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Implications of tropical cyclone power dissipation index

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ABSTRACT: Upward trends in the power dissipation index (PDI) in the North Atlantic (NA) and western North Pacific (WNP) basins and increases in the number and proportion of intense hurricanes (categories 4 and 5) in all tropical cyclone basins have been reported in recent studies. These changes have been arguably viewed as evidence of the responses of tropical cyclone intensity to the increasing tropical sea surface temperature (SST) over the past 30 years. Using the historical best-track datasets from 1975 to 2004, how the annual frequency, lifetime and intensity of tropical cyclones contribute to the changes in the annual accumulated PDI is examined. As the SST warmed in the NA, WNP and eastern North Pacific (ENP) basins over the past 30 years, the annual accumulated PDI trended upward significantly only in the NA basin, where the decreased vertical wind shear and warming ocean surface may have allowed more storms to form and to form earlier or dissipate later, increasing the lifetime and annual frequency of tropical cyclones. The moderate increase in the annual accumulated PDI in the WNP basin was primarily due to the significant increase in the average intensity. There are no significant trends in the accumulated PDI, average intensity, average lifetime, and annual frequency in the ENP basin. Copyright © 2007 Royal Meteorological Society

KEY WORDS tropical cyclone; power dissipation index; average intensity; climate change

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1. Introduction

In a theoretical model, Emanuel (1987) proposed that the maximum potential intensity (MPI) of tropical cyclones in a greenhouse gas-warming climate would increase. Using a simple thermodynamic MPI model (Holland, 1997), Henderson-Sellers *et al.* (1998) also predicted more intense tropical cyclones as the tropical sea surface temperatures (SSTs) warm. Knutson *et al.* (1998, 2001), and Knutson and Tuleya (1999, 2004) conducted hurricane model simulations with large-scale thermodynamic conditions (atmospheric temperature and moisture profiles, and SSTs) derived from global warming experiments and found that hurricanes simulated in warming conditions are stronger and have higher precipitation rates than under present-day conditions. The Intergovernmental Panel on Climate Change (IPCC) suggested that it is likely that peak wind intensities of tropical cyclones will increase by 5–10% in the 21st century (Houghton *et al.*, 2001).

Tropical SSTs have trended upward over the past 50 years (Kumar *et al.*, 2004). The warming trend, which is generally believed to be associated with the ongoing global warming since the 1970s (Houghton *et al.*, 2001), is statistically significant in all of the tropical cyclone basins except the southwest Pacific (Webster *et al.*, 2005). Several recent studies have explored changes in tropical cyclone activity over the past few decades. Trenberth (2005) noticed that Atlantic hurricane activity has been significantly enhanced since 1995 in terms of the accumulated cyclone energy (ACE) index. Defining the power dissipation index (PDI) of tropical cyclones, Emanuel (2005) demonstrated that the annual accumulated PDI has increased markedly in the western North Pacific (WNP) and North Atlantic (NA) basins since the mid-1970s and attributed the upward trend to both longer storm lifetimes and greater storm intensities. In addition, Webster *et al.* (2005) examined tropical cyclone numbers, durations, and intensities over the past 35 years for all tropical cyclone basins and found an increase in the number and proportion of tropical cyclones reaching categories 4 and 5 strengths (maximum wind speeds larger than 58.6 m s^{-1}). Constructing a new 23-year global record of tropical cyclone intensity, Kossin *et al.* (2007) found similar trends in the PDI and proportion of intense hurricanes in the Atlantic basin. However, they suggested that the trends in other basins might be inflated or spurious due to uncertainties in the data.

Hoyos *et al.* (2006) attributed these changes to the SST warming while Chan and Liu (2004) showed that in the WNP basin there was no significant relationship between typhoon activity parameters (the annual frequency of typhoons, ratio of intense storms to the total number of tropical cyclones, and its destruction potential) and the local SST warming during the period 1960–2003. Whether these changes in tropical cyclone activity are

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related to changes in the underlying SST remain controversial (Landsea, 2005). One of the important issues is that some of the tropical cyclone parameters such as ACE and PDI are the collective effect of the intensity, lifetime and annual frequency of tropical cyclones.

The objective of this paper is to understand how the individual changes in the annual frequency, lifetime and intensity contribute to the changes in the annual accumulated PDI. Our analysis will focus on the 30-year period from 1975 to 2004, in part because of uncertainties in the tropical cyclone intensity data before the mid-1970s, and also because upward trends in PDI in the NA and WNP basins and increases in the number and proportion of intense hurricanes (categories 4 and 5) in all tropical cyclone basins have been documented by Emanuel (2005) and Webster *et al*. (2005) during this period. The historical tropical cyclone data for the NA, WNP and eastern North Pacific (ENP) basins are used. The three basins generally represent the majority of the tropical cyclone activity in the Northern Hemisphere, accounting for 90 and 62% of the annual tropical cyclone activity in the Northern Hemisphere and globally, respectively.

2. Data and indices for tropical cyclone activity

The tropical cyclone data used in this study are obtained from the National Hurricane Center (NHC) and Joint Typhoon Warning Center (JTWC) best-track datasets. The information in these datasets includes the centre location (latitude and longitude) and maximum sustained wind speed in knots for each 6-h interval. In this study, tropical cyclones are defined as systems with the maximum wind speed exceeding 17 m s^{-1} in the best-track datasets. The SST and wind data are from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset.

A storm activity index (SAI) such as the annual ACE and accumulated PDI (Trenberth, 2005; Emanuel, 2005) can be written in a general form:

$$SAI = \sum_{0}^{N} \sum_{0}^{\tau} V_{\max}^{n} \qquad (1)$$

where $V_{\max}$ is the maximum sustained wind speed of tropical cyclones and n is an integer. The two $\sum$ denote the summations over the lifetime (τ) of each tropical cyclone at 6-h increments and for all of the tropical cyclones (N) that occurred each year in a specific basin. When $n = 2$ and 3, SAI becomes the annual ACE and accumulated PDI, respectively. When $n = 0$ and *1*, SAI can be called the annual accumulated tropical cyclone frequency (TCF) and tropical cyclone momentum (TCM). According to (1), except for the TCF, SAI is a function of the intensity, lifetime and annual frequency of tropical cyclones. TCF is independent of tropical cyclone intensity or maximum sustained wind speed ($V_{\max}$).

In order to distinguish the individual contributions from the intensity, lifetime and annual frequency from the PDI, we define an average intensity and lifetime of tropical cyclones for a specific basin in this study. The average intensity can be obtained by averaging the maximum wind speed first over the lifetime for each tropical cyclone and then for all the tropical cyclones each year in a basin. According to (1), in fact, it is the ratio of TCM to TCF (TCM/TCF). Similarly, the average lifetime is the ratio of TCF to the annual tropical cyclone frequency (TCF/N). Therefore, in addition to parameters such as in Emanuel (2005) and Webster *et al*. (2005), the annual tropical cyclone activity in a basin is characterised by an average intensity, lifetime, and annual frequency. In this study, Sen's method is used to detect the linear trends with a Kendall–Tau significance test (Sen, 1968), and all of the significant tests will be at the 95% level.

3. Changes in the annual accumulated PDI

Figure 1 shows the time series of the accumulated PDI and the mean SSTs. The SSTs are averaged over the primary tropical cyclone activity regions (5–30 °N, 40–90 °W for the NA basin; 5–30 °N, 120–180 °E for the WNP basin; and 5–20 °N, 100–140 °W for the ENP basin) for the peak months (July–October). The upward trend in the annual accumulated PDI can be seen after 1994 for the NA basin, before 1997 for the WNP and ENP basins (Figure 1). The annual accumulated PDI over the ENP markedly decreased after 1997 as the SST tended to decrease. While the upward trends in SST are statistically significant for all of the three tropical cyclone basins, the trend in the accumulated PDI is statistically significant only in the NA basin. Over the last 30 years, the linear trend is 0.024 m^3 s^{-3} $year^{-1}$. Although the PDI trend in the WNP basin is not significant, the upward trend in the NA and WNP basins generally agrees with Emanuel's (2005) results. The accumulated PDI is significantly correlated with the underlying SSTs in the NA and ENP basins, suggesting the role of the SSTs in the PDI changes.

Emanuel (2005) argued that the increasing trend in the annual accumulated PDI in the NA and WNP basins resulted from the collective increases in intensity and lifetime. Because the annual accumulated PDI can be written as a function of intensity, lifetime, and annual frequency of tropical cyclones in a basin, it is instructive to examine the trends of these parameters over the past 30 years. In comparison with the SSTs, Figure 2 shows the time series of tropical cyclone average intensity for the period 1975–2004 in the NA, WNP and ENP basins, respectively. Although theoretical studies (Emanuel, 1987; Holland, 1997) and numerical modelling (e.g. Knutson *et al*., 1998; Knutson and Tuleya, 2004) predict that tropical cyclone intensity increases with increasing SST, the upward trend that is statistically significant occurred only in the WNP, where the increasing trend is 0.104 m s^{-1} $year^{-1}$ over the past 30 years

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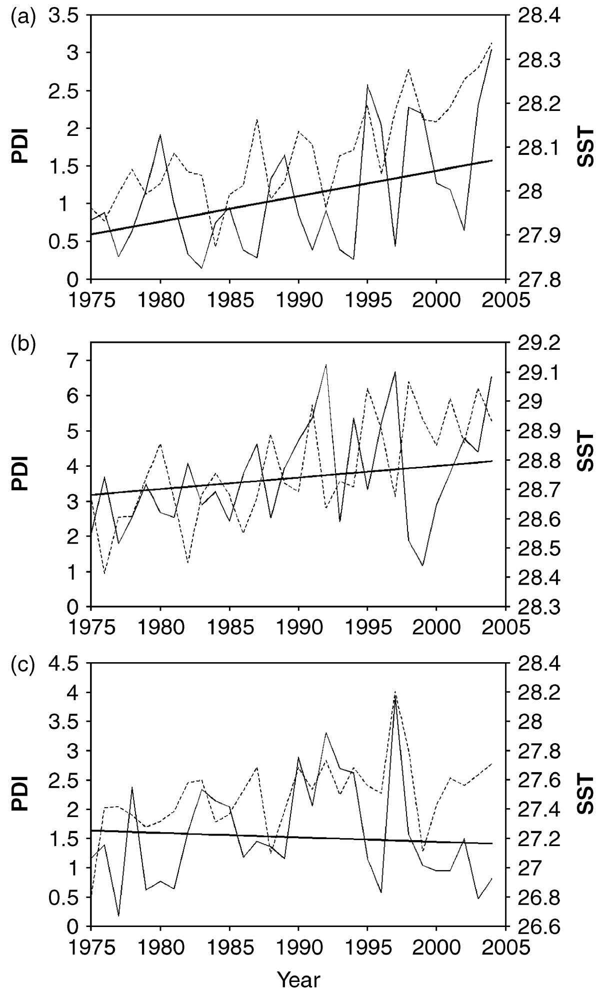

Figure 1. Time series of the annual accumulated PDI (solid, unit: 1.0×10^7 m^3 s^{-3}) and mean SSTs (dashed, unit: °C) for (a) the NA basin, (b) the WNP basin, and (c) the ENP basin. The SSTs are averaged over the areas of 5–30 °N, 40–90 °W in (a), 5–30 °N, 120–180 °E in (b), and 5–20 °N, 100–140 °W in (c) during July to October.

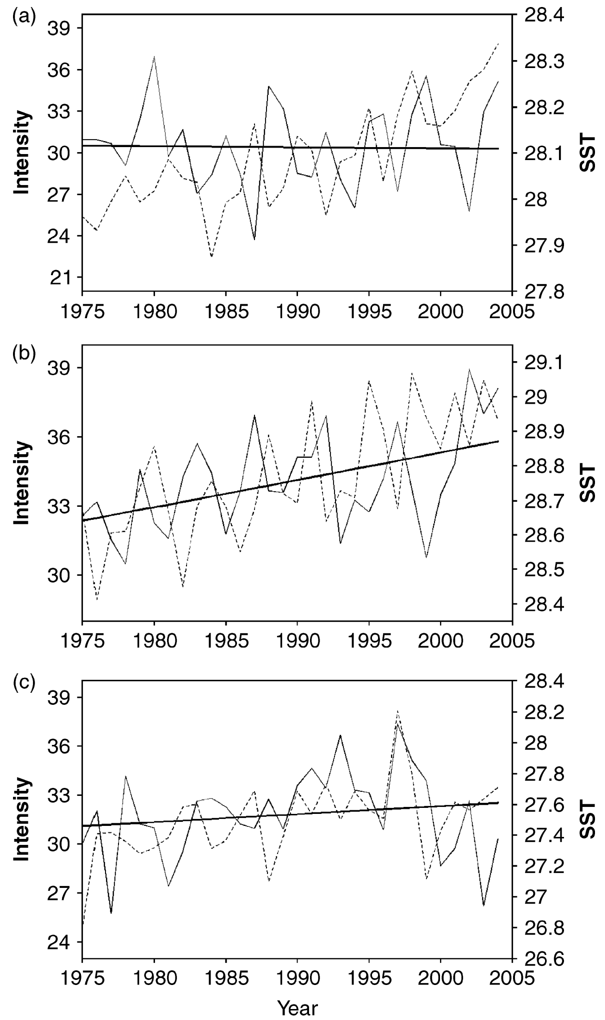

Figure 2. Time series of the tropical cyclone average intensity (solid, unit: m s^{-1}) and the mean SSTs (dashed, unit: °C) for (a) the NA basin, (b) the WNP basin, and (c) the ENP basin. The SSTs are the same as in Figure 1.

(Figure 2(b)). The average intensity has increased by 11% from 1975 to 2004. Given the ∼0.5 °C increase in the SST in the WNP basin, the intensity increase is much larger than the projected change from MPI theories (Emanuel, 1987; Henderson-Sellers *et al*., 1998). In the NA, except for various oscillations, no statistically significant trend is found for the average intensity (Figure 2(a)). In the ENP basin (Figure 2(c)), the average intensity generally increased prior to 1997 and then decreased rapidly. The overall trend is not statistically significant. The average intensities in these basins are not statistically correlated with the underlying SSTs.

Figure 3 shows the time series of the average lifetime of tropical cyclones in comparison with SST. In the NA basin, the increasing trend was 0.07 day year^{-1} from 1975 to 2004, which is statistically significant. According to the linear fitting, the lifetime increased from 4.2 days in 1975 to 6.3 days in 2004 in the NA basin, whereas there were no significant trends in lifetime in the WNP and ENP basins. Interestingly, during the mid-1990s, the NA replaced the WNP as the basin with the longest lifetime. Comparing Figure 3(a) and (b) with Figure 2(a) and (b), indicates that the significant increase in the average lifetime in the NA basin occurred with little change in the average intensity, while the significant increase in the average intensity over the WNP basin was not accompanied by a significant increase in the average lifetime. The average lifetime is not statistically correlated with the underlying SST in the three basins.

The changes in the annual frequency or number of tropical cyclones that are statistically significant occurred only in the NA basin with a linear trend of 0.18 year^{-1} over the past three decades (Figure 4(a)). In the WNP basin (Figure 4(b)), in agreement with Chan and Shi (1996), the annual frequency generally increased until the mid-1990s. Although the SST was still on a generally upward trend, the annual frequency trended downward after 1995. The linear fitting shows an overall increasing trend over the past 30 years, but it is not statistically significant. In the ENP basin (Figure 4(c)), the overall linear decrease in the annual frequency can be seen,

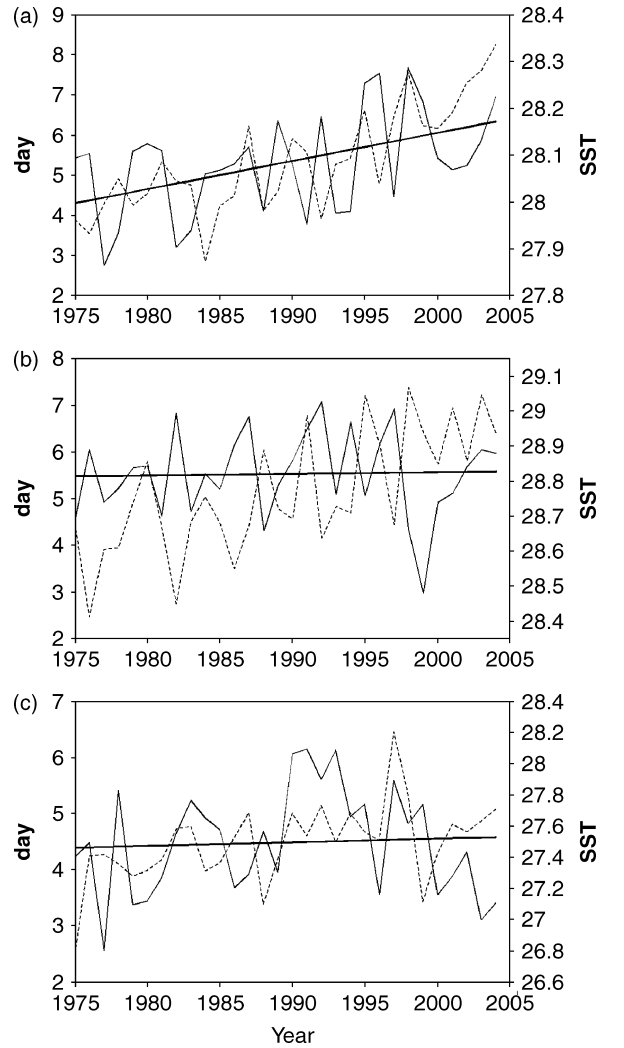

Figure 3. Time series of the average tropical cyclone lifetime (solid, unit: day) and the mean SSTs (dashed, unit: °C) for (a) the NA basin, (b) the WNP basin, and (c) the ENP basin. The SSTs are the same as in Figure 1.

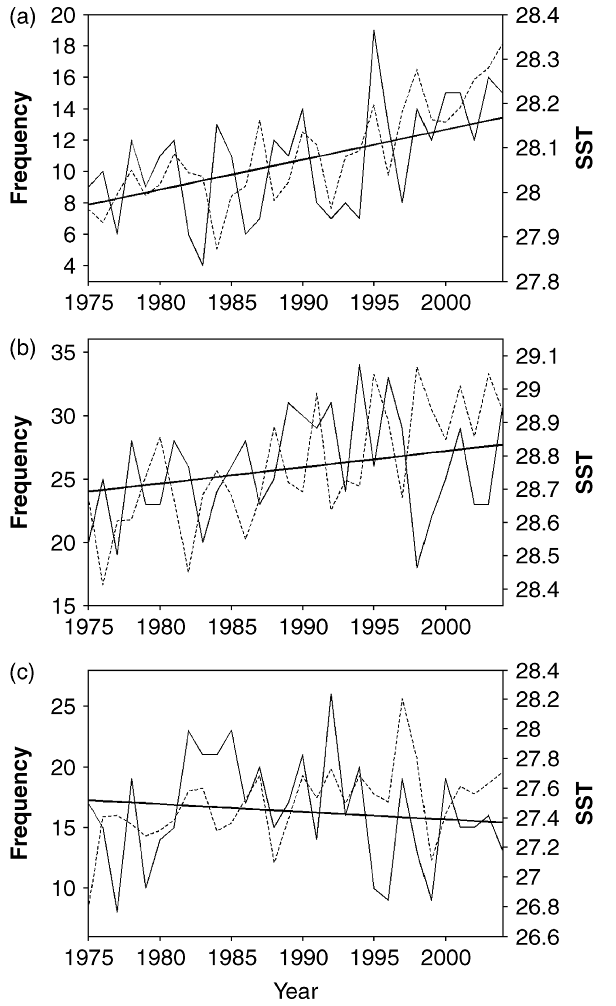

Figure 4. Time series of the annual tropical cyclone frequency (solid) and the mean SSTs (dashed, unit: °C) for (a) the NA basin, (b) the WNP basin, and (c) the ENP basin. The SSTs are the same as in Figure 1.

mostly occurring after 1992. At the 95% significance level, the annual TCF is correlated with the underlying SSTs only in the NA basin.

We also calculated the vertical wind shear, which is defined as the difference in monthly wind speeds between 200 and 850 hPa over the peak periods of tropical cyclone activity (July–September for the WNP and ENP basins and August–October for the NA basin) and in the primary regions of tropical cyclone activity (figure not shown). The vertical wind shear has significantly decreased in the NA, but the changes in the WNP and ENP basins were not statistically significant over the past 30 years. Although the decreasing shear is favourable for tropical cyclone intensification (Gray, 1968; Goldenberg *et al.*, 2001), the average intensity was approximately constant in the NA basin. The increases in the average lifetime and frequency suggest that the decreasing shear and warming SST may have allowed more storms to form and to form earlier or dissipate later, but the average intensity may also be controlled by factors other than SST and vertical wind shear. The calculations are based on the monthly NCEP-NCAR reanalysis data. In addition to the uncertainty in this dataset, the monthly mean data may underestimate the vertical shear.

4. Conclusions

Using historical best-track datasets from 1975 to 2004, tropical cyclone activity in a specific basin is characterised with average intensity, average lifetime and annual frequency. We examined how changes in the annual frequency, lifetime and intensity of tropical cyclones contribute to the changes in the annual accumulated PDI, which have been documented by Emanuel (2005).

Our analysis suggests that, as the SST warmed in the NA, WNP and ENP basins over the past 30 years, the annual accumulated PDI increased only in the NA basin. This increase resulted from the increases in the lifetime and annual frequency with no significant trend in the average intensity. The decreased vertical wind shear and warming ocean surface may have allowed more storms to

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form and to form earlier or dissipate later in the NA basin, increasing the lifetime and annual frequency of tropical cyclones and leading to the significant correlation of the annual accumulated PDI with the underlying SST.

The annual accumulated PDI increased moderately in the WNP basin, primarily resulting from a significant increase in the average intensity, while no significant trends in frequency and lifetime can be detected. The average intensity was not correlated with the underlying SST, suggesting that it may be controlled by other physical factors. In the ENP basin, although the underlying SSTs increased and were correlated with the annual accumulated PDI over the past 30 years, no significant trends can be found in the annual accumulated PDI, average intensity, average lifetime, and annual frequency.

In agreement with Emanuel (2005), this study suggests that the thermodynamic effect of the underlying SST alone cannot account for the documented changes in the annual accumulated PDI. Caution should be taken to interpret these results because concerns have been raised about the quality of the tropical cyclone datasets (Landsea, 2005; Klotzbach, 2006). Recently, Kossin *et al.* (2007) released a new homogeneous global record of hurricane intensity. Further analysis of the new dataset will improve our understanding of the changes in tropical cyclone intensity.

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References

Chan JCL, Liu KS. 2004. Global warming and western North Pacific typhoon activity from an observational perspective. *Journal of Climate* **17**: 4590–4602.

Chan JCL, Shi J. 1996. Long-term trends and interannual variability in tropical cyclone activity over the western North Pacific. *Geophyscial Research Letters* **23**: 2765–2767.

Emanuel KA. 1987. The dependence of hurricane intensity on climate. *Nature* **326**: 483–485.

Emanuel K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**: 686–688.

Goldenberg S, Landsea CW, Mestas-Nunez AM, Gray WM. 2001. The recent increase in Atlantic Hurricane activity: Causes and Implications. *Science* **293**: 474–478.

Gray WM. 1968. Global view of the origin of tropical disturbances and storms. *Monthly Weather Review* **96**: 669–700.

Henderson-Sellers A, Zhang H, Berz G, Emanuel K, Gray W, Landsea C, Holland G, Lighthill J, Shieh S-L, Webster P, McGuffle K. 1998. Tropical cyclones and global climate change: A post-IPCC assessment. *Bulletin of the American Meteorological Society* **79**: 19–38.

Holland GJ. 1997. The maximum potential intensity of tropical cyclones. *Journal of the Atmospheric Sciences* **54**: 2519–2541.

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds). 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press: Canbridge; 944.

Hoyos CD, Agudelo PA, Webster PJ, Curry JA. 2006. Deconvolution of the factors contributing to the increase in global hurricane intensity. *Science* **312**: 94–97.

Klotzbach PJ. 2006. Trends in global tropical cyclone activity over the past twenty years (1986–2005). *Geophysical Research Letters* **33**: 10805–10809.

Knutson TR, Tuleya RE. 1999. Increased hurricane intensities with CO_2-induced warming as simulated using the GFDL hurricane prediction system. *Climatic and Dynamic* **15**: 503–519.

Knutson TR, Tuleya RE. 2004. Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. *Journal of Climate* **17**: 3477–3493.

Knutson TR, Tuleya RE, Kurihara Y. 1998. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* **279**: 1018–1020.

Knutson TR, Tuleya RE, Shen W, Ginis I. 2001. Impact of CO_2-induced warming on hurricane intensities as simulated in a hurricane model with ocean coupling. *Journal of Climate* **14**: 2458–2468.

Kossin JP, Knapp KR, Vimont DJ, Murnane RJ, Harper BA. 2007. A globally consistent reanalysis of hurricane variability and trends. *Geophysical Research Letters* **34**: 4815–4820.

Kumar A, Yang F, Goddard L, Schubert S. 2004. Differing trends in the tropical surface temperatures and precipitation over land and oceans. *Journal of Climate* **17**: 653–664.

Landsea CW. 2005. Hurricanes and global warming. *Nature* **436**: 686–688.

Sen PK. 1968. Estimates of the regression coefficient based on Kendall's Tau. *Journal of the American Statistical Association* **63**: 1379–1389.

Trenberth K. 2005. Uncertainty in Hurricanes and Global Warming. *Science* **308**: 1753–1754.

Webster PJ, Holland GJ, Curry JA, Chang H-R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**: 1844–1846.

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