EXTENDED PDF FORMAT
SPONSORED BY
usb
www.usbweb.com



Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment

P. J. Webster, *et al.*

Science **309**, 1844 (2005);
DOI: 10.1126/science.1116448

The following resources related to this article are available online at www.sciencemag.org (this information is current as of May 7, 2008):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/cgi/content/full/309/5742/1844

A list of selected additional articles on the Science Web sites **related to this article** can be found at:
http://www.sciencemag.org/cgi/content/full/309/5742/1844#related-content

This article **cites 23 articles**, 2 of which can be accessed for free:
http://www.sciencemag.org/cgi/content/full/309/5742/1844#otherarticles

This article has been **cited by** 214 article(s) on the ISI Web of Science.

This article has been **cited by** 21 articles hosted by HighWire Press; see:
http://www.sciencemag.org/cgi/content/full/309/5742/1844#otherarticles

This article appears in the following **subject collections**:
Atmospheric Science
http://www.sciencemag.org/cgi/collection/atmos

Information about obtaining **reprints** of this article or about obtaining **permission to reproduce this article** in whole or in part can be found at:
http://www.sciencemag.org/about/permissions.dtl

Downloaded from www.sciencemag.org on May 7, 2008

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. Copyright 2005 by the American Association for the Advancement of Science; all rights reserved. The title *Science* is a registered trademark of AAAS.

16. E. Kalnay *et al.*, *Bull. Am. Meteorol. Soc.* **77**, 437 (1996).
17. J. E. Nilsen, Y. Gao, H. Drange, T. Furevik, M. Bentsen, *Geophys. Res. Lett.* **30**, 10.1029/2002GL016597 (2003).
18. H. Hátún, A. Sandø, H. Drange, M. Bentsen, in *The Nordic Seas: An Integrated Perspective, AGU Monograph 158*, H. Drange, T. Dokken, T. Furevik, R. Gerdes, W. Berger, Eds. (American Geophysical Union, Washington, DC, 2005), pp. 239–250.
19. M. Bersch, *J. Geophys. Res.* **107**, 10.1029/2001JC000901 (2002).
20. N. P. Holliday, *J. Geophys. Res.* **108**, 10.1029/2002JC001344 (2003).
21. T. P. Boyer, S. Levitus, J. I. Antonov, R. A. Locarnini, H. E. Garcia, *Geophys. Res. Lett.* **32**, 10.1029/2004GL021791 (2005).
22. T. M. Joyce, P. Robbins, *J. Clim.* **9**, 3121 (1996).
23. S. Häkkinen, P. B. Rhines, *Science* **304**, 555 (2004).
24. N. P. Holliday, R. T. Pollard, J. F. Read, H. Leach, *Deep-Sea Res.* **47**, 1303 (2000).
25. D. J. Ellett, J. H. A. Martin, *Deep-Sea Res.* **20**, 585 (1973).
26. D. J. Ellett, S. R. Jones, "Surface temperature and salinity time-series from the Rockall Channel, 1948-1992" (Fisheries research data report number 36, Ministry of Agriculture, Fisheries, and Food, Directorate of Fisheries Research, Lowestoft, 1994; www.cefas.co.uk/publications/files/datarep36.pdf).
27. We thank M. Bentsen for model development, P. Rhines for commenting on the paper; M. Miles for language editing, and S. Häkkinen for the extended gyre index in Fig. 2A, based on altimetry. The work is supported by the Nordic Council of Ministers program Vestnordisk Oceanklima; the Ocean Surface Topography Science Team of NASA; the Research Council of Norway through RegClim, NOClim, and the Program of Supercomputing; and the European Union DG-XII Climate and Environment Program through DYNAMITE (GOCE-0093903) and NOCES (EVK2-2001-00115).

Supporting Online Material
www.sciencemag.org/cgi/content/full/309/5742/1841/DC1
Materials and Methods
Figs. S1 to S6

12 May 2005; accepted 4 August 2005
10.1126/science.1114777

Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment

P. J. Webster,[1] G. J. Holland,[2] J. A. Curry,[1] H.-R. Chang[1]

We examined the number of tropical cyclones and cyclone days as well as tropical cyclone intensity over the past 35 years, in an environment of increasing sea surface temperature. A large increase was seen in the number and proportion of hurricanes reaching categories 4 and 5. The largest increase occurred in the North Pacific, Indian, and Southwest Pacific Oceans, and the smallest percentage increase occurred in the North Atlantic Ocean. These increases have taken place while the number of cyclones and cyclone days has decreased in all basins except the North Atlantic during the past decade.

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 United States 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 sea surface temperature (SST) has been posited (*3*), assuming an acceleration of the hydrological cycle arising from the nonlinear relation 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 in academic circles (*5*).

Numerous studies have addressed the issue of changes in the global frequency and intensity of hurricanes in the warming world. Our basic conceptual understanding of hurricanes suggests that there could be a relationship between hurricane activity and 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, strong interannual variability in hurricane statistics (*10*–*14*) and the possible influence of interannual variability associated with El Niño and the North Atlantic Oscillation (*11*, *12*) make it difficult to discern any trend relative to background SST increases 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.

Tropical ocean SSTs increased by approximately 0.5°C between 1970 and 2004 (*21*). Figure 1 shows the SST trends for the tropical cyclone season in each ocean basin. If the Kendall trend analysis is used, 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. To this end, we conducted a comprehensive analysis of global tropical cyclone statistics for the satellite era (1970–2004). In each tropical ocean basin, we examined 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

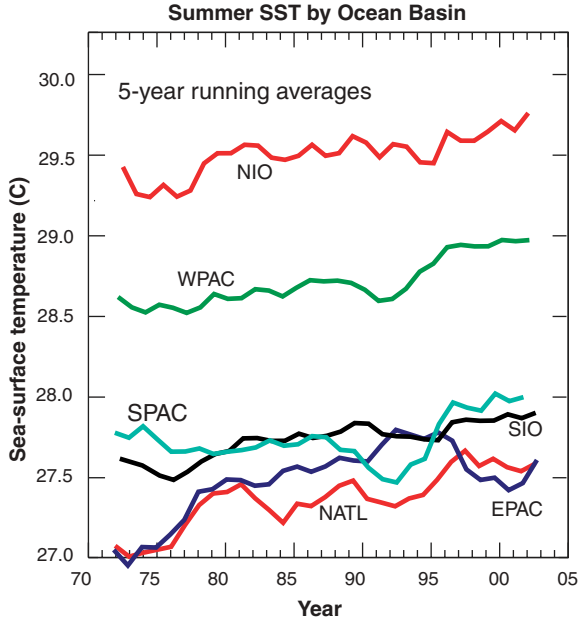


Fig. 1. Running 5-year mean of SST during the respective hurricane seasons for the principal ocean basins in which hurricanes occur: the North Atlantic Ocean (NATL: 90° to 20°E, 5° to 25°N, June-October), the Western Pacific Ocean (WPAC: 120° to 180°E, 5° to 20°N, May-December), the East Pacific Ocean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

[1]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332, USA. [2]National Center for Atmospheric Research, Boulder, CO, USA.

Downloaded from www.sciencemag.org on May 7, 2008

of the Joint Typhoon Warning Center and of international warning centers, including special compilations and quality control (*22*).

Tropical cyclonic systems attaining surface wind speeds between 18 and 33 m s^{-1} are referred to as tropical storms. Although storms of intensity >33 m s^{-1} have different regional names, we will refer to these storms as hurricanes for simplicity. Hurricanes in categories 1 to 5, according to the Saffir-Simpson scale (*23*), are defined as storms with wind speeds of 33 to 43 m s^{-1}, 43 to 50 m s^{-1}, 50 to 56 m s^{-1}, 56 to 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° to 20°W, 5° to 25°N), western North Pacific (120° to 180°E, 5° to 20°N), eastern North Pacific (90° to 120°W, 5° to 20°N), South Indian (50° to 115°E, 5°-20°S), North Indian (55° to 90°E, 5°-20°N), and Southwest Pacific (155° to 180°E, 5° to 20°S). Within these basins, total tropical storm days are defined as the total number of days of systems that only reached tropical storm intensity. Total hurricane days refer to systems that attained hurricane status, including the period when a system was at tropical storm intensity. Total tropical cyclone number or days refers 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 all cyclonic storms. None of these time series shows a trend that is statistically different from zero over the period (*24*). 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.

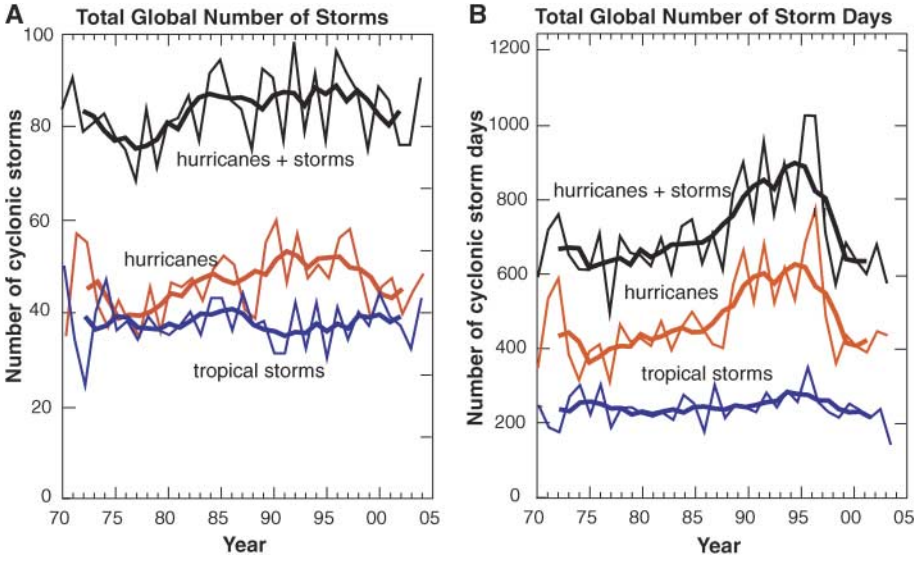


Fig. 2. Global time series for 1970–2004 of (**A**) number of storms and (**B**) number of storm days for tropical cyclones (hurricanes plus tropical storms; black curves), hurricanes (red curves), and tropical storms (blue curves). Contours indicate the year-by-year variability, and the bold curves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

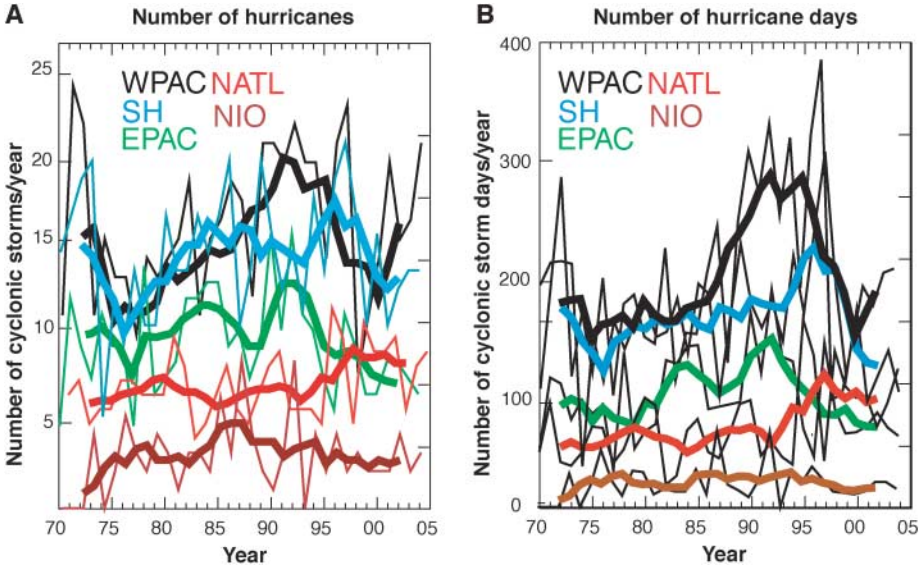


Fig. 3. Regional time series for 1970–2004 for the NATL, WPAC, EPAC, NIO, and Southern Hemisphere (SIO plus SPAC) for (**A**) total number of hurricanes and (**B**) total number of hurricane days. Thin lines indicate the year-by-year statistics. Heavy lines show the 5-year running averages.

Figure 3 shows that in each ocean basin time series, the annual frequency and duration of hurricanes exhibit the same temporal characteristics as the global time series (Fig. 2), with overall trends for the 35-year period that are not statistically different from zero. The exception is the North Atlantic Ocean, which possesses an increasing trend in frequency and duration that is significant at the 99% confidence level. The observation that increases in North Atlantic hurricane characteristics have occurred simultaneously with a statistically significant positive trend in SST has led to the speculation that the changes in both fields are the result of global warming (*3*).

It is instructive to analyze the relationship between the covariability of SST and hurricane characteristics in 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-1980s (19 storms and 150 storm days) has been followed by a general decrease up 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 the number of cyclone days, decreasing by 40% from 1995 to 2003.

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, a simple attribution of the increase in 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 observation that increases in North Atlantic hurricane characteristics have occurred simultaneously with a statistically significant positive trend in SST has led to the speculation that the changes in both fields are the result of global warming (*3*).

Examination of hurricane intensity (Fig. 4) shows a substantial change in the intensity distribution of hurricanes globally. The number of category 1 hurricanes has remained approxi-

Downloaded from www.sciencemag.org on May 7, 2008

mately constant (Fig. 4A) but has decreased monotonically as a percentage of the total number of hurricanes throughout the 35-year period (Fig. 4B). The trend of the sum of hurricane categories 2 and 3 is small also both in number and percentage. In contrast, hurricanes in the strongest categories (4 + 5) have almost doubled in number (50 per pentad in the 1970s to near 90 per pentad during the past decade) and in proportion (from around 20% to around 35% during the same period). These changes occur in all of the ocean basins. A summary of the number and percent of storms by category is given in Table 1, binned for the years 1975–1989 and 1990–2004. 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 past 35 years (solid black curve, Fig. 4A).

Cyclone intensities around the world are estimated by pattern recognition of satellite features based on the Dvorak scheme (*25*). The exceptions are the North Atlantic, where there has been continuous aircraft reconnaissance; the eastern North Pacific, which has occasional aircraft reconnaissance; and the western North Pacific, which had aircraft reconnaissance up to the mid-1980s. There have been substantial changes in the manner in which the Dvorak technique has been applied (*26*). These changes may lead to a trend toward more intense cyclones, but in terms of central pressure (*27*) and not in terms of maximum winds that are used here. Furthermore, the consistent trends in the North Atlantic and eastern North Pacific, where the Dvorak scheme has been calibrated against aircraft penetrations, give credence to the trends noted here as being independent of the observational and analysis techniques used. In addition, in the Southern Hemisphere and the North Indian Ocean basins, where only satellite data have been used to determine intensity throughout the data period, the same trends are apparent as in the Northern Hemisphere regions.

We deliberately limited this study to the satellite era because of the known biases before this period (*28*), which means that a comprehensive analysis of longer-period oscillations and trends has not been attempted. There is evidence of a minimum of intense cyclones occurring in the 1970s (*11*), which could indicate that our observed trend toward more intense cyclones is a reflection of a long-period oscillation. However, the sustained increase over a period of 30 years in the proportion of category 4 and 5 hurricanes indicates that the related oscillation would have to be on a period substantially longer than that observed in previous studies.

We conclude that global data indicate a 30-year trend toward more frequent and intense hurricanes, corroborated by the results of the recent regional assessment (*29*). This trend is not inconsistent with recent climate model simulations that a doubling of CO_2 may increase the frequency of the most intense cyclones (*18*, *30*), although attribution of the 30-year trends to global warming would require a longer global data record and, especially, a deeper understanding of the role of hurricanes in the general circulation of the atmosphere and ocean, even in the present climate state.

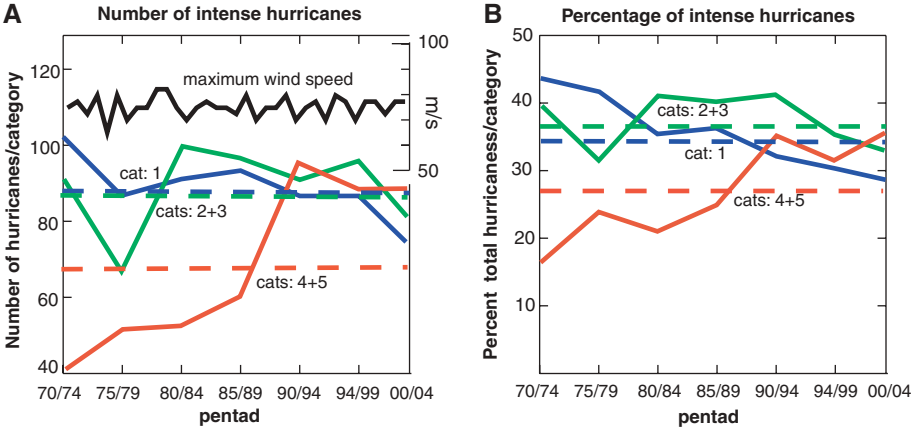


Fig. 4. Intensity of hurricanes according to the Saffir-Simpson scale (categories 1 to 5). (**A**) The total number of category 1 storms (blue curve), the sum of categories 2 and 3 (green), and the sum of categories 4 and 5 (red) in 5-year periods. The bold curve is the maximum hurricane wind speed observed globally (measured in meters per second). The horizontal dashed lines show the 1970–2004 average numbers in each category. (**B**) Same as (A), 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.

Table 1. Change in the number and percentage of hurricanes in categories 4 and 5 for the 15-year periods 1975–1989 and 1990–2004 for the different ocean basins.

Basin	Period			
	1975–1989		1990–2004	
	Number	Percentage	Number	Percentage
East Pacific Ocean	36	25	49	35
West Pacific Ocean	85	25	116	41
North Atlantic	16	20	25	25
Southwestern Pacific	10	12	22	28
North Indian	1	8	7	25
South Indian	23	18	50	34

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. Am. 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, *Clim. Change* **42**, 89 (1999).
12. J. C. L. Chan, K. S. Liu, *J. Clim.* **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*, A. Navarra, Ed. (Springer-Verlag, Berlin, 1999), pp. 73–102.
15. L. J. Shapiro, S. B. Goldenberg, *J. Clim.* **11**, 578 (1998).
16. H. G. Houghton *et al.*, *Climate Change—2001: The Scientific Basis* (Cambridge Univ. Press, Cambridge, 2001).
17. A. Henderson-Sellers *et al.*, *Bull. Am. Meteorol. Soc.* **79**, 19 (1998).
18. T. R. Knutson, R. E. Tuleya, *J. Clim.* **17**, 3477 (2004).
19. J. F. Royer, F. Chauvin, B. Timbal, P. Araspin, D. Grimal, *Clim. Dyn.* **38**, 307 (1998).
20. M. Sugi, A. Noda, N. Sato, *J. Meteorol. Soc. Jpn.* **80**, 249 (2002).
21. P. Agudelo, J. A. Curry, *Geophys. Res. Lett.* **31**, Art. No. L22207 (2004).
22. C. J. Neumann, in *Global Guide to Tropical Cyclone Forecasting*, G. J. Holland, Ed. (WMO/TD-560, World Meteorological Organization, Geneva, Switzerland, 1993), chap. 1.
23. See www.aoml.noaa.gov/general/lib/laescae.html for a description of the Saffir-Simpson scale.
24. R. M. Hirsche, J. R. Slack, R. Smith, *Water Resource Res.* **18**, 107 (1982).
25. V. F. Dvorak, *Mon. Weather Rev.* **103**, 420 (1975).
26. C. S. Velden, T. L. Olander, R. M. Zehr, *Weather and Forecasting* **13**, 172 (1998).
27. J. P. Kossin, C. S. Velden, *Mon. Weather Rev.* **132**, 165 (2004).
28. G. J. Holland, *Aust. Meteorol. Mag.* **29**, 169 (1981).
29. K. Emanuel, *Nature* **436**, 686 (2005).
30. See www.prime-intl.co.jp/kyosei-2nd/PDF/24/11_murakami.pdf.

31. This research was supported by the Climate Dynamics Division of NSF under award NSF-ATM 0328842 and by the National Center for Atmospheric Research, which is funded by NSF.

22 June 2005; accepted 18 August 2005
10.1126/science.1116448

Downloaded from www.sciencemag.org on May 7, 2008