Changes in tropical cyclone number, duration and intensity in a warming environment

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The number of tropical cyclones, cyclone days and tropical cyclone intensity are examined over the past 35 years in an environment of increasing sea surface temperature. A statistically significant increase is seen in the proportion of hurricanes reaching categories 4 and 5. The largest increase occurs in the North Pacific, the Indian and Southwest Pacific oceans and smallest increase in the North Atlantic Ocean. These changes in intensity have occurred while the number of cyclones and cyclone days have decreased in all basins during the last decade except the North Atlantic.

During the hurricane season of 2004, there were 14 named storms in the North Atlantic of which 9 achieved hurricane intensity. Four of these hurricanes struck the Southeast U.S. in rapid succession, causing considerable damage and disruption. Analysis of hurricane characteristics in the North Atlantic (*1, 2*) has shown an increase in hurricane frequency and intensity since 1995. Recently, a causal relationship between increasing hurricane frequency and intensity and increasing SST has been posited (*3*) based on an acceleration of the hydrological cycle arising from the nonlinear relationship between saturation vapor pressure and temperature (*4*). The issue of attribution of increased hurricane frequency to increasing SST has resulted in a vigorous debate in the press and academic circles (*5*).

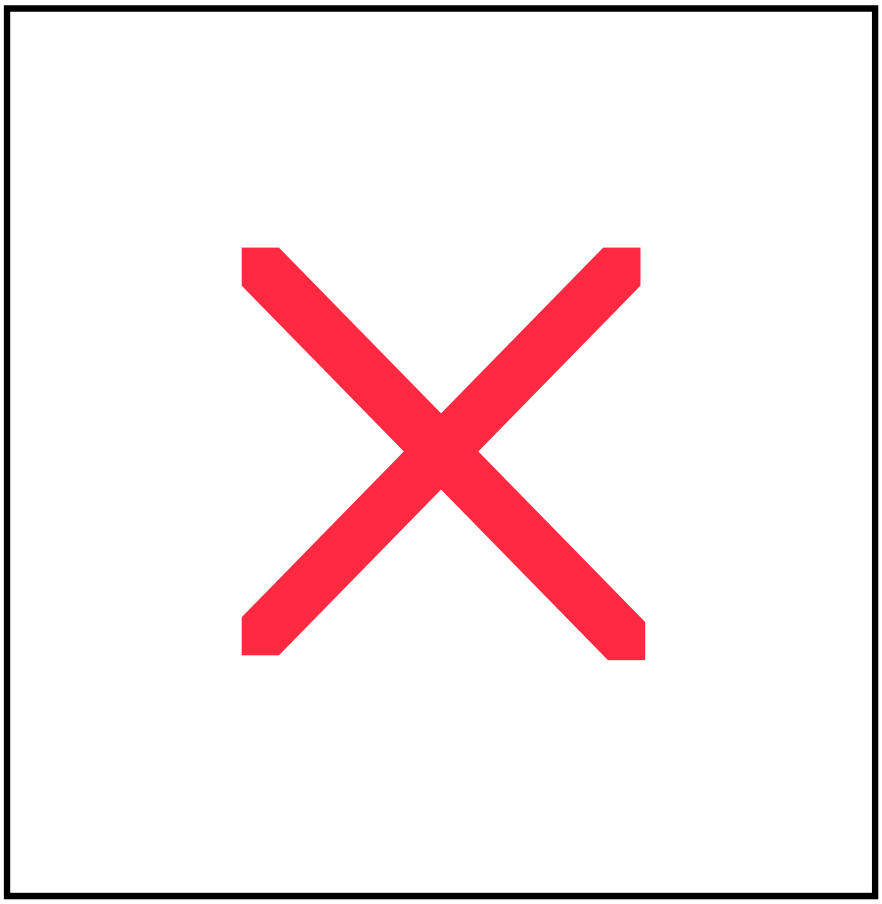

Figure 1: Running 5-year mean of SST during hurricane season for the principal ocean basins in which hurricanes occur: the North Atlantic Ocean (NATL: 90°-20°E, 5°-25°N, June-October), the Western Pacific Ocean (WPAC: 120°-180°E, 5°-20°N, May-December), the East Pacific Ocean (EPAC: 90°-120°W, 5°-20°N, June-October), the Southwest Pacific Ocean (SPAC: 155°-180°E, 5°-20°S, December-April), the North Indian Ocean (NIO: 55°-90°E, 5°-20°N, April-May and September-November) and the South Indian Ocean (SIO: 50°-115°E, 5°-20°S, November-April).

Numerous studies have addressed the issue of changes in global frequency and intensity of hurricanes in the warming world. Our basic conceptual understanding of hurricanes suggests relationships between hurricane activity and sea surface temperature (SST). It is well established that SST > 26°C is a requirement for tropical cyclone formation in the

current climate (*6,7*). There is also a hypothesized relationship between SST and the maximum potential hurricane intensity (*8,9*). However, globally there has been no increase in observed hurricane frequency (*2, 10*) or intensity (*11, 12*) over the past several decades. The strong interannual variability in hurricane statistics (*10, 13, 14*) makes it difficult to discern any trend with statistical veracity (*8*). Factors other than SST have been cited for their role in regulating hurricane characteristics, including vertical shear and mid-tropospheric moisture (*15*). Global modeling results for doubled CO_2 scenarios are contradictory (*15-20*), with simulations showing a lack of consistency in projecting an increase or decrease in the total number of hurricanes, although most simulations project an increase in hurricane intensity.

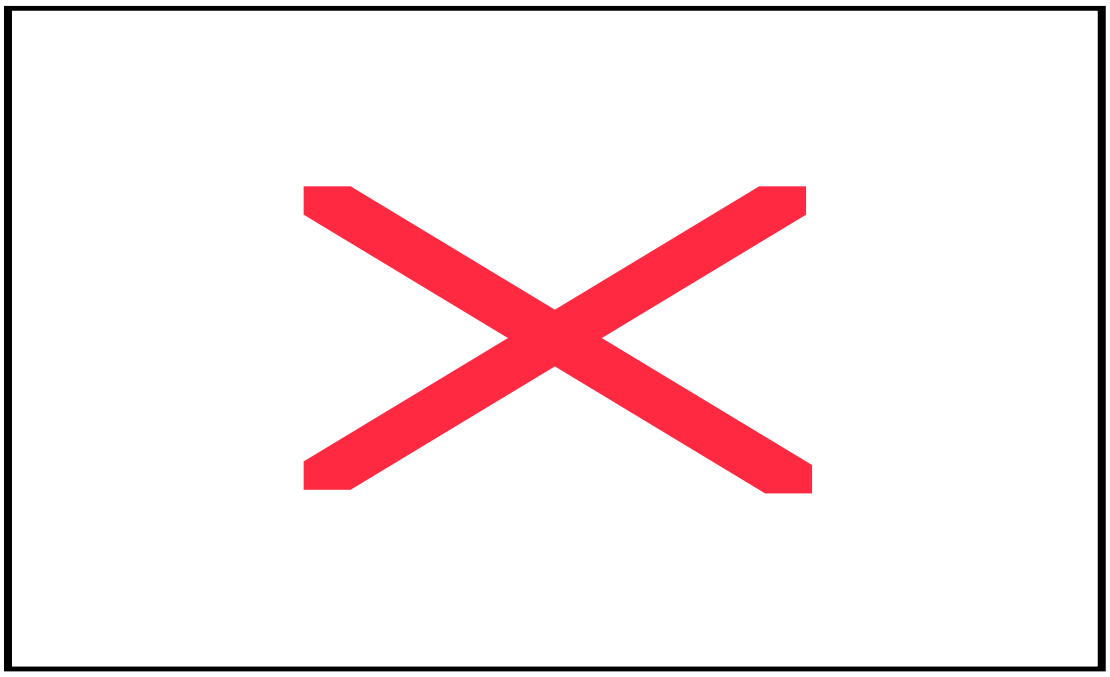

Figure 2: Global time series for 1970-2004 of (a) number of storms and (b) number of storm days for tropical cyclones (hurricanes plus tropical storms; black curves), hurricanes (red curves) and tropical storms (blue curves). Contours indicate the year-by-year variability and the bold curves show the 5-year running average.

To clarify the trends in the observational record of tropical cyclones and their interpretation in the context of variations in SST, we conduct a comprehensive analysis of global tropical cyclone statistics for the satellite era (1974-2004). In each tropical ocean basin we examine the numbers of tropical storms and hurricanes, the number of storm days, and the hurricane intensity distribution. The tropical cyclone data are derived from the best track archives of the Joint Typhoon Warning Center and international warning centers, including special compilations and quality control (*21*).

We use a common terminology to define tropical cyclones. Those attaining surface wind speeds between 18-33 m s^{-1} are referred to as tropical storms. Hurricanes occur when storm wind speeds exceed 33 m s^{-1}. Category 1-5 hurricanes, following the Saffir-Simpson scale (*22*), are defined as storms with wind speeds 33-43 m s^{-1}, 43-50 m s^{-1}, 50-56 m s^{-1}, 56-67 m s^{-1} and > 67 m s^{-1}, respectively. We define the ocean basins that

support tropical cyclone development as follows: North Atlantic (90°-20°W, 5°-25°N), western North Pacific (120°-180°E, 5°-20°N), eastern North Pacific (90°-120°W, 5°-20°N), South Indian (50°-115°E, 5°-20°S), North Indian (55°-90°E, 5°-20°N), and Southwest Pacific (155°-180°E, 5°-20°S). Within these basins, total tropical storm days are defined as the total number of days for systems that only reached tropical storm intensity. Total hurricane days refer to systems that attained hurricane status. Total tropical cyclone number or days refer to the sum of the statistics for both tropical storms and hurricanes.

Figure 2 shows the time series for the global number of tropical cyclones and the number of cyclone days for the period 1970-2004, for hurricanes, tropical storms and total cyclones. None of these time series show a trend that is statistically different from zero over the period using the Kendall trend analysis (*23*). However, there is a substantial decadal-scale oscillation that is especially evident in the number of tropical cyclone days. For example, globally, the annual number of tropical cyclone days reached a peak of 870 days around 1995, decreasing by 25% to 600 days by 2003.

Tropical oceans have been warming by approximately 0.5^{o}C between 1970 and 2004 (*24*). Figure 1 shows the SST trends for the tropical cyclone season in each ocean basin. Using the Kendall trend analysis, trends in each of the ocean basins are significantly different from zero at the 95% confidence level or higher, except for the Southwest Pacific Ocean. Here we examine the variations in hurricane characteristics for each ocean basin in the context of the basin SST variations.

Figure 3 shows that all basins except the North Atlantic exhibit similar time series characteristics for the number of tropical cyclones and the number of cyclone days to those of the globe, with overall 35-year trends that are not statistically different from zero. However, the trend of increasing cyclone numbers and cyclone days in the North Atlantic is significant at the 99% confidence level using the Kendall trend statistics. The simultaneous increase in SST in the North Atlantic has led to speculations of causality between increasing SST and increasing number of tropical cyclones (*3*).

It is instructive to analyze the relationship between the co-variability of SST and hurricane characteristics for two other ocean basins, specifically the eastern and western North Pacific. Decadal variability is particularly evident in the eastern Pacific, where a maximum in the number of storms and the number of storm days in the mid-1980's (19 storms and 150 storm days) has been followed by a general decrease to the present (15 storms and 100 storm days). This decrease accompanied a rising SST until the 1990-1994 pentad, followed by an SST decrease until the present. In the western North Pacific, where SSTs have risen steadily through the observation period, the number of storms and the number of storm days reach maxima in the mid-1990s before decreasing dramatically over the subsequent 15 years. The greatest change occurs in number of cyclone days, decreasing by 40% from 1995 to 2003.

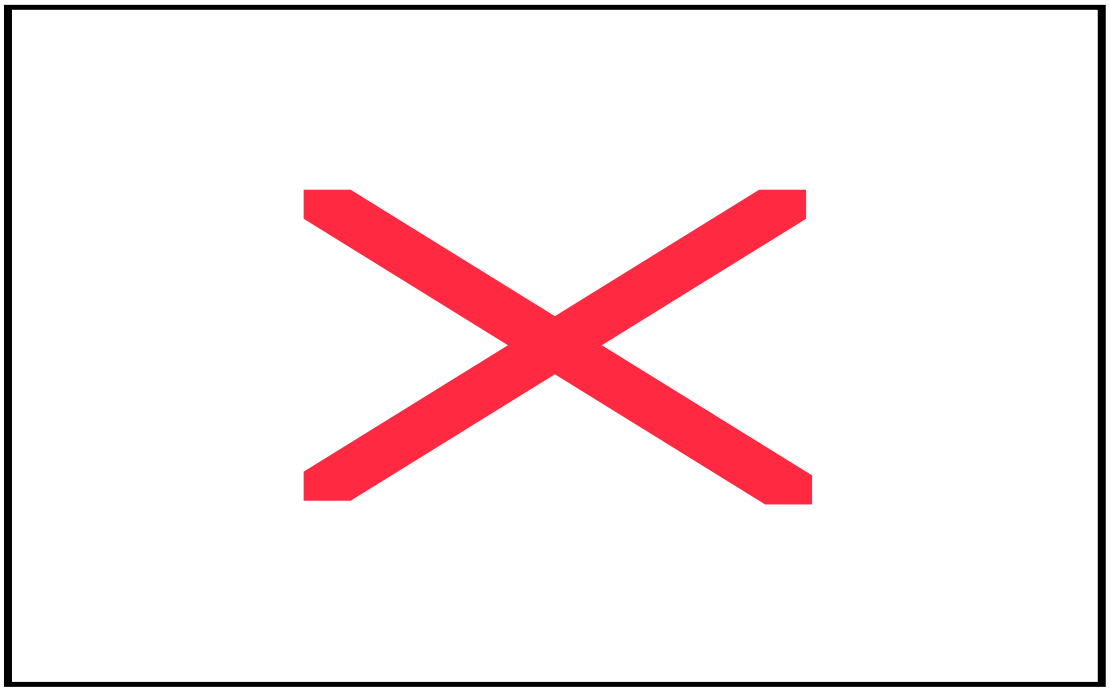

Figure 3: Regional time series for 1970-2004 for the NATL, WPAC, EPAC, NIO, and Southern Hemisphere (SIO plus SPAC) for (a) total number of hurricanes plus storms and (b) total number of hurricane plus storm days. Thin lines indicate the year by year statistics. Heavy lines show the 5-year running averages.

In summary, careful analysis of global hurricane data shows that, against a background of increasing SST, no global trend has yet emerged in the number of tropical storms and hurricanes. Only one region, the North Atlantic, shows a statistically significant increase, which commenced in 1995. However, attribution of the increase of numbers of storms to a warming SST environment is not supported because of the lack of a comparable correlation in other ocean basins where SST is also increasing. The current North Atlantic trend is an anomaly and probably a manifestation of the large amplitude and long-period oscillations observed in other basins.

Examination of hurricane intensity (Figure 4) shows a substantial change in the intensity distribution of hurricanes globally. The number of category 1 hurricanes has remained approximately constant in number (left hand panel) but has decreased as a percentage of the total number of hurricanes monotonically throughout the 35-year period since 1970 (right hand panel). The trend of the sum of hurricane categories 2 and 3 also is small and is not significantly different from zero either in number or percentage. By contrast, the strongest categories (4+5) hurricanes have doubled in number (50 per pentad in the 1970s to near 90 per pentad during the last decade) and in proportion (from around 20 to around 35% during the same period).

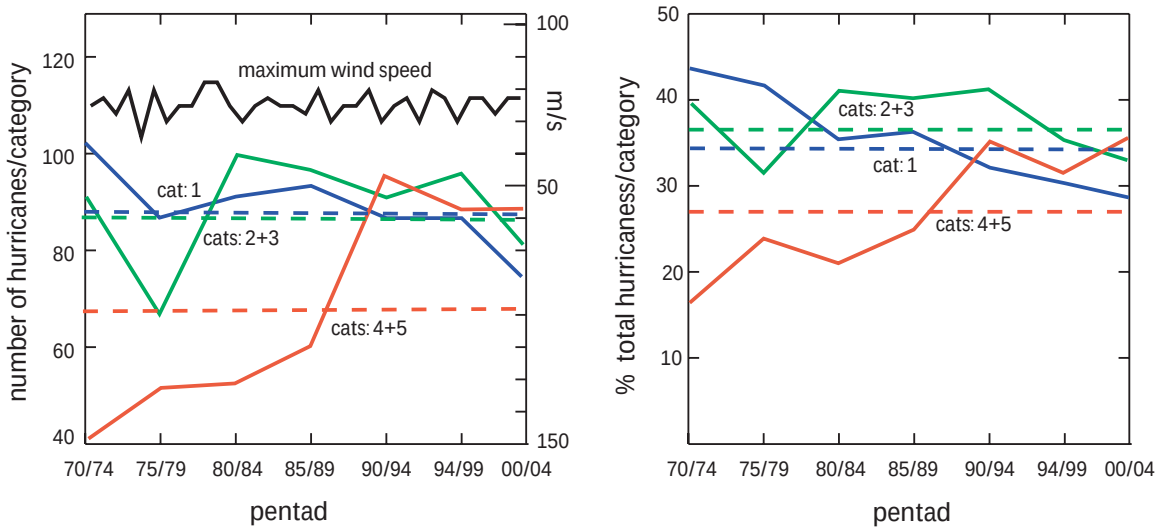

Figure 4: Intensity of hurricanes using the Saffir-Simpson scale (categories 1-5). (left panel) the total number of category 1 storms (blue curve), the sum of categories 2 and 3 (green), and the sum of categories 4 and 5 (red) in 5-year periods. The bold curve is the maximum hurricane wind speed observed globally (m s^{-1}). The horizontal dashed lines show the 1970-2004 average numbers in each category. (right panel) Same as left except for the percent of the total number of hurricanes in each category class. Dashed lines show average percentages in each category over the 1970-2004 period.

The increase in proportion and number of more intense hurricanes occurs in all of the ocean basins. A summary of the number and percent of storms by category is given in Table 1 for the years 1975-1989 and 1990-2004. The largest changes both in number and percentage is in the South Indian, the Southwest Pacific and North Indian ocean basins. Moderate increases have occurred in the western North Pacific and the eastern North Pacific, and the smallest percentage change has occurred in the North Atlantic. This increase in category 4 and 5 hurricanes has not been accompanied by an increase in the actual intensity of the most intense hurricanes: the maximum intensity has remained remarkably static over the last 35 years (dashed curve, left-hand panel Figure 4). These observations add credence to recent climate model simulations for a doubling CO_2 maximum intensity the most intense cyclones (25).

Table 1: Change in the number and percentage of hurricanes in categories 4 and 5 for the 15-year periods 1975-1989 and 1900-2004 for the different ocean basins.

	Period			
Basin	1975-1989		1900-2004	
	Number	Percentage	Number	Percentage
East Pacific Ocean	36	25	49	35
West Pacific Ocean	85	25	116	41
North Atlantic	16	20	25	25
South Western Pacific	10	12	22	28
North Indian	1	8	7	25
South Indian	23	18	50	34

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References and notes

(1) S. B. Goldenberg, C. W. Landsea, A. M. Maestas-Nunez, W. M. Gray, *Science, **293**, 474* (2001).

(2) J. B. Elsner, B. Kocher, *Geophys. Res. Lett., **27**, 129* (2000).

(3) K. E. Trenberth, *Science, 308,* 1753 (2005).

(4) K. E. Trenberth *et al.,* Bull. Am. Meteorol. Soc., 84, 1205 (2003).

(5) R. A. Pielke, Jr. *et al,. Bull. Amer. Meteorol. Soc., in press.* (available at http://sciencepolicy.colorado.edu/admin/publication_files/resourse-1762-hurricanes%20and_global_warming.pdf).

(6) J. Lighthill *et al., Bull. Am. Meterol. Soc., **75***, 2147 (1994).

(7) W. M. Gray, *Mon. Weather Rev., **96**, 669* (1968)

(8) K. A. Emanuel, *Nature, **326,*** 483 (1987)

(9) G. J. Holland, *J. Atmos. Sci., **54**, 2519* (1997)

(10) M. A. Lander, C. P. Guard, *Mon. Weather Rev., **126**, 1163* (1998).

(11) C. W. Landsea, R. A. Pielke Jr., A.M. Maestas-Nunez, J.A. Knaff, *Climatic Change, **42**, 89* (1999).

(12) J. C. L. Chan, K. S. Liu, *J. Climate, **17**, 4590* (2004).

(13) W. M. Gray, *Mon. Weather Rev., **112**, 1649* (1984).

(14) C. K. Folland, D. E. Parker, A. Colman, R. Washington, in *Beyond El Nino: Decadal and Interdecadal Climate Variability*, ed: A. Navarra (Springer-Verlag, Berlin, 73-102, 1999).

(15) L.J. Shapiro, S.B. Goldenberg, *J. Climate, **11**, 578* (1998)

(16) H. G. Houghton *et al., Climate Change- 2001: The Scientific Basis.* (Cambridge Univ. Press, 2001).

(17) A. Henderson-Sellers *et al., Bull. Am. Meteorol. Soc.*, ***79***, 19 (1998).

(18) T. R. Knutson, R. E. Tuleya, *J. Climate, **17**, 3477* (2004).

(19) J. F. Royer, F. Chauvin, B. Timbal, P. Araspin, D. Grimal, *Climate Dynamics, **38**, 307* (1998).

(20) M. Sugi, A. Noda, N. Sato, *J. Meteorol. Soc. Japan, **80**, 249* (2002).

(21) C.J. Neumann, in *Global Guide to Tropical Cyclone Forecasting*, ed: G. J. Holland (World Meteorol. Org, Geneva, WMO/TD-560, Chapter 1, 1993) Meteorological Organization, Geneva, 1.1.

(22) www.aoml.noaa.gov/general/lib/laescae.html.

(23) Hirsche, R. M., J. R. Slack, R. Smith, *Water Resour. Res., **18**, 107* (1982).

(24) P. Agudelo, J. A. Curry, *Geophys. Res. Lett., **31**, Art. No. L22207* (2004).

(25) www.prime-intl.co.jp/kyosei-2nd/PDF/24/11_**murakami**.pdf