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Trends in global tropical cyclone activity over the past twenty years (1986–2005)

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[1] The recent destructive Atlantic hurricane seasons and several recent publications have sparked debate over whether warming tropical sea surface temperatures (SSTs) are causing more intense, longer-lived tropical cyclones. This paper investigates worldwide tropical cyclone frequency and intensity to determine trends in activity over the past twenty years during which there has been an approximate 0.2°–0.4°C warming of SSTs. The data indicate a large increasing trend in tropical cyclone intensity and longevity for the North Atlantic basin and a considerable decreasing trend for the Northeast Pacific. All other basins showed small trends, and there has been no significant change in global net tropical cyclone activity. There has been a small increase in global Category 4–5 hurricanes from the period 1986–1995 to the period 1996–2005. Most of this increase is likely due to improved observational technology. These findings indicate that other important factors govern intensity and frequency of tropical cyclones besides SSTs. **Citation:** Klotzbach, P. J. (2006), Trends in global tropical cyclone activity over the past twenty years (1986–2005), *Geophys. Res. Lett.*, *33*, L10805, doi:10.1029/2006GL025881.

1. Introduction

[2] Recent papers by *Emanuel* [2005] and *Webster et al.* [2005] have caused a flurry of debate about the relationship between increasing tropical sea surface temperatures (SSTs) and intense tropical cyclones (TCs). *Emanuel* [2005] found that a Power Dissipation Index (PDI), effectively the six-hour TC one-minute maximum sustained wind speed cubed, had increased by approximately 50% for both the Atlantic basin and the Northwest Pacific basin since the mid 1970s. *Webster et al.* [2005] analyzed Category 4–5 hurricanes (maximum sustained winds (1-minute average) >= 115 knots) for all TC basins over the past 30 years and found that their numbers had nearly doubled between an earlier (1975–1989) and a more recent (1990–2004) 15-year period. Many questions have been raised regarding the data quality in the earlier part of their analysis periods (C. W. Landsea et al., Global warming and extreme tropical cyclones: Can we detect climate trends from existing tropical cyclone databases?, submitted to *Science*, 2006). Before the early 1980s, the Dvorak Technique [*Dvorak*, 1975], a method which utilizes satellite imagery to assign an intensity to TCs, was only applicable to visible satellite imagery and therefore could not be used at night. Since 1984, improved technology has allowed the technique to be applied to both infrared and visible imagery [*Dvorak*, 1984], and more accurate estimates of real-time intensity have become available. In addition, the quality and resolution of satellite imagery has continued to improve over time, and with this improved imagery, operational forecasters can be more confident of their satellite-derived intensity estimates. The elimination of aircraft reconnaissance in the Northwest Pacific in 1987 raised the importance of satellite-based intensity estimates even more. Also, the Joint Typhoon Warning Center urges caution in utilizing data prior to 1985 [*Chu et al.*, 2002]. Because of these earlier period limitations and the desire to obtain a near-homogeneous data set, only the past twenty years (1986–2005) are examined in this paper. If the trends shown by *Emanuel* [2005] and *Webster et al.* [2005] are to be accepted, then one should also find a similar increasing trend in global TC data sets over the last 20 years.

2. Methodology

[3] Global TC activity was tabulated using "best track" data sets from 1986–2004 for all TC basins (the North Atlantic, the Northeast Pacific, the Northwest Pacific, the North Indian, the South Indian, and the South Pacific). The "best track" data sets are the best estimates of the locations and intensities of TCs at six-hour intervals produced by the international warning centers. The "best track" data sets from the National Hurricane Center (NHC) were utilized for the North Atlantic [*Jarvinen et al.*, 1984] and the Northeast Pacific basins, and "best track" data from the Joint Typhoon Warning Center (JTWC) [*Chu et al.*, 2002] were utilized for the North Indian and Northwest Pacific basins.

[4] For the South Indian and South Pacific basins, a data set created by Neumann [*Neumann*, 1999] was used for 1986–2001 because it was utilized by *Webster et al.* [2005] in their study. The South Indian and South Pacific basins were divided at 135°E with storms forming east of this longitude being classified as South Pacific storms and storms forming west of this longitude being classified as South Indian storms. If a storm crossed 135°E longitude, it was classified into the basin in which it accrued more named storm days. The Neumann data set ended in June 2002, and after this point, the JTWC's "best track" data set was used. The JTWC data set overlaps the Neumann data set from 1970–2002, and the correlation between TC statistics calculated from these data sets is greater than 0.95. The consistency between data sets suggests that the JTWC "best track" data set can be utilized from July 2002–June 2004 without causing any spurious jumps in the data.

[5] For 2005 for the Northern Hemisphere and for July 2004–2005 for the Southern Hemisphere, operational TC

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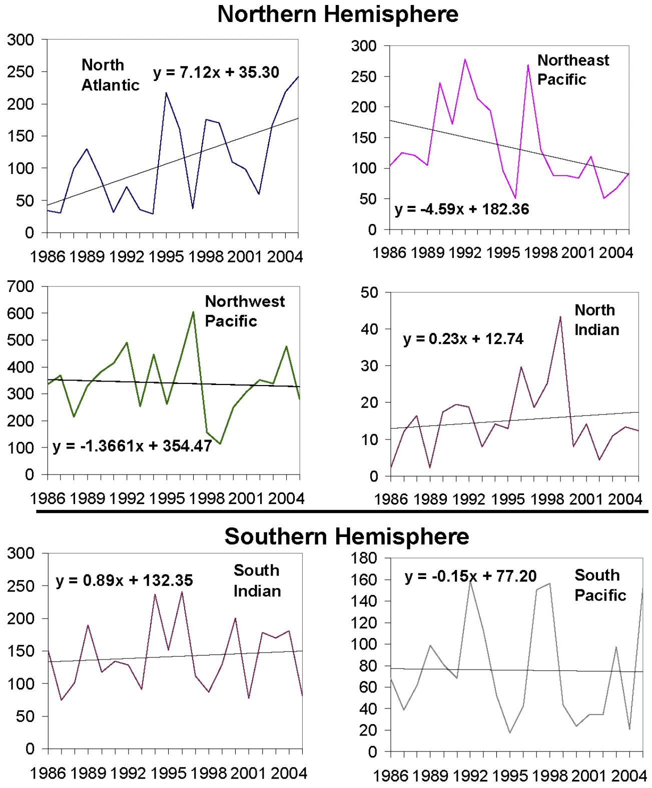

Figure 1. Accumulated Cyclone Energy (ACE) index values for individual TC basins from 1986–2005.

intensity estimates were utilized. These data were obtained from the NHC for the North Atlantic and the Northeast Pacific. JTWC data were utilized for all other basins. In the Southern Hemisphere, JTWC advisories were occasionally supplemented with data from the advisory centers in Perth, Darwin, Brisbane and La Reunion to extend a storm's length or increase its intensity slightly per the suggestion of Gary Padgett (personal communication, 2006). This was done for storms where the JTWC advisory intensities were considerably below the intensity recorded at the other centers. The combination of these data sets provides a comprehensive evaluation of global TC activity over the past twenty years (1986–2005).

3. Trends in Accumulated Cyclone Energy

[6] Figure 1 displays Accumulated Cyclone Energy (ACE) index values for all TC basins from 1986–2005. Linear trends have been fitted to all six TC basins. ACE is defined to be the sum of the maximum one-minute sustained surface wind speed squared at six-hourly intervals for all periods when the TC is at least of tropical storm strength (>= 34 knots) [*Bell et al.*, 2000]. ACE is proportional to the kinetic energy generated by the storm. This ACE index is quite similar to the Power Dissipation Index (PDI) created by *Emanuel* [2005], since PDI is defined to be the sum of the maximum one-minute sustained wind speed cubed at six-hourly intervals for all periods when the TC is at least of tropical storm strength. PDI is roughly proportional to the amount of monetary damage or power dissipation generated by a tropical cyclone [*Emanuel*, 2005]. In this paper, ACE is used instead of PDI as changes proportional to kinetic energy are being evaluated. Trends would be virtually the same using the PDI index, as the ACE and PDI indices correlate globally at 0.97. The largest trends in ACE noticeable in this figure are a large increase over the past twenty years in the North Atlantic and a considerable decrease over the Northeast Pacific. The large recent increase in North Atlantic activity has been noted extensively throughout the literature and has been attributed to an increase in strength of the Atlantic Thermohaline Circulation (THC) (alternatively referred to as a change in sign to a positive phase of the Atlantic multidecadal mode) [*Gray et al.*, 1997; *Goldenberg et al.*, 2001; *Klotzbach and Gray*, 2005; *Pielke et al.*, 2005]. The trends in all other basins are quite small.

[7] Figure 2 takes the ACE index values for all TC basins and sums them into values for the Northern Hemisphere, the Southern Hemisphere, and the entire globe. A five-year running mean of tropical SST anomalies (23.5°N–23.5°S, all longitudes) obtained from the NCEP Reanalysis [*Kistler et al.*, 2001] are also plotted for reference. A linear trend has been fitted to all three curves, and it is noted that there is a slight increase in ACE for the Northern Hemisphere, the Southern Hemisphere and consequently for the globe for the 1986–2005 period. As seen in Figure 3, if the last 16 years of the data set are examined (1990–2005), the trend in global ACE is actually slightly downward, although tropical SSTs increased by approximately 0.2°–0.3°C during this period.

[8] Table 1 displays total ACE for the ten-year periods of 1986–1995 and 1996–2005 for each of the individual TC basins as well as for the combination of the North Atlantic and Northeast Pacific, the Northern Hemisphere, the Southern Hemisphere and for all TCs worldwide. Ratios of the second ten-year period to the first ten-year period are calculated. Average tropical SSTs for each ten-year period are provided for reference. Effectively, when grouped into ten-year periods, there has been virtually no trend in globally-

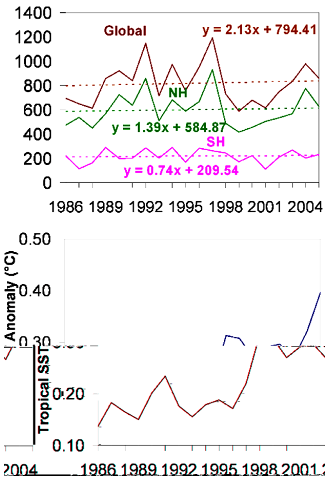

Figure 2. Accumulated Cyclone Energy (ACE) index values for 1986–2005 for the Northern Hemisphere (NH) (green line), the Southern Hemisphere (SH) (pink line) and the globe (brown line). The dashed lines are linear trends that have been fitted to the three curves. Five-year running mean tropical NCEP Reanalysis SST anomalies (23.5°N–23.5° S, all longitudes) (blue line) are also plotted. The base period for tropical SSTs is 1951–1980.

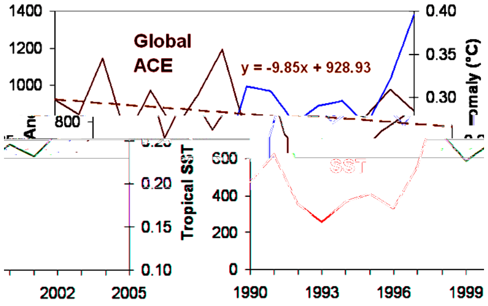

Figure 3. Global Accumulated Cyclone Energy (ACE) index values for 1990–2005 (brown line). A linear trend has been fitted to global ACE. Five-year running mean tropical NCEP Reanalysis SST anomalies (23.5°N–23.5° S, all longitudes) (blue line) are also plotted. The base period for tropical SSTs is 1951–1980.

summed ACE. The largest individual-basin trends are evident in the North Atlantic and the Northeast Pacific. There has been a large increase in ACE over the past decade in the North Atlantic, and there has been a large decrease in ACE over the past decade in the Northeast Pacific. When ACE in the North Atlantic and Northeast Pacific are added together, there has been a very small increase in Western Hemisphere TC activity over the past twenty years. A slight negative trend in ACE is noted in the Northwest Pacific, which is in contrast to the large increase in PDI noted by *Emanuel* [2005] since the mid 1970s. One would expect the increasing trend in PDI over the past thirty years to also show an increase over the past twenty years when sea surface temperatures have warmed by approximately 0.2°–0.4°C.

4. Trends in Category 4–5 Hurricanes

[9] *Webster et al.* [2005] report that there has been a large (nearly 100%) increase in Category 4–5 hurricanes since the mid 1970s. Table 2 displays the number of Category 4–5 hurricanes by individual TC basin, for the North Atlantic and the Northeast Pacific, for the Northern Hemisphere, the Southern Hemisphere and the globe by ten-year periods since 1986. Northern Hemisphere Category 4–5 hurricanes have remained virtually the same between the two ten-year periods, and a modest increase in Category 4–5 hurricanes has been observed in the Southern Hemisphere. Most of this Southern Hemisphere increase occurred in the first five years of the data set, and since the early 1990s, as satellite observational technology has continued to improve, there has been no continuation of this trend; even though global SSTs and oceanic heat content have continued to rise [*Levitus et al.*, 2000]. During the past twenty years, the number of Category 4–5 hurricanes has increased dramatically in the North Atlantic, and there has been a large decrease in the Northeast Pacific, in keeping with the ACE values for these basins. Since 1990, the number of Category 4–5 hurricanes across the globe has remained approximately constant which agrees with the findings of *Webster et al.* [2005, Figure 4] who show effectively no trend in Category 4–5 hurricanes from the 1990–1994 pentad to the 2000–2004 pentad.

Table 1. Accumulated Cyclone Energy (Ace) Index Values for Ten-Year Periods (1986–1995, 1996–2005) and the Ratio of the Second Ten-Year Period to the First Ten-Year Period for all TC Basins, the North Atlantic and the Northeast Pacific, the Northern Hemisphere, the Southern Hemisphere, and the Globe[a]

Basin	1986–1995	1996–2005	Ratio (1996–2005/ 1986–1995) %
North Atlantic	762	1438	189%
Northeast Pacific	1646	1037	63%
N. Atlantic + NE Pacific	2408	2475	103%
Northwest Pacific	3495	3307	95%
North Indian	123	180	146%
South Indian	1377	1456	106%
South Pacific	757	755	100%
Northern Hemisphere	6026	5962	99%
Southern Hemisphere	2134	2211	104%
Global	8160	8173	100%
Tropical SSTs, 23.5°N–23.5°S, all longitudes	0.18°C	0.29°C	ΔT = +0.11°C

[a] Tropical SSTs for each ten-year period (23.5°N–23.5°S, all longitudes) derived from the NCEP Reanalysis and the difference between these two periods are provided; the base period for tropical SSTs is 1951–1980.

Table 2. Category 4–5 Hurricanes by Ten-Year Periods (1986–1995, 1996–2005) for Individual TC Basins, the North Atlantic and the Northeast Pacific, the Northern Hemisphere, the Southern Hemisphere, and the Globe

Basin	1986–1995	1996–2005	Ratio (1996–2005/ 1986–1995)
North Atlantic	10	25	250%
Northeast Pacific	37	23	62%
N. Atlantic + NE Pacific	47	48	102%
Northwest Pacific	75	76	101%
North Indian	3	4	133%
South Indian	26	36	138%
South Pacific	13	16	123%
Northern Hemisphere	125	128	102%
Southern Hemisphere	39	52	133%
Global	164	180	110%

5. Correlations between ACE and Category 4–5 Hurricanes with Sea Surface Temperatures

[10] Table 3 shows the correlation between ACE and SSTs along with the correlation between Category 4–5 hurricanes and SSTs for each TC basin over the period 1986–2005 for the Northern Hemisphere and for 1985–1986 through the 2004–2005 hurricane seasons for the Southern Hemisphere. SSTs are taken from the Hadley SST data set [*Rayner et al.*, 2003]. The Hadley SST data set was correlated from 1986–2005 with the NCEP Reanalysis SST data set [*Kistler et al.*, 2001] and the Kaplan SST data set [*Kaplan et al.*, 1998], and both the NCEP Reanalysis and Kaplan SST data sets correlated at greater than 0.90 with Hadley SSTs for each TC basin. Therefore, the correlation would not change much if another SST data set were selected. TC basins are defined as in *Webster et al.* [2005].

[11] Based on theoretical research [*Emanuel*, 1987], one would expect there to be a positive correlation between SST in

Table 3. Correlations Between ACE and SSTs and Category 4–5 Hurricanes and SSTs for All TC Basins[a]

Basin	Correlation with ACE	Correlation with Cat. 4–5 Hurricanes
North Atlantic	**0.57**	**0.39**
Northeast Pacific	**0.58**	**0.59**
Northwest Pacific	−0.28	−0.11
North Indian	−0.07	−0.29
South Indian	−0.32	−0.18
South Pacific	−0.38	−0.20

[a] TC basins and seasons are defined by *Webster et al.* [2005] (North Atlantic Ocean - 5° to 25°N, 20° to 90°W, June–October), (Northeast Pacific Ocean - 5° to 20°N, 90° to 120°W, June–October), (Northwest Pacific Ocean - 5° to 20°N, 120° to 180°E, May–December), (North Indian Ocean - 5° to 20°N, 55° to 90°E, April–May and September–November), (South Indian Ocean - 5° to 20°S, 50° to 115°E, November–April), and the (South Pacific Ocean - 5° to 20°S, 155° to 180°E, December–April); correlations significant at the 95% level based on a one-tailed Student's t-test are bold-faced.

a TC basin and observed TC intensity, and therefore a one-tailed Student's t-test was used to test for statistical significance. Since there are 20 years of data, a correlation of 0.38 is needed to be statistically significant at the 95% level. There is a statistically significant relationship between SSTs and ACE as well as SSTs and Category 4–5 hurricanes for both the North Atlantic and the Northeast Pacific; however, correlations for the other four TC basins are actually slightly negative. Even for the North Atlantic and the Northeast Pacific, these correlations only explain between 25–30% of the variance, and therefore large amounts of variance are unexplained. Clearly, other atmospheric and oceanic features such as vertical wind shear, mid-level instability, etc. [e.g., *Gray*, 1968] are critical for TC development and intensification besides warm SSTs.

6. Conclusions

[12] These findings are contradictory to the conclusions drawn by *Emanuel* [2005] and *Webster et al.* [2005]. They do not support the argument that global TC frequency, intensity and longevity have undergone increases in recent years. Utilizing global "best track" data, there has been no significant increasing trend in ACE and only a small increase (~10%) in Category 4–5 hurricanes over the past twenty years, despite an increase in the trend of warming sea surface temperatures during this time period.

[13] The results of this paper are more in line with a prior study by *Shapiro and Goldenberg* [1998] and a project report by *Gray and Klotzbach* [2005]. *Shapiro and Goldenberg* [1998] showed only marginally significant correlations between SSTs in the tropical Atlantic and major hurricane development in the basin. Vertical wind shear was shown to be a much more fundamental component for major hurricane development and maintenance. *Gray and Klotzbach* [2005], while developing seasonal hurricane forecasts for TC activity, found only a modest correlation (~0.4) between seasonal and monthly Atlantic basin SSTs and major (Category 3–4–5) hurricane frequency. This study indicates that, based on data over the last twenty years, no significant increasing trend is evident in global ACE or in Category 4–5 hurricanes.

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