Impacts of Atmospheric Temperature Trends on Tropical Cyclone Activity

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ABSTRACT

Impacts of tropical temperature changes 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 temperature changes at 70 hPa and higher have negligible effect. Idealized experiments with a high-resolution global model show that lower temperatures in the UT are associated with increases in global and North Atlantic TC frequency, but modeled TC frequency changes are not significantly affected by TTL temperature changes nor do they scale directly with PI.

Future projections of hurricane activity have been made with models that simulate the recent upward Atlantic TC trends while assuming or simulating very different tropical temperature trends. Recent Atlantic TC trends have been simulated by (i) high-resolution global models with nearly moist-adiabatic warming profiles and (ii) regional TC downscaling systems that impose the very strong UT and TTL trends of the NCEP–NCAR reanalysis, an outlier among observational estimates. The impact of these differences in temperature trends on TC activity is comparable to observed TC changes, affecting assessments of the connection between hurricanes and climate. Therefore, understanding the character of and mechanisms behind changes in UT and TTL temperature is important to understanding past and projecting future TC activity changes. The UT and TTL temperature trends in the NCEP–NCAR reanalysis are unlikely to be accurate and likely drive spuriously positive TC and PI trends and an inflated connection between absolute surface temperature warming and TC activity increases.

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, hereafter K10), motivated in large part by the societal and economic impact of hurricanes (e.g., Pielke 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 hurricane activity changes and predictive capability for changes (e.g., Gray 1984; Elsner and Jagger 2006; Oouchi et al. 2006; Camargo et al. 2007; Knutson et al. 2007, 2008, 2013; Swanson 2007, 2008; Emanuel et al. 2008, hereafter E08; Gualdi et al. 2008; LaRow et al. 2008; Vecchi et al. 2008, 2011, 2013; Zhao et al. 2009, 2010; Bender et al. 2010; Chen and Lin 2011; Smith et al. 2010; Villarini et al. 2011a,b, 2012; Villarini and Vecchi 2012; Zhao and Held 2012). Most of these studies, as well as others (e.g., Emanuel 2005; Vecchi and Soden 2007; Ramsay and Sobel 2011), have focused

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attention on the role of sea surface temperature (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 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. 2013).

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; Murakami et al. 2012a) or coupled to ocean models (e.g., Gualdi et al. 2008; Smith et al. 2010; Scoccimarro et al. 2011) and 2) regional–limited-domain models that are forced by estimates of the large-scale three-dimensional (3D) structure of the atmosphere, in addition to SST (e.g., Knutson et al. 2007, 2008; E08; 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 large-scale 3D structure of the atmosphere.

In particular, as was shown in K10, the observed history of Atlantic hurricane activity (including the multidecadal 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 E08. This similarity in historical North Atlantic hurricane hindcast skill emerges even though these limited-domain models were forced with the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), which has tropical atmospheric temperature trends that are outliers when compared to other reanalyses and homogenized radiosonde data (e.g., Pawson and Fiorino 1998; Santer et al. 2004), and differ considerably from the tropical-mean moist-adiabatic warming and stratospheric cooling exhibited by the global models. Therefore, to the extent that atmospheric temperature changes have been important to hurricane activity, different limited-domain and global modeling systems 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.

To what extent do different estimates of past tropical atmospheric temperature changes impact hurricane activity in numerical models? In addition, at which pressure levels in the atmosphere are temperature/heating uncertainties–perturbations most influential? In this manuscript, specific attention is given to the possibility of an influence of temperatures in the upper troposphere (UT), tropical tropopause layer (TTL), and lower stratosphere on hurricane intensity and trends (e.g., Emanuel 2010; Emanuel et al. 2013). 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) and may not be captured by models that do not adequately simulate stratospheric dynamics and chemistry.

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 diabatic heating perturbations on hurricane activity in an AGCM. In section 6, we discuss the implications of these results for interpreting the fidelity of models used to make projections of hurricane activity. In section 7, we summarize our results and offer some discussion of their implications.

2. Data and methods

a. Observational analyses

We explore six 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 selected stations:

(i) the Met Office (UKMO) Hadley Centre Atmospheric Temperature, version 2 (HadAT2), analysis (Thorne et al. 2005) and
(ii) version 1.51 of the Radiosonde Innovation Composite Homogenization (RICH) made available at the University of Vienna (Haimberger et al. 2012), which is homogenized using information from neighboring radiosonde stations and 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 the National Oceanic and Atmospheric Administration (NOAA)/NCEP and NCAR, referred to as the NCEP–NCAR Global Reanalysis 1 (NCEP-1; Kalnay et al. 1996). The data used are on a monthly 2.5° × 2.5° grid and archived at 17 standard pressure levels.
(ii) The European Centre for Medium-Range Weather Forecasting (ECMWF) Interim Re-Analysis (ERA-Interim; Dee et al. 2011). The data used are on a monthly 1° × 1° grid and archived at 60 pressure levels between the surface and 0.1 hPa.
(iii) The Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011), produced by the National Aeronautics and Space Administration (NASA). The data used are on a monthly 1.25° × 1.25° grid with 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° × 2.5° longitude–latitude grid and archived at standard pressure levels with additional intermediate pressure levels.

The use of the older NCEP–NCAR reanalysis [bullet (i)], in addition to the three newer reanalyses [bullets (ii)–(iv)], is motivated by its use in several regional downscaling studies.

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 for SST and sea level pressure and profiles of atmospheric temperature and humidity, using FORTRAN code (available at ftp://texmex.mit.edu/pub/emanuel/TCMAX/).

c. Model: HiRAM

The High Resolution Atmospheric Model (HiRAM) is a global high-resolution atmospheric model developed at the Geophysical Fluid Dynamics Laboratory (GFDL) with a goal of providing an improved simulation of the statistics of tropical storms. At about 50-km horizontal grid size, HiRAM forced by the observed sea surface temperatures [Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST)] reproduces 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, the interannual variability, and the decadal trend of hurricane frequency over multiple ocean basins. HiRAM has also been used to study hurricane seasonal forecasting in the North Atlantic (Zhao et al. 2010; Chen and Lin 2011; Vecchi et al. 2011, 2013), with results supporting 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 (three-member ensemble) for GFDL's participation in the phase 5 of the Coupled Model Intercomparison Project (CMIP5) high-resolution time-slice simulations and the U.S. Climate Variability and Predictability (CLIVAR) Hurricane Working Group.

3. Observed and modeled temperature changes

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 Atmospheric Model Intercomparison Project (AMIP) experiment, focusing on the tropical average (30°S–30°N). Because hurricane changes in the tropical Atlantic have been a topic of particular interest in atmospheric general circulation models (AGCM) and limited-domain hindcasts, we also explore values at the data point nearest the San Juan, Puerto Rico radiosonde station (18°N, 66°W). Both in the tropical mean and at San Juan, all the observational estimates show long-term cooling in the lower stratosphere (50 hPa) and upper TTL (70 hPa), punctuated by warming in response to the eruptions of El Chichón (1983) and Pinatubo (1991). HiRAM shows weaker 50–70-hPa cooling than that of any of the observationally based estimates even though it is forced with estimates of past ozone changes and stratospheric aerosols, and it also shows reduced variability, in part because HiRAM does not have a good representation of the quasi-biennial oscillation (QBO; Baldwin et al. 2001).

In the lower TTL (100–150 hPa), HiRAM tends to track the observations relatively well. The NCEP–NCAR reanalysis stands out as an outlier among the observational estimates, by exhibiting very large cooling in the lower TTL and in the UT. Most observational estimates have the sign of the long-term trend in temperature change from negative to positive between 150 and 200 hPa, while that in NCEP-1 has its zero crossing below 250 hPa. The zero crossing for HiRAM, near 150 hPa, is higher than most observational estimates.

The results are similar over San Juan and in the tropical mean, with the outlier nature of NCEP-1 in the lower TTL and UT more notable than in the tropical mean. In

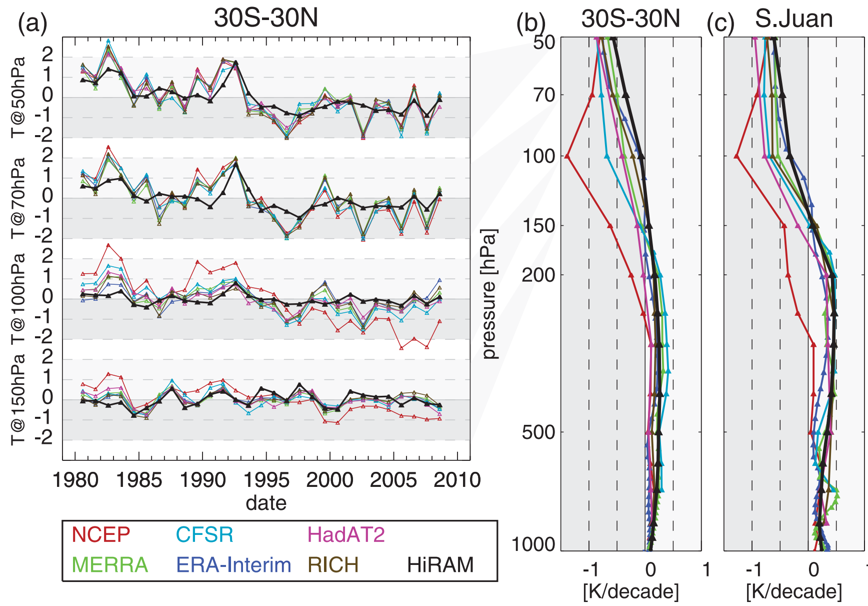

FIG. 1. Estimates of 1980–2008 atmospheric temperature changes from six observationally based products, including four assimilation products (NCEP–NCAR reanalysis in red, NASA MERRA in green, NOAA CFSR in cyan, and ERA-Interim in dark blue) and two radiosonde-only products (UKMO HadAT2 in pink and the 32-member ensemble-mean RICH in brown), and from a three-member ensemble mean of the HiRAM-C180 AGCM. (a),(b) Tropical (30°S–30°N) averages and (c) the data point nearest the radiosonde station at San Juan, Puerto Rico. In (a) the time series show the evolution of annual-mean atmospheric temperature anomalies at three levels in the TTL (150–70 hPa) and one in the lower stratosphere. (b),(c) The linear least squares trend of temperature over 1980–2008 for each product. Values in the time series are in K, and values of the trends are in K decade^{-1}.

the upper TTL, the trends from NCEP-1 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, NCEP-1 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 HiRAM deviate from the non-NCEP-1 datasets in the opposite direction to those of NCEP-1. In the UT, the temperature trends in HiRAM are less of an outlier, relative to the population, whereas the NCEP-1 trends depart from the population as a whole down to ~300 hPa.

Two divergent views of the past evolution of tropical atmospheric temperatures (NCEP-1 and HiRAM) have been used in assessments of the changes of hurricane activity since 1980. Exemplifying these two views, the GFDL Zeta-coordinate, nonhydrostatic, compressible (ZETAC) regional model (Knutson et al. 2007, 2008, 2013; Garner et al. 2009) and the statistical–dynamical methodology of E08 use the NCEP-1 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 (2012), and Held and Zhao (2011). Therefore, it is important to understand the extent to which these differences in the multidecadal 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-1, HiRAM, and MERRA reanalysis on the Bister and Emanuel (1998, 2002) TC PI. Overall, the differences in atmospheric temperature trends between NCEP-1, MERRA, and HiRAM in the Atlantic main development region (MDR; 10°–25°N, 80°–20°W) are of a similar character to those averaged over the tropics. The NCEP-1 PI trends differ from those of both HiRAM and MERRA PI across the tropics (Figs. 2a–c). NCEP-1 has positive PI trends almost everywhere in the tropics, which exceed 2.5 m s^{-1} decade^{-1} over large areas of the tropics. Meanwhile, MERRA and HiRAM PI are positive in as many places as they are negative, and the increases are almost everywhere less than 2 m s^{-1} decade^{-1}.

There are also differences between NCEP-1 and the two other datasets in the relationship between trends in

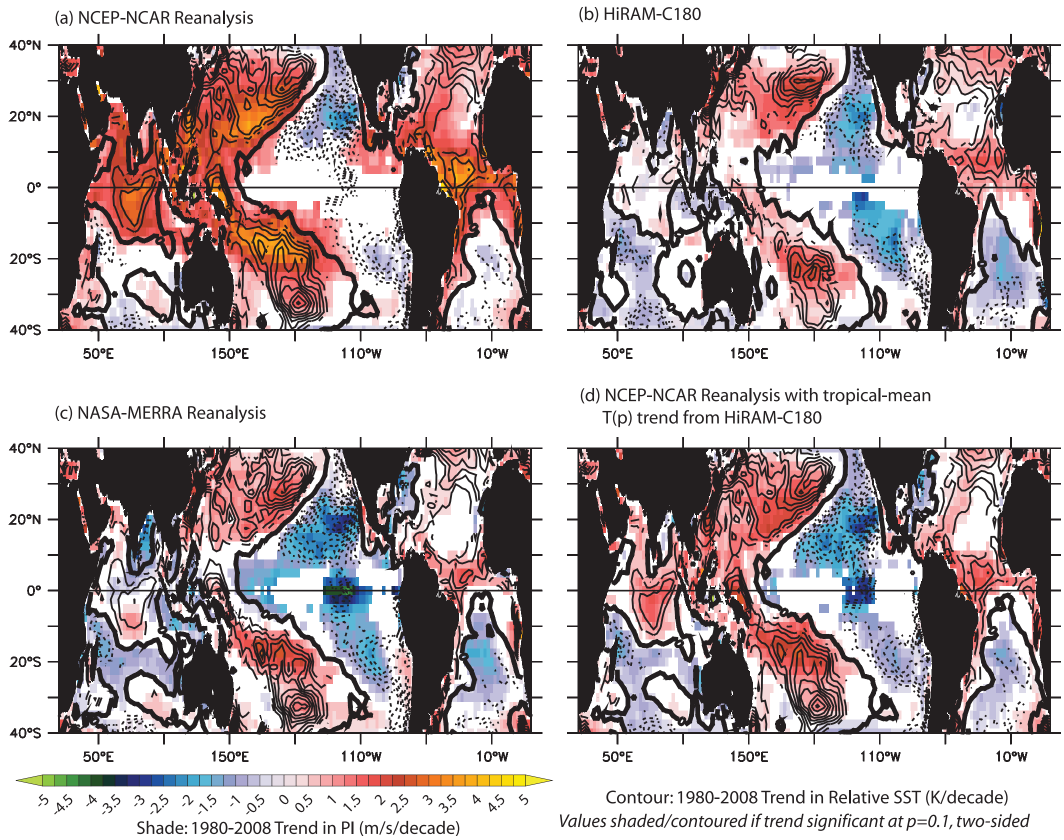

FIG. 2. The 1980–2008 linear least squares trends in monthly Bister and Emanuel (1998, 2002) PI (shaded) and relative SST (contours) computed from (a) NCEP–NCAR reanalysis; (b) C180-HiRAM; (c) NASA MERRA reanalysis; and (d) adjusted NCEP–NCAR reanalysis, in which the tropical-mean air temperature trend is replaced with that from C180-HiRAM [see Eq. (1)]. Relative SST is the difference between SST (K) at a location and the tropical average (30°S–30°N). Values are only shaded and contoured if the trends are significantly different from zero at $p = 0.1$ using a two-sided Student's t test (Zwillinger 1996, p. 627), adjusting the degrees of freedom using the lag-1 autocorrelation of the linear trend residuals as in Bretherton et al. (1999). The zero relative SST line is indicated by the thick black contour.

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. 2008; Xie et al. 2010; Ramsay and Sobel 2011; Camargo et al. 2013). The patterns of PI trends exhibit some relationship to patterns of SST change in both datasets but, while in HiRAM and MERRA the zero line of relative SST trends corresponds strongly to the zero line of PI trends, in NCEP-1 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 of NCEP-1 with those of HiRAM and MERRA emerge clearly in their tropical-mean behavior (Fig. 3a), with NCEP-1 showing a clear increase but little change in HiRAM and a slight decrease in MERRA. The difference in PI trends emerges in the regional, seasonal PI as well; for example, Fig. 3b shows time series of PI from NCEP-1, HiRAM, and MERRA averaged over the Atlantic hurricane MDR (10°–25°N, 80°–20°W) over the hurricane season (June–November). All three products exhibit increases in MDR PI over the 1980–2008 period, but the increase in NCEP-1 is more than twice as large as that in HiRAM or MERRA. The difference in the trend of June–November North Atlantic PI (Fig. 3b) between the three products is comparable to the tropical-mean differences (Fig. 3a).

PI depends on the surface enthalpy disequilibrium as well as the vertical profile of temperature in the atmosphere, with larger enthalpy disequilibrium or lower UT–TTL temperatures leading to larger PI. The main source of the difference between HiRAM and NCEP-1 PI trends is the difference in tropical-mean atmospheric temperature trends. To demonstrate this, we recomputed PI from the NCEP-1 data, after replacing the NCEP-1 tropical-mean temperature linear least squares trend at each point with that from HiRAM. We scale the HiRAM

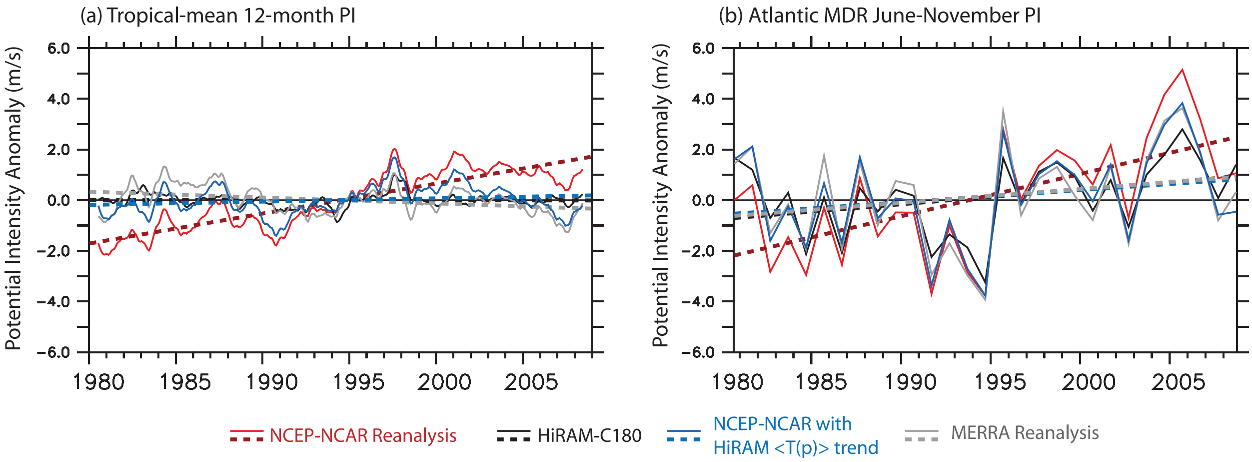

FIG. 3. Time series of Bister and Emanuel (1998) PI from NCEP-1 (red); HiRAM-C180 (black); MERRA (gray); and the modified NCEP-1 (blue), in which the tropical-mean atmospheric temperature trend is replaced with that from HiRAM-C180. (a) The 12-month running mean of tropical-mean (30°S–30°N, 0°–360°) PI and (b) the June–November average over the Atlantic hurricane MDR (10°–25°N, 80°–20°W). Dashed lines show the 1980–2008 linear least squares trends.

temperature change by the SST trend in NCEP-1 in order to isolate the impact of differences in the profile of tropical-mean temperature trend on PI. The modified temperature profile T^* at each point is

$$T^*(x, y, p, t) = T_N(x, y, p, t) - \mathcal{L}_{\langle T_N \rangle}(p)t + \frac{\mathcal{L}_{\langle T_H \rangle}(p)\mathcal{L}_{\langle S_N \rangle}}{\mathcal{L}_{\langle S_H \rangle}}t, \tag{1}$$

where T_N and S_N are the NCEP-1 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 $\langle \cdot \rangle$ is the tropical average of a quantity. Differences between the NCEP-1 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-1 and HiRAM. We refer to this modified NCEP-1 temperature field as NCEP*.

As can be seen in Fig. 2d, the PI trends over the globe are very similar between HiRAM and NCEP*, indicating that a large contribution to the regional differences in PI trend between NCEP-1 and HiRAM arises from differences in tropical-mean atmospheric temperature trends. There are still differences between the NCEP* and HiRAM trends in certain regions: NCEP* has its largest Atlantic PI increase off the coast of South America, while HiRAM has its largest positive Atlantic trends off the coast of Africa. However, these regional differences are much smaller than the differences between NCEP-1 and HiRAM.

Differences in regional PI trends between the NCEP* and HiRAM may be tied to differences in their relative SST trends; this HiRAM experiment is forced with the HadISSTv1 product (Rayner et al. 2003), while NCEP-1 uses a different optimal-interpolation estimate of SST (Kalnay et al. 1996). For example, 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-1 corresponds very well with the zero line of PI trends in NCEP*, in contrast to that in the original NCEP-1 (Fig. 2a) but similar to HiRAM (Fig. 2b) and MERRA (Fig. 2c).

The influence of the differences in tropical-mean temperature trends on PI can be seen by comparing the red and blue lines in Fig. 3; area-averaged evolution and trends of PI computed from the NCEP* temperature are much more similar to those in HiRAM and MERRA than to NCEP-1, although the year-to-year values can still differ from HiRAM. This analysis indicates that the dominant contribution to differences in trends in PI between NCEP-1 and HiRAM is the difference in the profile of tropical-mean atmospheric temperature trends in these two datasets.

To determine the atmospheric levels that contribute most to these PI differences, we perform additional partial perturbations to the temperature profile in NCEP-1, 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 Fig. 4, focusing on the TTL (blue), UT (dark orange), and the rest of the troposphere (light orange). More than half the difference between HiRAM and NCEP-1 tropical-mean (and regional, not shown) PI trends is due to differences in temperature

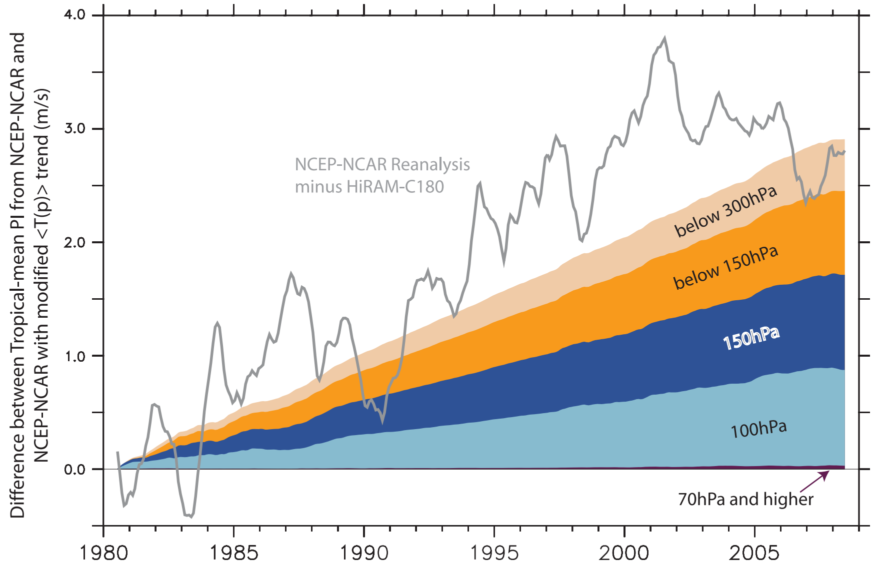

FIG. 4. Contribution to PI differences between NCEP-1 and HiRAM from different trends in tropical temperature at different atmospheric levels. The gray line shows the 12-month running mean of the difference between tropical-mean PI in NCEP-1 and HiRAM. The different wedges show the impact on tropical-mean PI of replacing the tropical-mean temperature trend in NCEP-1 with that from HiRAM [see section 4, Eq. (1)].

trends in the TTL, primarily from the large differences at 100 and 150 hPa. Differences in temperature trends at and above 70 hPa have a negligible impact on the differences in PI trends between NCEP-1 and HiRAM. The differences in temperature trends in the troposphere also contribute a substantial amount to the differences in PI trends between the NCEP-1 and HiRAM, with NCEP-1 cooling between 150 and 300 hPa and HiRAM warming at those levels (Fig. 1).

Therefore, to the extent that PI is an important control on hurricane intensity and possibly frequency as well (e.g., Emanuel and Nolan 2004; Emanuel 2007; Emanuel et al. 2008), it is important to understand temperature trends that impact its evolution. We have found that differences between HiRAM and NCEP-1 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 100 hPa—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 diabatic heating perturbation 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 because of the quality of its simulation of TC genesis: climatology, variability, and trends (Zhao et al. 2009, 2010). 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 horizontally uniform and time-invariant atmospheric diabatic cooling rates of different amplitudes were imposed to produce a prescribed temperature perturbation with two different vertical structures, with one targeting the TTL and the other targeting the UT (see Table 1).

The impact of the prescribed diabatic cooling rates on tropical-mean temperature, averaged over 20 yr of model simulation, is shown (Fig. 5, left). For reference, the right panel of Fig. 5 shows the linear trends in tropical-mean temperature from NCEP-1, HiRAM AMIP, and their difference. All of the idealized heating experiments exhibit their largest temperature anomalies in the TTL, even when the heating is applied to the UT. In this model, UT heating 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.

The model response in hurricane activity can be explored by tracking hurricane-like vortices in HiRAM;

TABLE 1. Perturbation experiments run with HiRAM-C180 to explore impact of atmospheric cooling on TC frequency. Radiative forcing also includes aerosols.

Expt name	SST forcing	Radiative forcing	Cooling location (hPa)	Diabatic cooling rate (K day^{-1})	Temperature anomaly	
					75–150 hPa	150–300 hPa
AMIP	Monthly 1979–2008 HadISST	Time-varying CO_2, O_3	—	—	—	—
CTL	Monthly HadISST climatology	Climatological CO_2, O_3	—	—	—	—
TT1	Monthly HadISST climatology	Climatological CO_2, O_3	75–150	0.25	−3.6	−0.62
TT2	Monthly HadISST climatology	Climatological CO_2, O_3	75–150	0.375	−5.4	−0.87
TT3	Monthly HadISST climatology	Climatological CO_2, O_3	75–150	0.5	−7.0	−1.1
UT1	Monthly HadISST climatology	Climatological CO_2, O_3	150–300	0.5	−1.8	−1.2
UT2	Monthly HadISST climatology	Climatological CO_2, O_3	150–300	1.25	−3.5	−2.2
UT3	Monthly HadISST climatology	Climatological CO_2, O_3	150–300	2.0	−6.1	−4.1

we identify TCs from the model output using instantaneous values every 6 h of 850-hPa vorticity, sea level pressure, surface wind, and upper-tropospheric temperature, as in Zhao et al. (2009). 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, which 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 TT3, but it has the third weakest response in either hurricane measure, weaker than all the UT experiments, which have smaller cooling of the TTL. However, the mean cooling of the UT (150–300 hPa) is well correlated to the response of global and Atlantic frequency and HU/TC ratio (Fig. 6, top).

We also explore the relationship between PI changes and frequency changes in the bottom panels of Fig. 6. PI changes in this set of experiments are well correlated with the change in HU/TC ratio (Fig. 6d), showing a response of ~5% $(m\ s^{-1})^{-1}$. However, for hurricane frequency PI does not provide a clean description of the response across the six experiments: it can discriminate between the frequency response of the TTL and UT cooling experiments, but it cannot explain the differences in frequency response across them. For example, experiments TT3 and UT2 have a similar PI change, but hurricane frequency in TT3 changes increases by less than 30% while UT2 has a ~90% 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-1 and HiRAM. Based on the HiRAM AGCM's sensitivity of frequency to UT temperature changes, the differences in UT temperature trends between NCEP-1 and HiRAM project onto fractional changes that are comparable compared to the observed changes. That is, the impact on hurricane activity of the PI and UT temperature differences between HiRAM and NCEP-1 trends in this AGCM appear to be a first-order effect relative to the observed TC frequency trends in the Atlantic in this AGCM. Meanwhile, the estimated impact of the differences of PI and UT temperature trends between HiRAM and MERRA is a small fraction of observed changes. For the HU/TC ratio changes, the observed trends have been much smaller [indistinguishable from zero but nominally $-5\%\ (29\ yr)^{-1}$: other observations measures of intensity show a clearer increase in the Atlantic over this period; e.g., Elsner et al. (2008)] so the discrepancies between NCEP-1 and HiRAM trends in their PI and UT temperature trends are proportionately large.

6. Reconciling sensitivities in hurricane downscale methodologies

The multidecadal evolution of atmospheric temperature and TC PI in the hindcast experiments with HiRAM (Zhao et al. 2009, 2010) differs considerably from that of NCEP-1, which was used in ZETAC (Knutson et al. 2007, 2008) and the downscaling studies of E08; yet these three studies reported comparable hindcast skill in tropical Atlantic hurricane activity (see Fig. 1 of K10 for a comparison of all three methodologies). Historical hindcasts with HiRAM (Zhao et al. 2009) and ZETAC

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

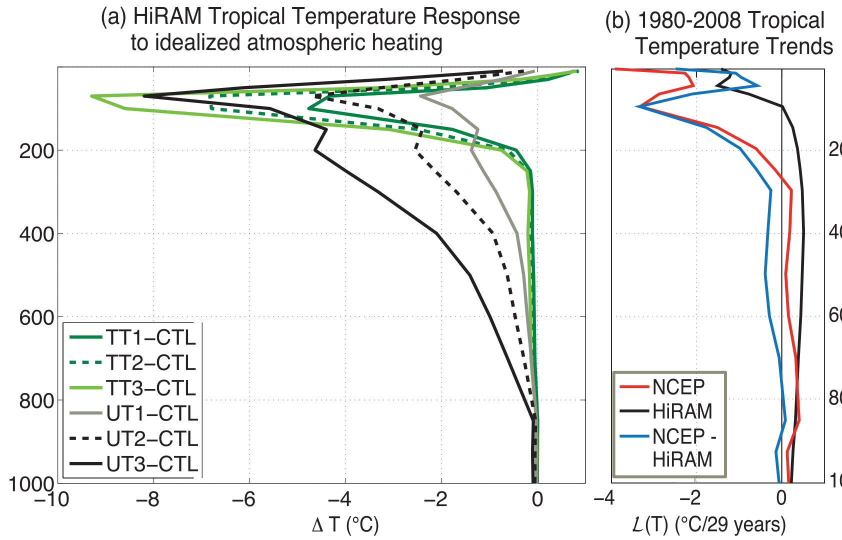

FIG. 5. (a) Annual-mean tropical (30°S–30°N) atmospheric temperature response in HiRAM-C180 to the idealized tropospheric and TTL heating anomalies described in Table 1 and section 5. (b) Tropical atmospheric temperature trends over 1980–2008 in NCEP-1 (red) and HiRAM AMIP (black); the blue line shows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

(Knutson et al. 2007) over 1980–2006 reported linear trends[2] 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 the atmospheric temperature profile 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. 2013), suggesting some level of commonality in their sensitivity to climate.

Figure 7 shows an extended time series (1980–2008) of hurricane frequency from HiRAM and ZETAC and suggests a path toward 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 [the 2007 and 2008 integrations with ZETAC were not available for Knutson et al. (2007, 2008)]. The difference in the HiRAM and ZETAC trends over 1980–2008 is 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. We hypothesize that the unrealistically large trend in ZETAC hurricane counts over 1980–2008 reflects the influence of an unrealistic cooling of the UT in NCEP-1 and that ZETAC simulations with large-scale conditions like those of HiRAM or MERRA would produce more realistic hurricane frequency trends; experiments are underway to explicitly test this hypothesis.

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. 2013); 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 difference in sensitivity of frequency to PI: in the E08 methodology PI is a primary thermodynamic constraint on storm genesis, while in HiRAM there is no consistent emergent relationship between PI and genesis. Since PI is impacted by TTL temperature changes (Fig. 4),

[2] We note that, since hurricane frequency is not normally distributed, caution should be exercised in interpreting linear least squares trends.

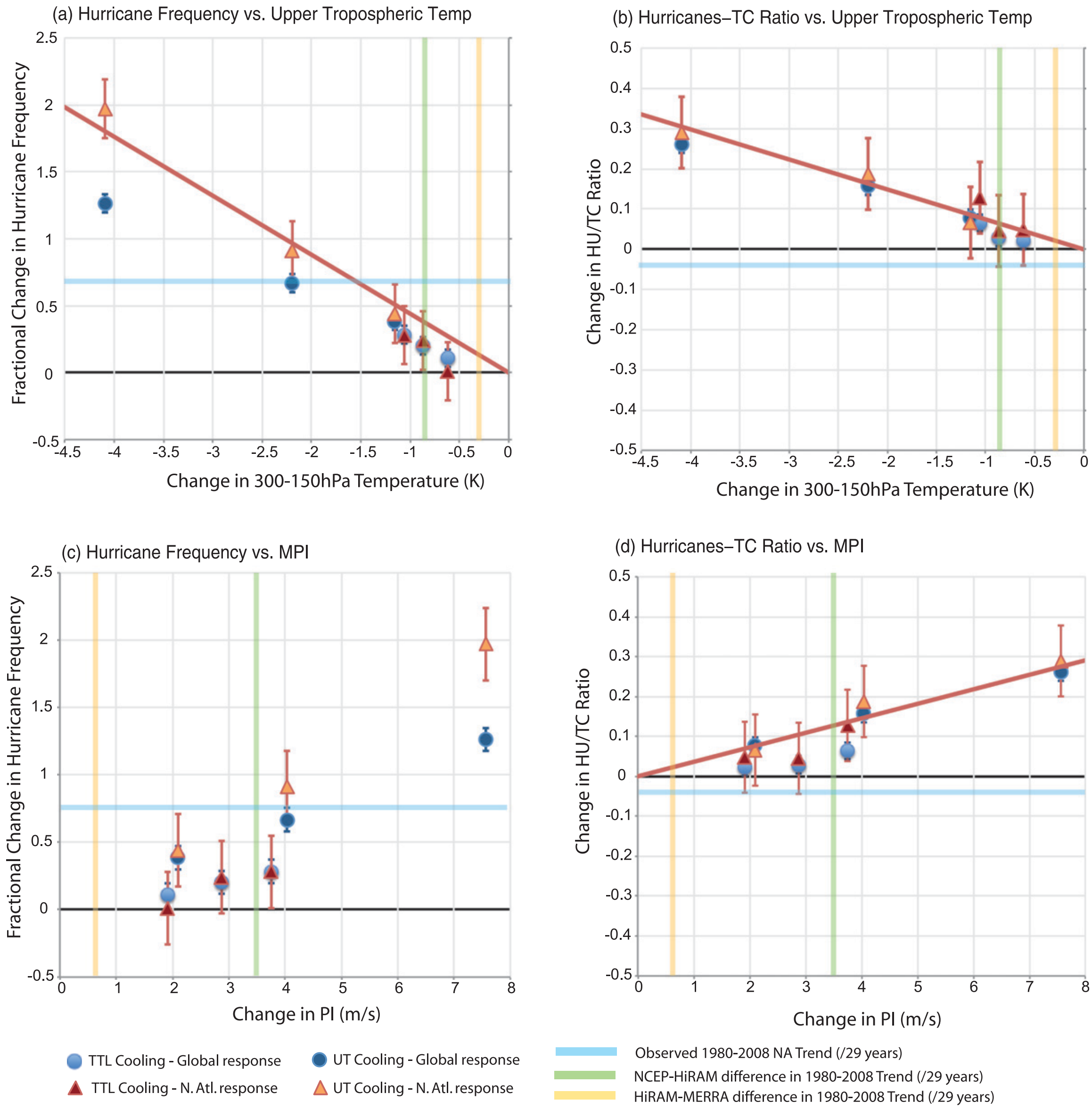

FIG. 6. Response of TC activity in the Atlantic (red symbols) and the globe (blue symbols) from HiRAM-C180 to the UT and TTL heating experiments described in Table 1. (a),(b) Plots of measures of TC activity against the tropical-mean change in upper-tropospheric temperature. (c),(d) Plots of measures of TC activity against the tropical-mean change in Bister and Emanuel (1998, 2002) PI. (a),(c) The fractional change in hurricane frequency and (b),(d) the change in the ratio of hurricane to TC frequency. The blue horizontal bars indicate the observed 1980–2008 trends in North Atlantic activity based on the Atlantic Hurricane Database (HURDAT; Jarvinen et al. 1984); the green vertical bars indicate the difference in the 1980–2008 trends between NCEP-1 and HiRAM. In (a),(d), the solid diagonal red line shows the linear least squares fit to the six North Atlantic points, with a zero intercept.

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 (Figs. 6d,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; Murakami et al. 2012b; 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 monthly midtropospheric vertical velocity, for which tropospheric stability is of greater relevance than TTL temperatures.

It appears that HiRAM and the E08 downscaling technique have distinct sensitivity to climate; in fact, a downscale of HiRAM shown here using E08 technique

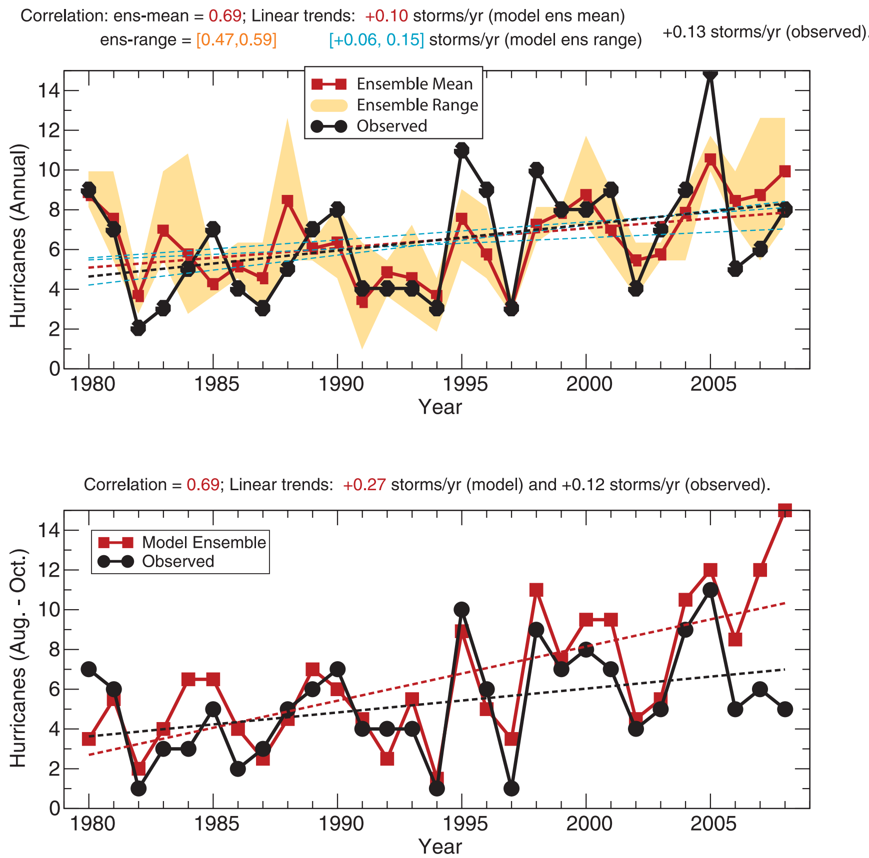

FIG. 7. (top) The North Atlantic annual hurricane frequency from the HiRAM AGCM (Zhao et al. 2009, 2010) and (bottom) the August–October frequency from the ZETAC regional model (Knutson et al. 2007, 2008), compared against observations. Black lines with circles show the evolution of hurricane frequency in observations (dashed line shows linear trend). The thick red line with squares shows the ensemble-mean evolution of each model; the dark red dashed line shows the trend of the ensemble mean. In (top), the light orange shading shows the three-member ensemble spread and the dashed light blue lines show the trend of each ensemble member.

does not recover the trends in Atlantic hurricane frequency that emerge in HiRAM (Emanuel et al. 2013). We speculate that the similar sensitivity to relative SST in future projections from HiRAM and E08 (e.g., Villarini et al. 2011b; Knutson et al. 2013) 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.

7. Summary and discussion

We have explored uncertainties in multidecadal 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 sign of temperature changes in the upper troposphere (UT) and tropical tropopause layer (TTL). The large differences in temperature trends between different observational estimates, as well as their difference to the trend in the HiRAM AGCM, project onto uncertainties in TC metrics.

We have focused primarily on the differences (and impacts) of the 1980–2008 trends in the NCEP–NCAR reanalysis (NCEP-1) and of the SST-forced HiRAM AGCM because HiRAM has been used to explore the sensitivity of hurricanes to climate (e.g., Zhao et al. 2009, 2010) and NCEP-1 has been used as a forcing to limited-domain models used to understand the hurricane–climate connection (e.g., Knutson et al. 2007, 2008; E08; Emanuel et al. 2013; Emanuel 2010). The trends from the NCEP-1 reanalysis product deviate most strongly from the rest of the estimates explored in this paper and show much stronger cooling of the TTL and UT than any other estimate, with cooling extending from the stratosphere to 300 hPa (Fig. 1). Overall, the tropical-mean and Atlantic atmospheric temperature trends in HiRAM tend to be within the spread of the various non-NCEP-1 estimates, while the trend in NCEP-1 between 300 and 100 hPa is an extreme outlier among the various products explored (Fig. 1).

Trends in TC potential intensity (PI) calculated according to Bister and Emanuel (1998, 2002) using NCEP-1 data differ considerably from those using the newer MERRA data or using model data from the HiRAM AGCM. The principal contributors to the difference between PI trends from NCEP-1 and the other data are the differences in the temperature trends of the UT (300–150 hPa) and lower TTL (150–100 hPa). NCEP-1 reports a substantial cooling of these layers, and correspondingly PI calculated from NCEP-1 data shows a positive trend. Temperature trend differences in the upper TTL and higher have negligible impact on PI, while differences in lower-tropospheric temperature trends contribute <20% to the PI trend differences. Over the period 1980–2008, tropical-mean PI calculated from HiRAM data does not show a significant trend, while that calculated from MERRA shows a decrease.

The strong TTL and UT cooling in NCEP-1 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. 2013). The large tropical-mean trend in PI that has been noted in the literature (e.g., Emanuel 2007, 2010; Emanuel et al. 2013) arises primarily from the large cooling in the lower TTL and UT in NCEP-1 (Fig. 3), which is not evident in the HiRAM integrations or in the radiosonde observations and more modern reanalysis (Figs. 1–3).

Beyond differences in atmospheric temperature trends, NCEP-1, MERRA, and HiRAM also use SST products that have exhibited different trends in tropical mean and in patterns of SST (Fig. 2; Vecchi and Soden 2007). These differences in the patterns of SST change lead to differences in trends of regional PI between HiRAM, MERRA, and NCEP-1. There are indications that differences in SST reconstructions can also lead do differences in the vertical structure of atmospheric temperature change (Po-Chedley and Fu 2012).

In sensitivity experiments with an idealized diabatic heating anomaly imposed on HiRAM (section 5), a measure of intensity (the ratio of the number of hurricanes to TCs) shows a strong relationship to both PI and UT temperature change (Fig. 6). 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). In HiRAM, there is no direct dependence of TC frequency on PI, with an indirect covariation coming through the dependence of both TC frequency and PI on UT temperature changes. That is, HiRAM does not support the use of PI as a genesis index.

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 nonsignificant 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.

If the spread in tropical atmospheric temperature trends shown in Fig. 1 represents our true uncertainty about the character of past tropical temperature trends, then there is a large resulting limitation in our ability to attribute the causes of past trends and project future changes in hurricane frequency and intensity. However, the spread temperature trends in the UT is dominated by NCEP-1, so one must consider whether the upper-tropospheric cooling in NCEP-1 is as plausible as the other estimates shown in Fig. 1. Although 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, there is growing evidence that the tropical upper troposphere has warmed (Thorne et al. 2005, 2011; Santer et al. 2005, 2008; Sherwood et al. 2008; Po-Chedley and Fu 2012; Seidel et al. 2012). Further, 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 has warmed, perhaps approximately moist adiabatically. Other questions have been raised in the literature regarding the accuracy of atmospheric trends in

NCEP-1 (e.g., Pawson and Fiorino 1998; Santer et al. 2004). Therefore, we conclude that NCEP-1 is unlikely to be an accurate representation of the multidecadal trends in tropical atmospheric temperature that appear so influential to hurricane activity, and the estimates of the uncertainty in past tropical temperature trends, as well as the impacts of these uncertainties, should exclude NCEP-1.

Agreement between observed and historical simulations with hurricane downscaling methodologies has been used to justify their use in climate change applications, but different methodologies have assumed different atmospheric temperature trends in historical simulations (section 6). Given that tropical UT and TTL temperature trends in NCEP-1 appear unreliable and since upper-atmospheric temperature trends can impact hurricane activity, the reliability of downscaling methodologies that depend on NCEP-1 atmospheric temperature trends should be questioned (e.g., Knutson et al. 2007, 2008; E08; section 6). The E08 methodology is unable to recover the observed trend in Atlantic hurricane activity with atmospheric reanalyses other than NCEP-1 (Emanuel et al. 2013), which may indicate some deficiency in that methodology.

Conversely, the Knutson et al. (2007, 2008) methodology overestimates the observed trend in Atlantic hurricanes when forced with NCEP-1 (Fig. 7), which is what one would expect a ''correct'' model to do in the case that the NCEP-1 underestimated upper-tropospheric warming. We speculate that the Knutson et al. (2007, 2008) methodology may perform more faithfully if nudged to atmospheric conditions without the large UT and TTL cooling trend seen in NCEP-1.

These results highlight the need to understand tropical atmospheric temperature changes. In particular, if the tropical-mean troposphere has not been warming like that of GCMs between 300 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 150 hPa, this could influence TC frequency. Currently, most dynamical model historical simulations of the twentieth century and projections of the twenty-first century show something resembling moist-adiabatic warming in the tropics (e.g., Santer et al. 2005; Seidel et al. 2012) 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 and interpretation of the mechanisms responsible for observed hurricane changes. For example, past changes in TC intensity may include a signature from radiative forcing agents that have influenced TTL temperatures, such as volcanic aerosols. If current models overestimate the warming of the upper troposphere and lower TTL in response to increasing CO_2 or other changes in radiative forcing, we would expect that current projections of twenty-first-century hurricane intensity underestimate the potential for future increases in TC intensity (e.g., Knutson and Tuleya 2004; E08; Bender et al. 2010; K10, Knutson et al. 2013; Villarini and Vecchi 2013) and the CO_2 influence on past TC intensity changes (e.g., Villarini and Vecchi 2013). On the other hand, if there has been an underestimated TTL cooling due to a misrepresentation of the impact of chlorofluorocarbon (CFC)-driven stratospheric ozone decreases, which are expected to recover over the coming century (WMO 2011), or the impact of volcanic aerosols, we would expect that projections for the coming century may overestimate the potential increases of TC intensity.

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