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LETTERS

Increasing destructiveness of tropical cyclones over the past 30 years

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Theory[1] and modelling[2] 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 increase[5]. 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 US[6]. 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 climate[7].

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 Oscillation[8], the stratospheric quasi-biennial oscillation[9], and multi-decadal oscillations in the North Atlantic region[10]. 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 theory[11] 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 intensity[12]. 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 time[1]. This prediction has been echoed in climate change assessments[13]. A recent comprehensive study using a detailed numerical hurricane model run using climate predictions from a variety of different global climate models[2] 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 speed[14] 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:

$$\mathrm{PD} = 2\pi \int_0^{\tau} \int_0^{r_0} C_{\mathrm{D}} \rho |\mathbf{V}|^3 r \mathrm{d}r \mathrm{d}t \qquad (1)$$

where C_{D} is the surface drag coefficient, ρ is the surface air density, $|\mathbf{V}|$ 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 similar[16] whereas the peak wind speeds exhibit little if any correlation with measures of storm dimensions[17]. 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 $30\,\mathrm{m\,s^{-1}}$ (ref. 18). As the integral in equation (1) will, in practice, be dominated by high wind speeds, we approximate the product $C_{\mathrm{D}}\rho$ as a constant and define a simplified power dissipation index as:

$$\mathrm{PDI} \equiv \int_0^{\tau} V_{\max}^3 \mathrm{d}t \qquad (2)$$

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 circulation[7]. This index is similar to the 'accumulated cyclone energy' (ACE) index[19], 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:

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

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 Atlantic[20]. 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 Sobel[19]. 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.

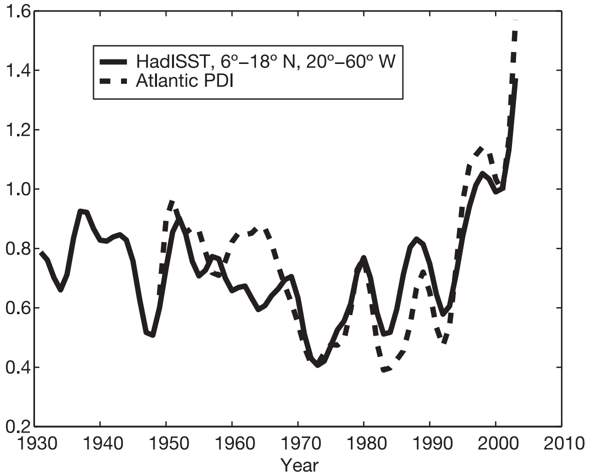

Figure 1 | A measure of the total power dissipated annually by tropical cyclones in the North Atlantic (the power dissipation index, PDI) compared to September sea surface temperature (SST). The PDI has been multiplied by 2.1×10^{-12} and the SST, obtained from the Hadley Centre Sea Ice and SST data 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.

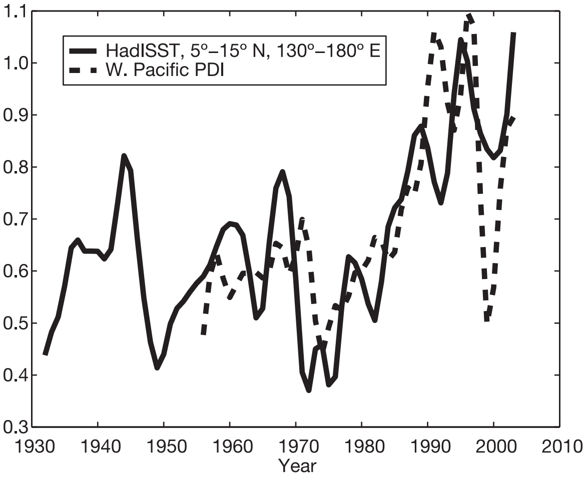

Figure 2 | Annually accumulated PDI for the western North Pacific, compared to July–November average SST. The PDI has been multiplied by a factor of 8.3×10^{-13} and the HadISST (with a constant offset) is averaged over a box bounded in latitude by 5° N and 15° N, and in longitude by 130° E and 180° 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; times 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

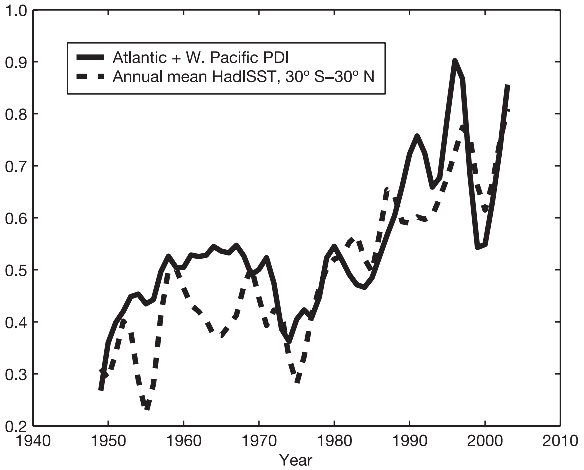

Figure 3 | Annually accumulated PDI for the western North Pacific and North Atlantic, compared to annually averaged SST. The PDI has been multiplied by a factor of 5.8×10^{-13} and the HadISST (with a constant offset) is averaged between 30° S and 30° N. Both quantities have been smoothed twice using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

by about 5% for every 1 °C increase in tropical ocean temperature[1]. 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 $0.3\,\mathrm{m\,s^{-1}}$ 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 increasing[21], 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 author[7], 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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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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