nature

Vol 436|4 August 2005|doi:10.1038/nature03906

LETTERS

Increasing destructiveness of tropical cyclones over the past 30 years

Kerry Emanuel[1]

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:

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

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.

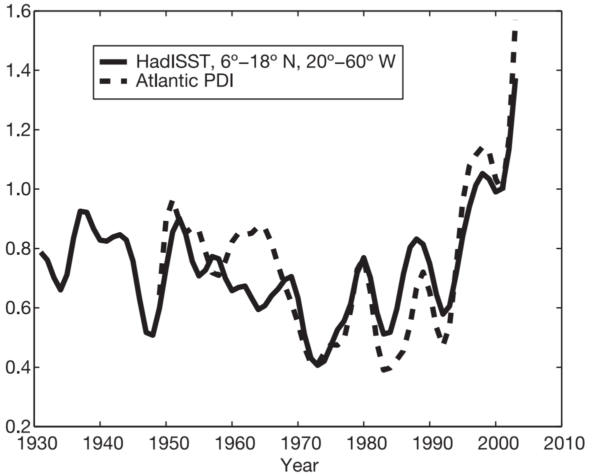

Figure 1 | A measure of the total power dissipated annually by tropical cyclones in the North Atlantic (the power dissipation index, PDI) compared to September sea surface temperature (SST). The PDI has been multiplied by 2.1×10^{-12} and the SST, obtained from the Hadley Centre Sea Ice and SST data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

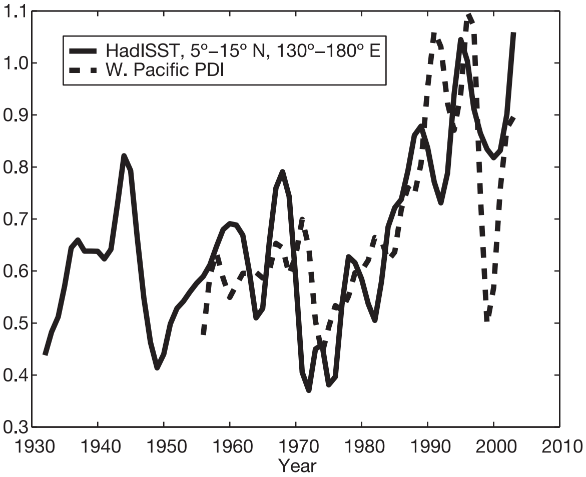

Figure 2 | Annually accumulated PDI for the western North Pacific, compared to July–November average SST. The PDI has been multiplied by a factor of 8.3×10^{-13} and the HadISST (with a constant offset) is averaged over a box bounded in latitude by 5° N and 15° N, and in longitude by 130° E and 180°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

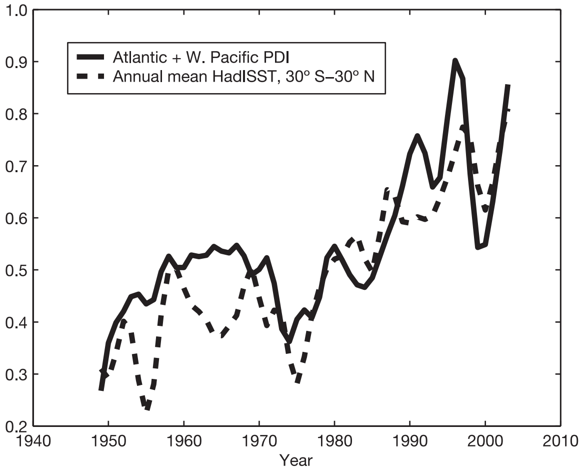

Figure 3 | Annually accumulated PDI for the western North Pacific and North Atlantic, compared to annually averaged SST. The PDI has been multiplied by a factor of 5.8×10^{-13} and the HadISST (with a constant offset) is averaged between 30° S and 30° N. Both quantities have been smoothed twice using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

Received 28 January; accepted 3 June 2005.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements The author is grateful for correspondence with S. Camargo, C. Guard, C. Landsea and A. Sobel.

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METEOROLOGY

Are there trends in hurricane destruction?

Arising from: K. Emanuel *Nature* **436,** 686–688 (2005)

Since the record impact of Hurricane Katrina, attention has focused on understanding trends in hurricanes and their destructive potential. Emanuel[1] reports a marked increase in the potential destructiveness of hurricanes based on identification of a trend in an accumulated annual index of power dissipation in the North Atlantic and western North Pacific since the 1970s. If hurricanes are indeed becoming more destructive over time, then this trend should manifest itself in more destruction. However, my analysis of a long-term data set of hurricane losses in the United States shows no upward trend once the data are normalized to remove the effects of societal changes.

Historical hurricane losses can be adjusted to a base year's values through adjustments related to inflation, population and wealth[2]. For at least three reasons, this data set is appropriate for identifying long-term climate signals. First, a long-term record of flood damage (collected in a similar way to and by the same agency as the hurricane data) is of sufficient quality to identify long-term trends[3]. Second, a methodology[2] developed in 1998 produces results that are consistent with the results of catastrophe models used by the insurance industry to assess hurricane losses[4]. Third, and most crucially, the data set contains climate signals, such as that of the El Niño–Southern Oscillation, which has a well established climatological relationship with interannual hurricane behaviour (see refs 5, 6, for example).

Specifically, an index of sea-surface-temperature anomalies of the Niño 3.4 region of the central Pacific in August, September and October is highly correlated with observed normalized damages in the same year[5]. The observed intensity change[7] in Atlantic basin hurricanes between El Niño and La Niña events is of similar magnitude to the changes in annual accumulated power-dissipation index identified by Emanuel[1]; the ability to identify the signal of the former suggests therefore that the normalized damage database is of sufficient size and quality to identify climate signals of the magnitude discussed by Emanuel.

A data set of hurricane losses (focusing on direct damages related to wind, and generally excluding rain-caused flood damage) for individual storms[6] extended to 2004, which includes only those storms causing damage, shows no upward trend. For example, take the 86 storms causing at least US$1 billion in normalized damages, which removes a bias caused by small storms resulting in no damage in the early twentieth century (that is, not subjected to normalization). There is an average per-storm loss in 1900–50 for 40 storms (0.78 events per year) of $9.3 billion, and an average per-storm loss in 1951–2004 for 46 storms (0.85 events per year) of $7.0 billion; this difference is not statistically significant. Adding Hurricane Katrina to this data set, even at the largest loss figures currently suggested, would not change the interpretation of these results.

These loss data indicate two possibilities with respect to Emanuel's analysis[1]: if the power-dissipation index metric is an accurate indicator of hurricane destructiveness, then the trend identified by Emanuel could be an artefact of the data and/or methods; alternatively, the trend he identifies is an accurate reflection of trends in the real-world characteristics of storms, but the power-dissipation index is a weak indicator of hurricane destructiveness — which would call for the identification of climate metrics more directly associated with societal outcomes. In any case, it is misleading to characterize Emanuel's results as indicating an increase in "destructiveness" or as an indication of future increases in destruction resulting from changes in the power-dissipation index.

The bottom line is that, with no long-term trend identified in normalized hurricane damage over the twentieth century (in the United States or elsewhere; see ref. 8, for example), it is exceedingly unlikely that scientists will identify large changes in historical storm behaviour that have significant societal implications. Looking to the future, Emanuel[1] provides no evidence to alter the conclusion that changes in society will continue to have a much larger effect than changes in climate on the escalating damage resulting from tropical cyclones[9].

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doi:10.1038/nature04426

METEOROLOGY

Hurricanes and global warming

Arising from: K. Emanuel *Nature* **436,** 686–688 (2005)

Anthropogenic climate change has the potential for slightly increasing the intensity of tropical cyclones through warming of sea surface temperatures[1]. Emanuel[2] has shown a striking and surprising association between sea surface temperatures and destructiveness by tropical cyclones in the Atlantic and western North Pacific basins. However, I question his analysis on the following grounds: it does not properly represent the observations described; the use of his Atlantic bias-removal scheme may not be warranted; and further investigation of a substantially longer time series for tropical cyclones affecting the continental United States does not show a tendency for increasing destructiveness. These factors indicate that instead of "unprecedented" tropical cyclone activity having occurred in recent years, hurricane intensity was equal or even greater during the last active period in the mid-twentieth century.

My first concern is that Emanuel's figures[2] do not match their description: his Figs 1–3 aim to present smoothed power-dissipation index (PDI) time series with two passes of a 1-2-1 filter, but the end-points — which are crucial to his conclusions — instead retain data unaltered by the smoothing; this is important because the last data point plotted in Emanuel's Fig. 1 is far larger than any other portion of the time series. Even after adding last year's busy hurricane season into the analysis and then properly using the filter, as described, the crucial end-point of the smoothed time series no longer jumps up dramatically in the last couple of years (Fig. 1a). About one-third of the increase in Atlantic PDI in Emanuel's graph for the past ten years is incorrect owing to inappropriate plotting of the data, even if the active 2004 season is incorporated.

A second concern is the bias-removal scheme used to alter the data for the Atlantic for 1949–69. Emanuel can demonstrate "unprecedented" activity in the past ten years only by markedly reducing the tropical-cyclone winds for the first two decades of the time series. He attempts to use a bias-removal scheme[3] that recommends reduction of the tropical-cyclone winds by 2.5–5.0 m s^{-1} for the 1940s–60s because of an inconsistency in the pressure–wind relationship during those years compared with subsequent (and presumably more accurate) data. However, the function used by Emanuel to reduce the winds in the earlier period goes well beyond this recommendation, as the bias removal used continued to increase with increasing wind intensity and reached a reduction of as much as 12.2 m s^{-1} for the strongest hurricane in the 1949–69 original data set.

In major hurricanes, winds are substantially stronger at the ocean's surface[4–7] than was previously realized, so it is no longer clear that Atlantic tropical cyclones of the 1940s–60s call for a sizeable systematic reduction in their wind speeds. It is now understood to be physically reasonable that the intensity of hurricanes in the 1970s through to the early 1990s was underestimated, rather than the 1940s and 1960s being overestimated[8]. To examine changes in intensity over time, it is therefore better to use the original hurricane database than to apply a general adjustment to the data in an attempt to make it homogenous.

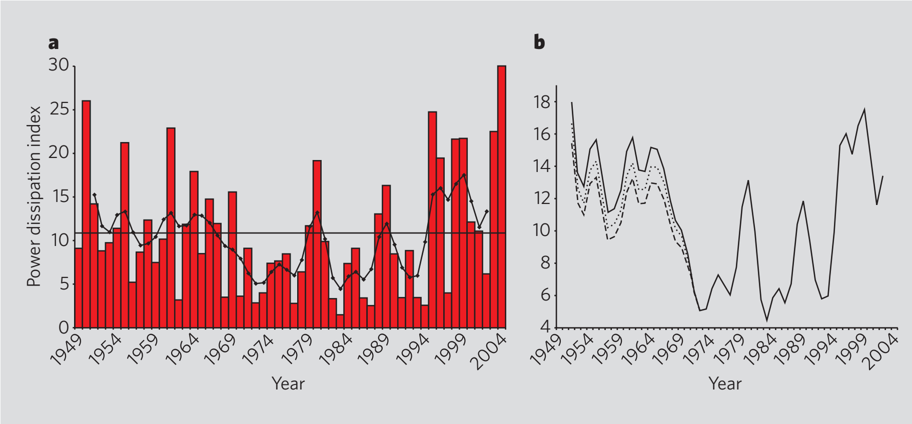

Figure 1 | Derivation of Atlantic power-dissipation index (PDI). **a**, Emanuel's bias-correction version[2] of PDI for the North Atlantic tropical cyclones for 1949–2004. PDI takes into account frequency, duration and intensity of tropical cyclones by cubing the winds during the lifetime of the systems while they are of at least tropical-storm force (18 m s^{-1}) and summing them up for the year. Values shown are multiplied by 10^{-6} in units of m^3 s^{-3}. Horizontal line, time-series mean of 10.8; black curve, data after smoothing with two passes of a 1-2-1 filter. **b**, Three versions of the smoothed PDI for the North Atlantic using: dashed line, Emanuel's applied bias-removal scheme; dotted line, 1993 version[3] of the bias-removal scheme; solid line, original hurricane database. All three versions are identical from 1970 onwards.

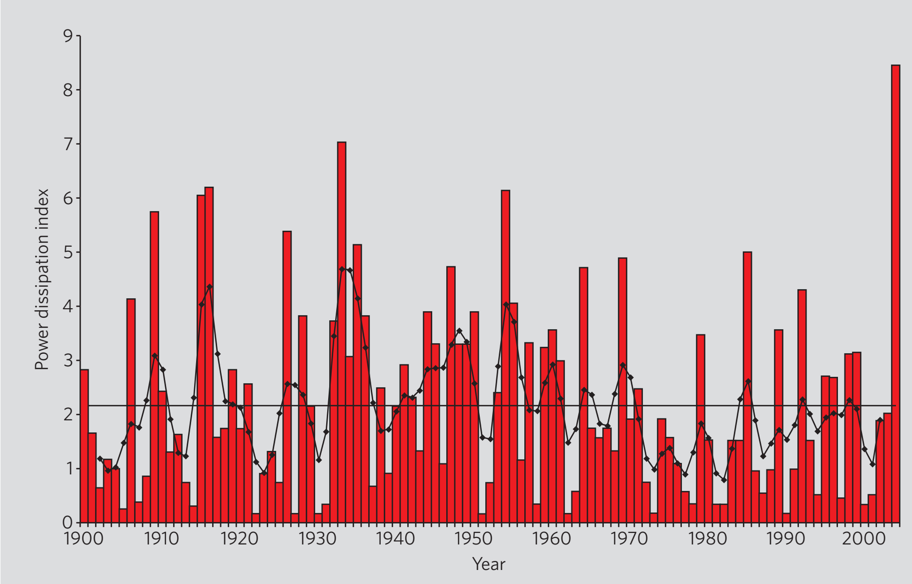

Figure 2 | The continental United States PDI at the time of impact for the reliable-period record of 1900–2004. This is computed from the best estimate of the peak sustained (1 min) surface (10 m) winds to have affected the US coastline for all tropical storms, subtropical storms and hurricanes causing at least gale-force (18 m s^{-1}) winds. Values shown are multiplied by 10^{-5} in units of m^3 s^{-3}. Horizontal line, time-series mean; black curve, data after smoothing with two passes of a 1-2-1 filter. For the continental US coast, the year 1900 roughly marks the start of a complete database. (Before that, portions of Florida, Louisiana and Texas were too sparsely settled to ensure adequate monitoring of all tropical cyclones, particularly those that were small but intense like 2004's hurricane Charley.) The year 2004 stands out as the busiest from the twentieth century to the beginning of the twenty-first century, with 20% more PDI than the second most-active year in 1933. (However, 2004's US PDI value is slightly less than that estimated to have occurred in 1886, as at least seven landfalling hurricanes struck that season, the busiest on record since 1851.)

Figure 1b shows Emanuel's bias-removed smoothed curve and the substantially larger PDI values in the original hurricane data set; the latter indicates that amplitudes for 1949–69 are comparable to those for the most recent decade. This is consistent with earlier work[9,10], emphasizing the large multidecadal oscillations in activity. It is also likely that values of PDI from the 1940s to the mid-1960s are substantially undercounted owing to the lack of routine aircraft reconnaissance and geostationary satellite monitoring of tropical cyclones far from land.

A third concern is that it is difficult to separate out any anthropogenic signal from the substantial natural multidecadal oscillations with a relatively short record of tropical-cyclone activity. One way to extend the PDI analysis back to include several additional decades of reliable records is to examine only those tropical cyclones that made landfall along populated coastlines[11,12]. Figure 2 shows that tropical-cyclone activity in the United States was generally extremely busy between the 1930s and 1960s, but fell below average between the 1970s and early 1990s. Despite the extreme value for 2004, the most recent decade has a PDI that is near-average for the United States, rather than showing an increase in the overall number and intensity of hurricane strikes.

Despite these problems, Emanuel's study illustrates the pressing need for a completion of the storm-by-storm reanalysis of the Atlantic hurricane database[8,11], which will provide a more homogeneous time series of tropical-cyclone intensities and so avoid the application of arbitrary bias-removal schemes. But, on the basis of the evidence I present here, claims to connect Atlantic hurricanes with global warming are premature. The Atlantic hurricane basin is currently seeing enhanced, rather than "unprecedented", storminess that is comparable to, or even less active than, that seen in earlier busy cycles of activity.

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doi:10.1038/nature04477

METEOROLOGY

Emanuel replies

Replying to: R. A. Pielke *Nature* 438, doi:10.1038/nature04426 (2005) and C. W. Landsea *Nature* 438, doi:10.1038/nature04477 (2005)

In my original Article[1], I showed that there has been a significant upward trend in a measure of tropical-cyclone power dissipation over the past 30 years[1]. It is important to note that this measure is integrated over the life of the storm, and that the upward increase is evident in all major ocean basins prone to tropical cyclones. However, Pielke[2] finds no discernible trend in hurricane damage in the United States after correction for inflation and demographic trends, and Landsea[3] finds no trend in US landfall-based hurricane power dissipation back to the turn of the last century.

Pielke suggests[2] that this apparent disparity could be explained if the power-dissipation trend I find is an artefact of the data and/or analysis methods, or if the trend is accurate but not a good predictor of damage. As this trend is large and universal — having about the same value in all the major ocean basins, despite different measurement techniques — and as it is well correlated with sea surface temperature (SST), which is relatively well measured, I stand by my conclusions about the trends in tropical-cyclone power dissipation.

I cannot discount the second of Pielke's conjectures, but the reason for the disparity may be more prosaic. Although Atlantic hurricanes do most of their destruction within 6–12 hours after landfall, they last for an average of 180 hours; moreover, only a fraction of hurricanes ever affect the US coastline. This means that the power-dissipation index (PDI) I used, which is accumulated over all storms and over their entire lives, contains about 100 times more data than an index related to wind speeds of hurricanes at landfall. There is large variability in wind speed over the life of each storm and large storm-to-storm random variability: detecting a temporal trend in the presence of this variability requires separation of the signal from the noise. With 100 times more data, my index has a signal-to-noise ratio that is ten times that of an index based on landfalling wind speeds. It is therefore possible that the real trend is detectable in the power dissipation but not in landfalling statistics. A simple calculation based on the observed root-mean-square variability of hurricane activity indicates that this is indeed the case, and probably explains why Pielke[2] and Landsea[3] find no trends in US landfall data.

Pielke argues that because El Niño can be detected in hurricane damage, a trend related to PDI should also be evident, if it exists. But the detectability of an El Niño signal in US hurricane damage is marginal, explaining only 3–4% of the variance[4]. Tropical Atlantic SST explains far more of the variance of both total Atlantic tropical-cyclone numbers and average tropical-cyclone intensity than does El Niño; but curiously, SST is even less correlated with a measure of US landfalling storm activity than El Niño. This probably once again reflects the difficulty of detecting trends in sparse time series in which the amplitude of random fluctuations is large compared with the signal.

The failure of any trend in landfall statistics to emerge from the noise is itself significant, and supports Pielke's view that demographic trends will be more important than climate change in coming years. But this is a short-term and US-centric view. When global tropical-cyclone activity is considered, and not just the 12% that occurs in the Atlantic region, a trend in landfalling intensity is already apparent; even in the Atlantic the signal, if it exists, is similar to the PDI trend, and if it continues should emerge from the noise in a few decades.

Landsea[3] starts by saying that increasing SST has the potential for "slightly" increasing the intensity of tropical cyclones. But, as I discussed[1], the existing theory and modelling[5] on which this assertion is based suggest that the predicted ~2 °C increase in tropical SST would increase wind speeds by 10% and, accounting for increased storm lifetime, increase power dissipation by 40–50%. This is hardly slight. The existing theory and modelling work[5] are limited, however, in that they do not account for changes in environmental conditions, such as wind shear, and so only provide a loose guide as to what to expect.

Landsea correctly points out that in applying a smoothing to the time series, I neglected to drop the end-points of the series, so that these end-points remain unsmoothed. This has the effect of exaggerating the recent upswing in Atlantic activity. However, by chance it had little effect on the western Pacific time series, which entails about three times as many events. As it happens, including the 2004 and 2005 Atlantic storms and correctly dropping the end-points restores much of the recent upswing evident in my original Fig. 1 and leaves the western Pacific series, correctly truncated to 2003, virtually unchanged. Moreover, this error has comparatively little effect on the high correlation between PDI and SST that I reported[1].

In correcting for biases in the original Atlantic tropical-cyclone data, I relied on a bias correction applied by Landsea[6], presented as a table. I had fitted a polynomial to that correction, as I felt that a continuous rather than discrete correction was more defensible. Landsea believes that this had the effect of overcorrecting the most intense storms in the pre-1970 record, and I accept his revision to my analysis (Fig. 1b of ref. 3).

The Atlantic hurricane-intensity record by itself is not long enough to infer any connection between hurricanes and either global warming or multi-decadal cycles, but the high correlation between hurricane activity and tropical SST is remarkable (and largely unaffected by the corrections discussed), and the SST record is long enough to show the influence of global warming. To detect correlations with hurricane activity, tropical cyclones in the North Atlantic can be counted, assuming that detection of the presence of a storm by ships and islands is reliable (although intensity estimation is dubious before the mid-1940s). This count is highly correlated with both tropical Atlantic SST and Northern Hemispheric mean surface temperature through the entire record, casting doubt on whether the recent multi-decadal variability in tropical SST and hurricane activity is due purely to natural causes, as Landsea implies[3].

I maintain that current levels of tropical storminess are unprecedented in the historical record and that a global-warming signal is now emerging in records of hurricane activity. This is especially evident when one looks at global activity and not just the 12% of storms that occur in the Atlantic. But I agree that there is a pressing need for a storm-by-storm reanalysis of tropical cyclones, not only in the North Atlantic, but also in the western North Pacific, where aircraft reconnaissance records also extend back to the 1940s.

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doi:10.1038/nature04427