

Lab # 2

Attached are three articles published in *Nature* and *Science* in 2005 discussing the potential effects of global warming on hurricanes. Write a one-page essay (single-space typed with font size # 12) to summarize:

- a. The scientific basis for the effect of global warming on tropical storms.
- b. History of hurricanes in terms of their intensity and direction from these articles.
- c. Uncertainty in the correlation of hurricanes and global warming associated with man-made perturbations.

You may find additional articles from the references to support your discussion (due Tuesday, May 16).

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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 Oseanklima; 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

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

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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 CO₂ 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

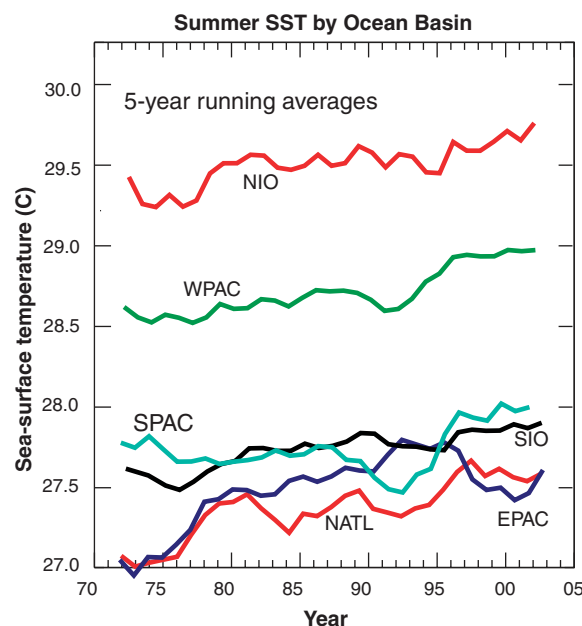


Fig. 1. Running 5-year mean of SST during the respective hurricane seasons for the principal ocean basins in which hurricanes occur: the North Atlantic Ocean (NATL: 90° to 20°E, 5° to 25°N, June–October), the Western Pacific Ocean (WPAC: 120° to 180°E, 5° to 20°N, May–December), the East Pacific Ocean (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).

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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.

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-

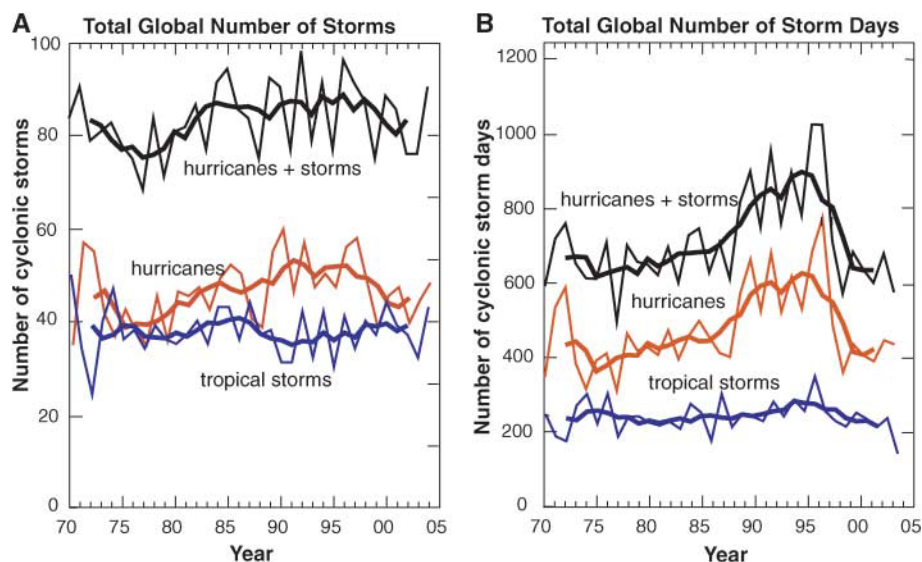


Fig. 2. Global time series for 1970–2004 of (A) number of storms and (B) number of storm days for tropical cyclones (hurricanes plus tropical storms; black curves), hurricanes (red curves), and tropical storms (blue curves). Contours indicate the year-by-year variability, and the bold curves show the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

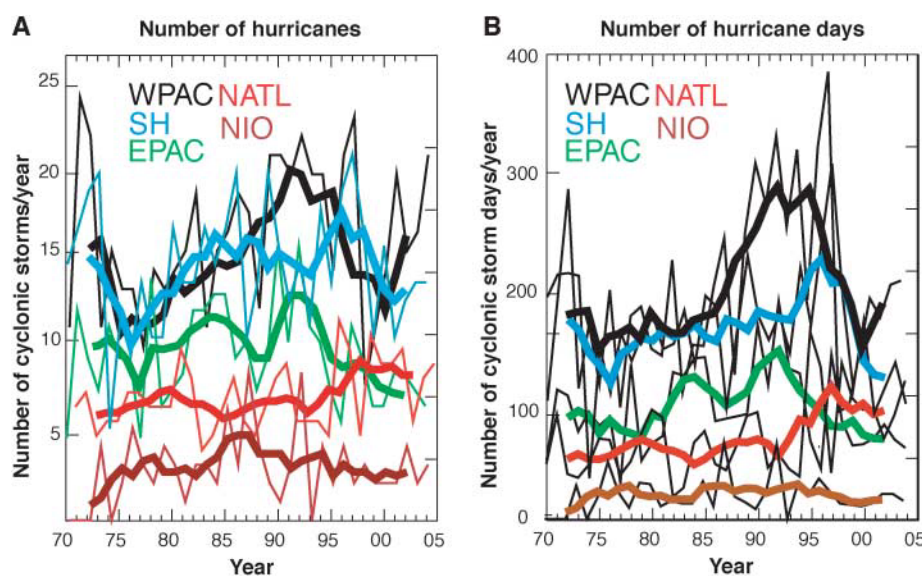


Fig. 3. Regional time series for 1970–2004 for the NATL, WPAC, EPAC, NIO, and Southern Hemisphere (SIO plus SPAC) for (A) total number of hurricanes and (B) total number of hurricane days. Thin lines indicate the year-by-year statistics. Heavy lines show the 5-year running averages.

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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. How-

ever, 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 CO₂ 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.

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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.

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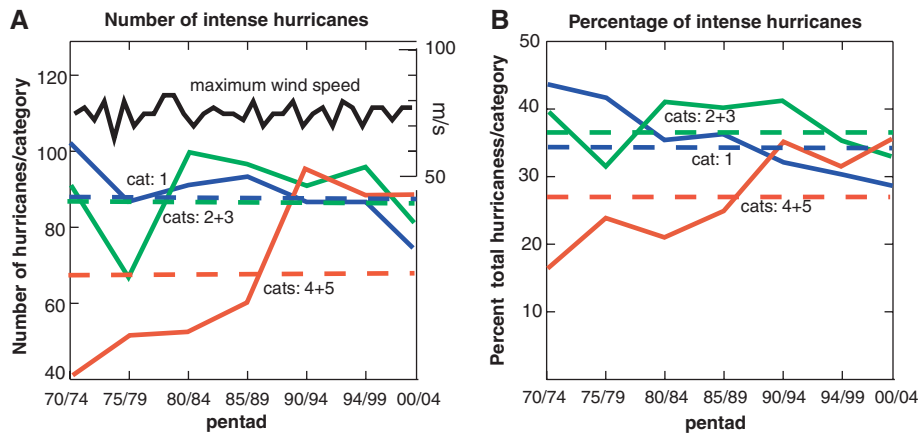


Fig. 4. Intensity of hurricanes according to the Saffir-Simpson scale (categories 1 to 5). (A) The total number of category 1 storms (blue curve), the sum of categories 2 and 3 (green), and the sum of categories 4 and 5 (red) in 5-year periods. The bold curve is the maximum hurricane wind speed observed 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

plexity. The rapidity of the diversification and the ecological interactions between species suggests that, as in the plants and insects of the Hawaiian and Canary islands, species beget species. In terms of MacArthur and Wilson's model, these macroevolutionary events should be limited by the extent to which new resources increased the carrying capacity of the environment. But if there is feedback between diversifying species, and a total potential diversity that is not limited by resources, then we may need a class of models in which future diversity is a function of current diversity.

Diversity cannot continue to increase forever, and ultimately resource availability must play a role, but perhaps a smaller one over evolutionary time than has been

thought. Paleontologists, taking their cue from ecologists, have generally assumed that resource limitation controls the diversity of a community, but some have wondered whether changes in diversity might come from periodic disturbance. There have been few explicit considerations of this possibility, but Stanley (11) suggested that the apparent periodicity of mass extinctions and biotic crises reflected prolonged environmental disturbance and lengthy rediversification, not a periodic external forcing factor (such as periodic meteor bombardment). If periodic disturbance does provide a major control on diversity, then niche generation may be an ongoing process, more rapid during macroevolutionary transitions, but providing a regular source of new adaptive possibility until the next crisis occurs.

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CLIMATE

Uncertainty in Hurricanes and Global Warming

Kevin Trenberth

During the 2004 hurricane season in the North Atlantic, an unprecedented four hurricanes hit Florida; during the same season in the Pacific, 10 tropical cyclones or typhoons hit Japan (the previous record was six) (1). Some scientists say that this increase is related to global warming; others say that it is not. Can a trend in hurricane activity in the North Atlantic be detected? Can any such trend be attributed to human activity? Are we even asking the right questions?

In statistics, a null hypothesis—such as “there is no trend in hurricane activity”—may be formed, and it is common to reject the null hypothesis based on a 5% significance level. But accepting the null hypothesis does not mean that there is no trend, only that it cannot be proven from the particular sample and that more data may be required. This is frequently the case when the signal being sought is masked by large variability. If one instead formulates the inverse null hypothesis—“there is a trend in hurricane activity”—then the 5% significance level may bias results in favor of this hypothesis being accepted, given the variability. Acceptance of a false hypothesis (a “type II” error) is a common mistake. Rather than accept the hypothesis, one may be better off reserving judgment. Because of the weak-

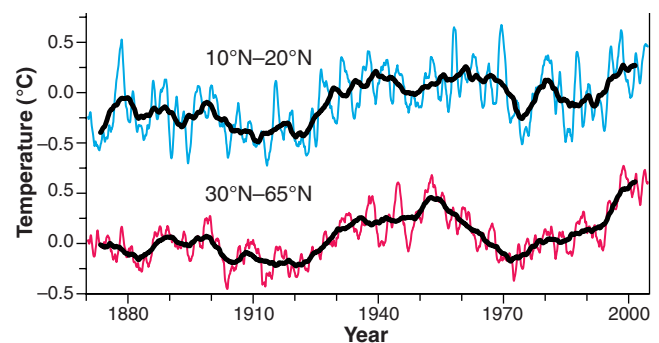
ness associated with statistical tests, it is vital to also gain a physical understanding of the changes in hurricane activity and their origins.

Hurricane activity generally occurs over the oceans in regions where sea surface temperatures (SSTs) exceed 26°C (2). In the Atlantic, SSTs and hurricane activity (see both figures) vary widely on interannual and multidecadal time scales. One factor in the year-to-year variability is El Niño: Atlantic hurricanes are suppressed when an El Niño is under way in the Pacific (3, 4). The decadal variability is thought to be associated with the thermohaline circulation and is referred to as the Atlantic multidecadal oscillation. It affects the number of hurricanes and major hurricanes that form from tropical storms first named in the tropical Atlantic and the Caribbean Sea (5–7).

In addition to interannual and multidecadal variability, there is a nonlinear upward trend in SSTs over the 20th century. This trend is most pronounced in the past 35 years in the extratropical North Atlantic (see the first figure). It is associated with global

warming and has been attributed to human activity (8). In the tropical North Atlantic—the region of most relevance to hurricane formation—multidecadal variability dominates SSTs (see the first figure), but the 1995–2004 decadal average is nonetheless the highest on record by >0.1°C. Hence, although the warming in the tropical North Atlantic is not as pronounced, it is probably related to that in the extratropical North Atlantic.

SSTs are not the only important variable affecting hurricanes (2, 9, 10). Other factors that have influenced the increase in hurricane activity in the past decade (11) include an amplified high-pressure ridge in the upper troposphere across the central and eastern North Atlantic; reduced vertical wind shear over the central North Atlantic [wind shear tends to inhibit the vortex from forming (2)]; and African easterly lower atmospheric winds that favor the development of hurricanes from tropical disturbances moving westward from the African coast. Atmospheric stability is also important (4).



Getting warmer. Annual mean SST anomalies relative to 1961 to 1990 (23) for 1870 to 2004, averaged over the tropical Atlantic (10°N to 20°N, excluding the Caribbean west of 80°W) (**top**) and the extratropical North Atlantic (30°N to 65°N) (**bottom**). Heavy lines are 10-year running means.

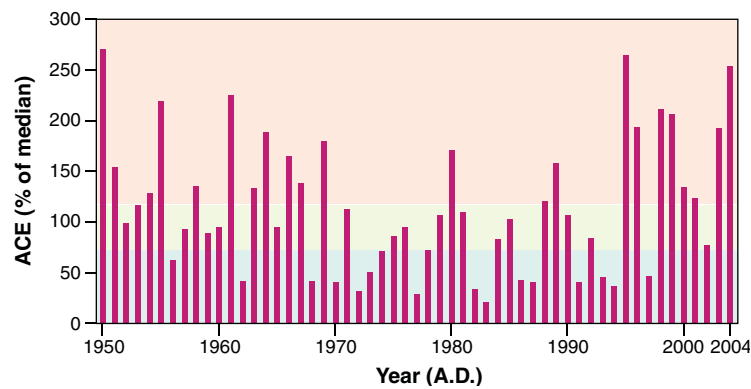
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PERSPECTIVES

Higher SSTs are associated with increased water vapor in the lower troposphere. Since 1988, the amount of total column water vapor over the global oceans has increased by 1.3% per decade (12); the variability and trends in water vapor are strongly related to SST anomalies. This behavior is similar to that expected theoretically (13) and supports model projections (14) suggesting that relative humidity remains about the same as temperatures increase. Both higher SSTs and increased water vapor tend to increase the energy available for atmospheric convection, such as thunderstorms, and for the development of tropical cyclones (9, 15). However, the convective available potential energy (15) is also affected by large-scale subsiding air that increases the stability and dryness of the atmosphere, and is often associated with wind shear throughout the troposphere (16). The convective available potential energy appears to have increased in the tropics from 1958 to 1997 (17, 18), which should increase the potential for enhanced moist convection, and thus—conceivably—for more hurricanes.

An important measure of regional storm activity is the Accumulated Cyclone Energy (ACE) index (see the second figure) (1). Since 1995, the ACE indexes for all but two Atlantic hurricane seasons have been above normal; the exceptions are the El Niño years of 1997 and 2002. According to the National Oceanic and Atmospheric Administration (NOAA), the hurricane seasons from 1995 to 2004 averaged 13.6 tropical storms, 7.8 hurricanes, and 3.8 major hurricanes, and the ACE index was 169% of the median. In contrast, the hurricane seasons during the previous 25-year period (1970 to 1994) averaged 8.6 tropical storms, five hurricanes, and 1.5 major hurricanes, and the ACE index was 70% of the median. In 2004, ACE reached the third-highest value since 1950 (1); there were 15 named storms, including nine hurricanes.

Despite this enhanced activity, there is no sound theoretical basis for drawing any conclusions about how anthropogenic climate change affects hurricane numbers or tracks, and thus how many hit land. The environmental changes that are under way favor enhanced convection and thus more thunderstorms. But to get a hurricane, these thunderstorms must first be organized into a tropical storm (which is essen-



A measure of regional storm activity. The ACE index reflects the collective intensity and duration of tropical storms and hurricanes during a given hurricane season. Values are given as percentage of the median from 1951 to 2000; the white band indicates normal conditions, the blue is below normal, and the pink is above normal, according to NOAA. [Adapted from (1)]

tially a collection of thunderstorms that develops a vortex). Model projections of how wind shear in the hurricane region responds to global warming caused by increased carbon dioxide in the atmosphere tend to differ (14), and it is not yet possible to say how El Niño and other factors affecting hurricane formation may change as the world warms.

However, once a tropical storm has formed, the changing environmental conditions provide more energy to fuel the storm, which suggests that it will be more intense than it would otherwise have been, and that it will be associated with heavier rainfalls (14). Groisman *et al.* (19) found no statistically significant evidence that precipitation associated with hurricanes increased along the southeastern coast of the contiguous United States during the 20th century; however, their analysis did not include years after 2000, and there was a distinct increase in hurricane precipitation after 1995. Groisman *et al.* found a linear upward trend in precipitation amount by 7% in the 20th century in the contiguous United States; the increases in heavy precipitation (the heaviest 5%) and very heavy precipitation (the heaviest 1%) were much greater at 14% and 20%, respectively (19). Such trends are likely to continue (20).

Thus, although variability is large, trends associated with human influences are evident in the environment in which hurricanes form, and our physical understanding suggests that the intensity of and rainfalls from hurricanes are probably increasing (8), even if this increase cannot yet be proven with a formal statistical test. Model results (14) suggest a shift in hurricane intensities toward extreme hurricanes.

The fact that the numbers of hurricanes have increased in the Atlantic is no guarantee that this trend will continue, owing to the need for favorable conditions to allow a

vortex to form while limiting stabilization of the atmosphere by convection. The ability to predict these aspects requires improved understanding and projections of regional climate change. In particular, the tropical ocean basins appear to compete to be most favorable for hurricanes to develop; more activity in the Pacific associated with El Niño is a recipe for less activity in the Atlantic. Moreover, the thermohaline circulation and other climate factors will continue to vary naturally.

Trends in human-influenced environmental changes

are now evident in hurricane regions. These changes are expected to affect hurricane intensity and rainfall, but the effect on hurricane numbers remains unclear. The key scientific question is not whether there is a trend in hurricane numbers and tracks, but rather how hurricanes are changing.

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LETTERS

Increasing destructiveness of tropical cyclones over the past 30 years

Kerry Emanuel¹

Theory¹ and modelling² predict that hurricane intensity should increase with increasing global mean temperatures, but work on the detection of trends in hurricane activity has focused mostly on their frequency^{3,4} and shows no trend. Here I define an index of the potential destructiveness of hurricanes based on the total dissipation of power, integrated over the lifetime of the cyclone, and show that this index has increased markedly since the mid-1970s. This trend is due to both longer storm lifetimes and greater storm intensities. I find that the record of net hurricane power dissipation is highly correlated with tropical sea surface temperature, reflecting well-documented climate signals, including multi-decadal oscillations in the North Atlantic and North Pacific, and global warming. My results suggest that future warming may lead to an upward trend in tropical cyclone destructive potential, and—taking into account an increasing coastal population—a substantial increase in hurricane-related losses in the twenty-first century.

Fluctuations in tropical cyclone activity are of obvious importance to society, especially as populations of afflicted areas increase⁵. Tropical cyclones account for a significant fraction of damage, injury and loss of life from natural hazards and are the costliest natural catastrophes in the US⁶. In addition, recent work suggests that global tropical cyclone activity may play an important role in driving the oceans' thermohaline circulation, which has an important influence on regional and global climate⁷.

Studies of tropical cyclone variability in the North Atlantic reveal large interannual and interdecadal swings in storm frequency that have been linked to such regional climate phenomena as the El Niño/Southern Oscillation⁸, the stratospheric quasi-biennial oscillation⁹, and multi-decadal oscillations in the North Atlantic region¹⁰. Variability in other ocean basins is less well documented, perhaps because the historical record is less complete.

Concerns about the possible effects of global warming on tropical cyclone activity have motivated a number of theoretical, modelling and empirical studies. Basic theory¹¹ establishes a quantitative upper bound on hurricane intensity, as measured by maximum surface wind speed, and empirical studies show that when accumulated over large enough samples, the statistics of hurricane intensity are strongly controlled by this theoretical potential intensity¹². Global climate models show a substantial increase in potential intensity with anthropogenic global warming, leading to the prediction that actual storm intensity should increase with time¹. This prediction has been echoed in climate change assessments¹³. A recent comprehensive study using a detailed numerical hurricane model run using climate predictions from a variety of different global climate models² supports the theoretical predictions regarding changes in storm intensity. With the observed warming of the tropics of around 0.5 °C, however, the predicted changes are too small to have been observed, given limitations on tropical cyclone intensity estimation.

The issue of climatic control of tropical storm frequency is far

more controversial, with little guidance from existing theory. Global climate model predictions of the influence of global warming on storm frequency are highly inconsistent, and there is no detectable trend in the global annual frequency of tropical cyclones in historical tropical cyclone data.

Although the frequency of tropical cyclones is an important scientific issue, it is not by itself an optimal measure of tropical cyclone threat. The actual monetary loss in wind storms rises roughly as the cube of the wind speed¹⁴ as does the total power dissipation (PD; ref. 15), which, integrated over the surface area affected by a storm and over its lifetime is given by:

$$PD = 2\pi \int_0^\tau \int_0^{r_0} C_D \rho |V|^3 r dr dt \quad (1)$$

where C_D is the surface drag coefficient, ρ is the surface air density, $|V|$ is the magnitude of the surface wind, and the integral is over radius to an outer storm limit given by r_0 and over τ , the lifetime of the storm. The quantity PD has the units of energy and reflects the total power dissipated by a storm over its life. Unfortunately, the area integral in equation (1) is difficult to evaluate using historical data sets, which seldom report storm dimensions. On the other hand, detailed studies show that radial profiles of wind speed are generally geometrically similar¹⁶ whereas the peak wind speeds exhibit little if any correlation with measures of storm dimensions¹⁷. Thus variations in storm size would appear to introduce random errors in an evaluation of equation (1) that assumes fixed storm dimensions. In the integrand of equation (1), the surface air density varies over roughly 15%, while the drag coefficient is thought to increase over roughly a factor of two with wind speed, but levelling off at wind speeds in excess of about 30 m s⁻¹ (ref. 18). As the integral in equation (1) will, in practice, be dominated by high wind speeds, we approximate the product $C_D \rho$ as a constant and define a simplified power dissipation index as:

$$PDI \equiv \int_0^\tau V_{\max}^3 dt \quad (2)$$

where V_{\max} is the maximum sustained wind speed at the conventional measurement altitude of 10 m. Although not a perfect measure of net power dissipation, this index is a better indicator of tropical cyclone threat than storm frequency or intensity alone. Also, the total power dissipation is of direct interest from the point of view of tropical cyclone contributions to upper ocean mixing and the thermohaline circulation⁷. This index is similar to the 'accumulated cyclone energy' (ACE) index¹⁹, defined as the sum of the squares of the maximum wind speed over the period containing hurricane-force winds.

The analysis technique, data sources, and corrections to the raw data are described in the Methods section and in Supplementary Methods. To emphasize long-term trends and interdecadal variability, the PDI is accumulated over an entire year and, individually, over

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each of several major cyclone-prone regions. To minimize the effect of interannual variability, we apply to the time series of annual PDI a 1-2-1 smoother defined by:

$$x'_i = 0.25(x_{i-1} + x_{i+1}) + 0.5x_i \quad (3)$$

where x_i is the value of the variable in year i and x'_i is the smoothed value. This filter is generally applied twice in succession.

Figure 1 shows the PDI for the North Atlantic and the September mean tropical sea surface temperature (SST) averaged over one of the prime genesis regions in the North Atlantic²⁰. There is an obvious strong relationship between the two time series ($r^2 = 0.65$), suggesting that tropical SST exerts a strong control on the power dissipation index. The Atlantic multi-decadal mode discussed in ref. 10 is evident in the SST series, as well as shorter period oscillations possibly related to the El Niño/Southern Oscillation and the North Atlantic Oscillation. But the large upswing in the last decade is unprecedented, and probably reflects the effect of global warming. We will return to this subject below.

Figure 2 shows the annually accumulated, smoothed PDI for the western North Pacific, together with July–November average smoothed SST in a primary genesis region for the North Pacific. As in the Atlantic, these are strongly correlated, with an r^2 of 0.63. Some of the interdecadal variability is associated with the El Niño/Southern Oscillation, as documented by Camargo and Sobel¹⁹. The SST time series shows that the upswing in SST since around 1975 is unusual by the standard of the past 70 yr.

There are reasons to believe that global tropical SST trends may have less effect on tropical cyclones than regional fluctuations, as tropical cyclone potential intensity is sensitive to the difference between SST and average tropospheric temperature. In an effort to quantify a global signal, annual average smoothed SST between 30° N and 30° S is compared to the sum of the North Atlantic and western North Pacific smoothed PDI values in Fig. 3. The two time series are correlated with an r^2 of 0.69. The upturn in tropical mean surface temperature since 1975 has been generally ascribed to global warming, suggesting that the upward trend in tropical cyclone PDI values is at least partially anthropogenic. It is interesting that this trend has involved more than a doubling of North Atlantic plus western North Pacific PDI over the past 30 yr.

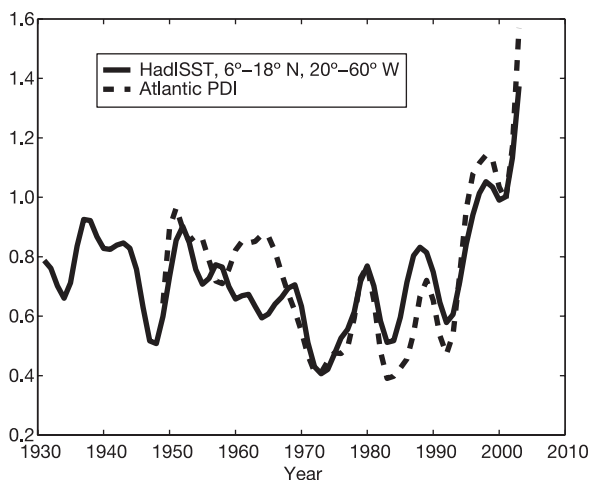


Figure 1 | A measure of the total power dissipated annually by tropical cyclones in the North Atlantic (the power dissipation index, PDI) compared to September sea surface temperature (SST). The PDI has been multiplied by 2.1×10^{-12} and the SST, obtained from the Hadley Centre Sea Ice and SST data set (HadISST)²², is averaged over a box bounded in latitude by 6° N and 18° N, and in longitude by 20° W and 60° W. Both quantities have been smoothed twice using equation (3), and a constant offset has been added to the temperature data for ease of comparison. Note that total Atlantic hurricane power dissipation has more than doubled in the past 30 yr.

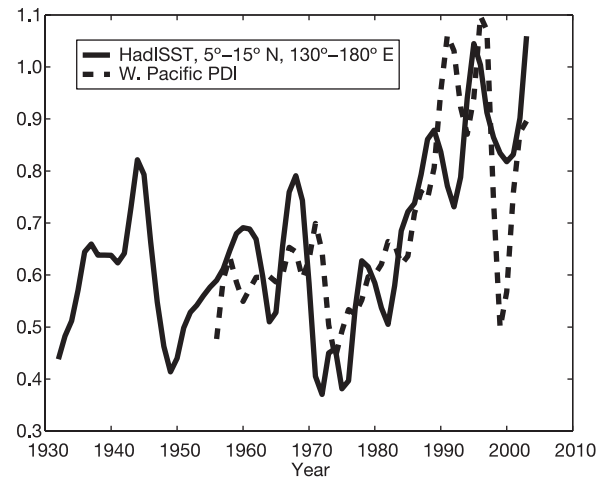


Figure 2 | Annually accumulated PDI for the western North Pacific, compared to July–November average SST. The PDI has been multiplied by a factor of 8.3×10^{-13} and the HadISST (with a constant offset) is averaged over a box bounded in latitude by 5° N and 15° N, and in longitude by 130° E and 180° E. Both quantities have been smoothed twice using equation (3). Power dissipation by western North Pacific tropical cyclones has increased by about 75% in the past 30 yr.

The large increase in power dissipation over the past 30 yr or so may be because storms have become more intense, on the average, and/or have survived at high intensity for longer periods of time. The accumulated annual duration of storms in the North Atlantic and western North Pacific has indeed increased by roughly 60% since 1949, though this may partially reflect changes in reporting practices, as discussed in Methods. The annual average storm peak wind speed summed over the North Atlantic and eastern and western North Pacific has also increased during this period, by about 50%. Thus both duration and peak intensity trends are contributing to the overall increase in net power dissipation. For fixed rates of intensification and dissipation, storms will take longer to reach greater peak winds, and also take longer to dissipate. Thus, not surprisingly, stronger storms last longer; time series of duration and peak intensity are correlated with an r^2 of 0.74.

In theory, the peak wind speed of tropical cyclones should increase

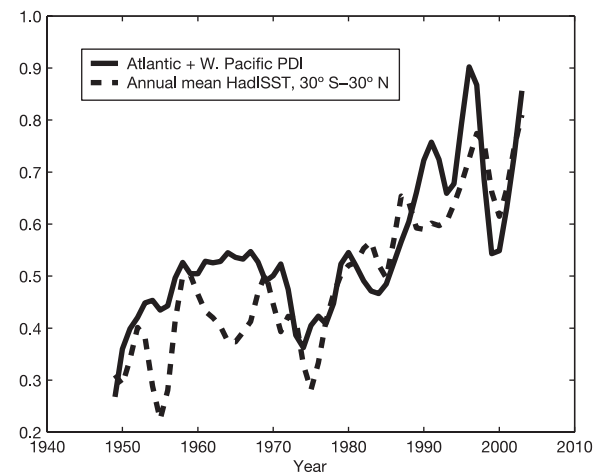


Figure 3 | Annually accumulated PDI for the western North Pacific and North Atlantic, compared to annually averaged SST. The PDI has been multiplied by a factor of 5.8×10^{-13} and the HadISST (with a constant offset) is averaged between 30° S and 30° N. Both quantities have been smoothed twice using equation (3). This combined PDI has nearly doubled over the past 30 yr.

by about 5% for every 1 °C increase in tropical ocean temperature¹. Given that the observed increase has only been about 0.5 °C, these peak winds should have only increased by 2–3%, and the power dissipation therefore by 6–9%. When coupled with the expected increase in storm lifetime, one might expect a total increase of PDI of around 8–12%, far short of the observed change.

Tropical cyclones do not respond directly to SST, however, and the appropriate measure of their thermodynamic environment is the potential intensity, which depends not only on surface temperature but on the whole temperature profile of the troposphere. I used daily averaged re-analysis data and Hadley Centre SST to re-construct the potential maximum wind speed, and then averaged the result over each calendar year and over the same tropical areas used to calculate the average SST. In both the Atlantic and western North Pacific, the time series of potential intensity closely follows the SST, but increases by about 10% over the period of record, rather than the predicted 2–3%. Close examination of the re-analysis data shows that the observed atmospheric temperature does not keep pace with SST. This has the effect of increasing the potential intensity. Given the observed increase of about 10%, the expected increase of PDI is about 40%, taking into account the increased duration of events. This is still short of the observed increase.

The above discussion suggests that only part of the observed increase in tropical cyclone power dissipation is directly due to increased SSTs; the rest can only be explained by changes in other factors known to influence hurricane intensity, such as vertical wind shear. Analysis of the 250–850 hPa wind shear from reanalysis data, over the same portion of the North Atlantic used to construct Fig. 1, indeed shows a downward trend of 0.3 m s⁻¹ per decade over the period 1949–2003, but most of this decrease occurred before 1970, and at any rate the decrease is too small to have had much effect. Tropical cyclone intensity also depends on the temperature distribution of the upper ocean, and there is some indication that sub-surface temperatures have also been increasing²¹, thereby reducing the negative feedback from storm-induced mixing.

Whatever the cause, the near doubling of power dissipation over the period of record should be a matter of some concern, as it is a measure of the destructive potential of tropical cyclones. Moreover, if upper ocean mixing by tropical cyclones is an important contributor to the thermohaline circulation, as hypothesized by the author⁷, then global warming should result in an increase in the circulation and therefore an increase in oceanic enthalpy transport from the tropics to higher latitudes.

METHODS

Positions and maximum sustained surface winds of tropical cyclones are reported every six hours as part of the 'best track' tropical data sets. (In the data sets used here, from the US Navy's Joint Typhoon Warning Center (JTWC) and the National Oceanographic and Atmospheric Administration's National Hurricane Center (NHC), 'maximum sustained wind' is defined as the one-minute average wind speed at an altitude of 10 m.) For the Atlantic, and eastern and central North Pacific, these data are available from the NHC, while for the western North Pacific, the northern Indian Ocean, and all of the Southern Hemisphere, data from JTWC were used.

Owing to changes in measuring and reporting practices since systematic observations of tropical cyclones began in the mid-1940s, there are systematic biases in reported tropical cyclone wind speeds that must be accounted for in

analysing trends. The sources of these biases and corrections made to account for them are described in Supplementary Methods.

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