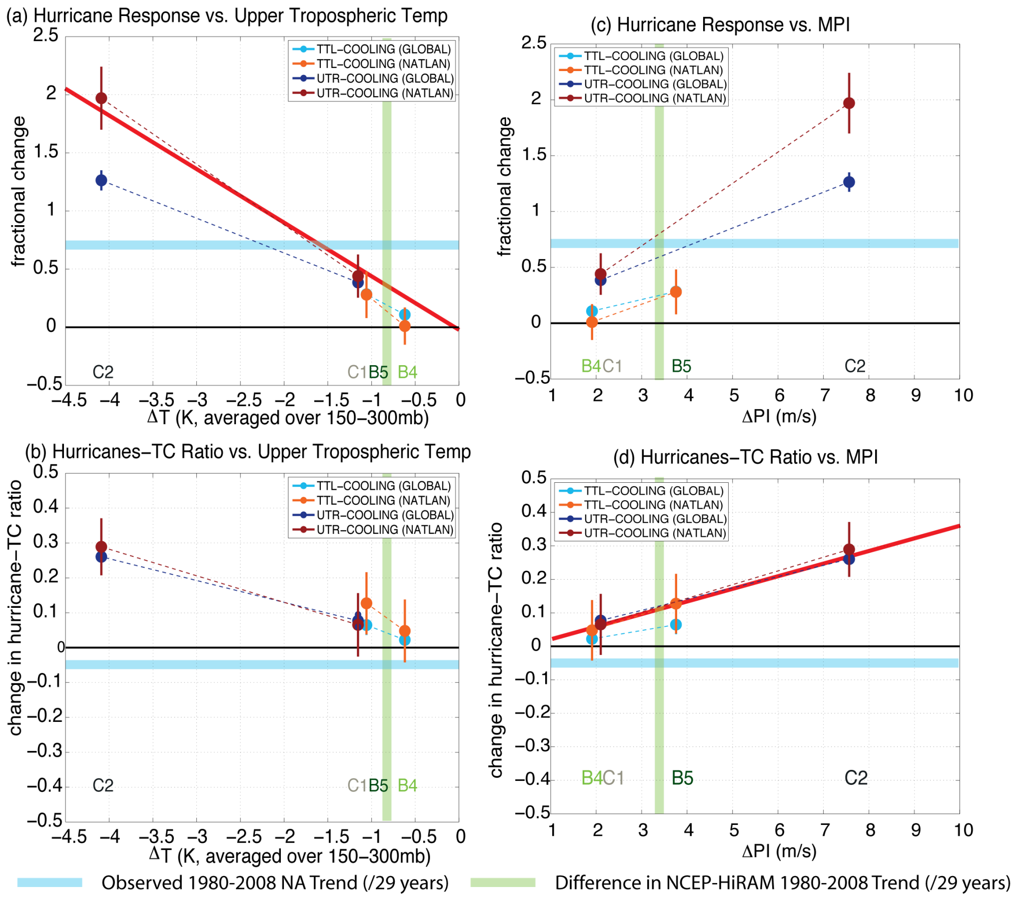

Figure 6: Response of TC activity in the Atlantic (red symbols) and globe (blue symbols) from HiRAM-C180 to the tropospheric and TTL heating experiments described in Table 1. Left panels plot measures of TC activity against the tropical-mean change in upper-tropospheric temperature. Right panels plot measures of TC activity against the tropical-mean change in Bister and Emanuel (1998, 2002) PI. Shown are the fractional change in hurricane frequency (top panels), and the change in the ratio of hurricane to TC frequency (bottom panels). The blue horizontal bars indicate the observed 1980-2009 trends in North Atlantic activity based on HURDAT; the green vertical bars indicate the difference in the 1980-2009 trends between NCEP and HiRAM. In panels (a) and (d), the solid diagonal red line shows the linear-least squares fit to the four North Atlantic points, with a zero intercept.

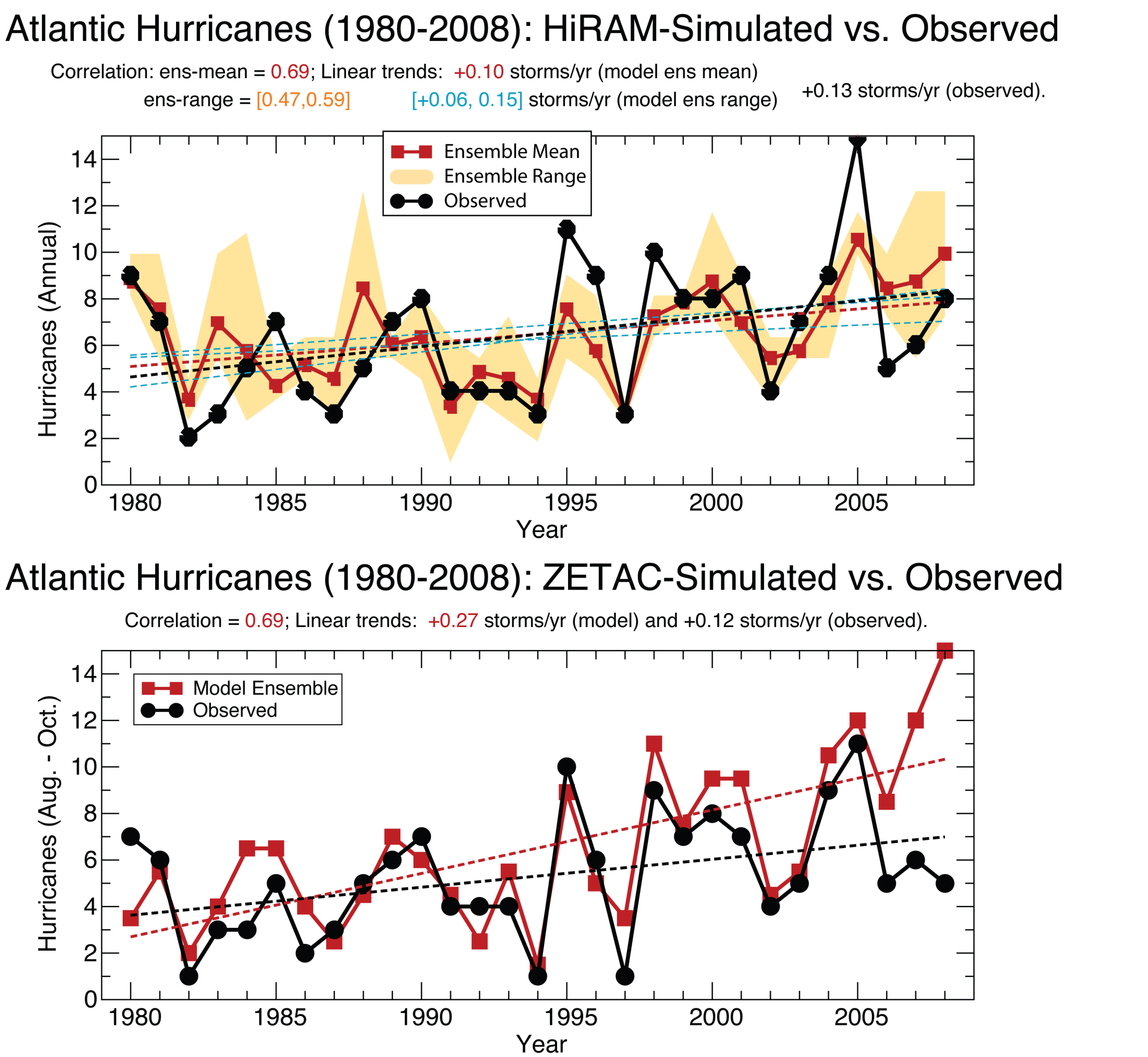

Figure 7: North Atlantic hurricane frequency in the HiRAM AGCM (Zhao *et al.* 2009, 2010; upper panel) and the ZETAC regional model (Knutson *et al.* 2007, 2008; lower panel), compared against observations. Upper panel is for annual hurricane frequency, lower panel is for August-October hurricane frequency. Black lines and circles show the evolution of hurricane frequency in observations (dashed line shows linear trend). Thick red line and squares shows the ensemble-mean evolution of each model; dark red dashed line shows the trend of the ensemble mean. In the upper panel the light orange shading shows the three member ensemble spread, and the dashed light blue lines show the trend of each ensemble member.