

Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend?

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We find that long-period variations in tropical cyclone and hurricane frequency over the past century in the North Atlantic Ocean have occurred as three relatively stable regimes separated by sharp transitions. Each regime has seen 50% more cyclones and hurricanes than the previous regime and is associated with a distinct range of sea surface temperatures (SSTs) in the eastern Atlantic Ocean. Overall, there appears to have been a substantial 100-year trend leading to related increases of over 0.7°C in SST and over 100% in tropical cyclone and hurricane numbers. It is concluded that the overall trend in SSTs, and tropical cyclone and hurricane numbers is substantially influenced by greenhouse warming. Superimposed on the evolving tropical cyclone and hurricane climatology is a completely independent oscillation manifested in the proportions of tropical cyclones that become major and minor hurricanes. This characteristic has no distinguishable net trend and appears to be associated with concomitant variations in the proportion of equatorial and higher latitude hurricane developments, perhaps arising from internal oscillations of the climate system. The period of enhanced major hurricane activity during 1945–1964 is consistent with a peak period in major hurricane proportions.

Keywords: hurricanes; tropical cyclones; climate trends; regime change; global warming

1. Introduction

The North Atlantic Ocean (NATL) region experienced unprecedented tropical cyclone activity in 2005, with records including 28 named systems, 14 hurricanes (of which 7 were major hurricanes), 3 category 5 hurricanes and 2 category 4 hurricanes in July. The number of tropical cyclones and hurricanes was, respectively, 2.5 and 2.2 times the long-term seasonal means, and the previous record for overall tropical cyclone numbers was exceeded by 33%. While the entire season was active, August and September, each with five tropical cyclones, were below previous records. The truly anomalous months were July and October, with five and six tropical cyclones, respectively. October experienced

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almost twice the mean of 3.1 hurricanes and equalled the previous record set in 1950. July tropical cyclones are relatively rare, typically occurring in less than one every two seasons, with an overall average of 1.2, providing less than 5% of Atlantic tropical cyclones. July 2005 was a record with 20% of all 2005 tropical cyclones and an unprecedented two category 4 hurricanes. Several cyclones also developed during June and November–December; however, for this study, we shall confine ourselves to the period from July to October, inclusive.

The anomalous year of 2005 occurred at the end of an extremely active decade. When compared with the previous most active decade in the North Atlantic, the number of named tropical storms increased by 43%, hurricanes by 51% and category 4 and 5 storms by 47%. This recent decade of high activity has raised questions of whether it has arisen from ‘natural’ variations (not influenced by humans) or the result of substantial influence of anthropogenically induced climate changes. A formal statement released by NOAA after the 2005 hurricane season stated unequivocally, with no reference to peer-reviewed literature to the contrary, that the current high level of activity was entirely due to natural variations (<http://www.magazine.noaa.gov/stories/mag184.htm>).

Here we present an analysis of the variations in NATL tropical cyclone activity over the past 100 years in an attempt to clarify the potential impact of anthropogenic climate change on tropical cyclone and hurricane activity.

2. Data and method

(a) NATL tropical cyclone data

A definition for hurricane intensity is given by the Saffir–Simpson Hurricane Categories (<http://www.nhc.noaa.gov/aboutsshs.shtml>) that can be used to define three basic classes of tropical storm: major hurricanes (hurricane category 3–5 and winds $> 49 \text{ m s}^{-1}$); minor hurricanes (hurricane categories 1 and 2 and winds $33\text{--}48 \text{ m s}^{-1}$); and tropical storms (maximum winds $17\text{--}32 \text{ m s}^{-1}$). We use the ‘best track’ tropical cyclone database from the National Hurricane Center (Jarvinan *et al.* 1984). The only changes to the dataset data have been to include the intensity corrections recommended by Landsea (1993). While these data represent the best available descriptions of track and intensity, they are variable in quality and accuracy to a largely unknown degree due to changes in observing systems and analysis practices. The major observing system change points are (figure 1): the implementation of routine aircraft reconnaissance in 1944–1945; the use of satellite observations and related analysis procedures from the late 1960s onwards; and a change in analysis practice by the NHC from 1970 to include more mid-latitude systems. In addition, there have been steady improvements in techniques and instrumentation. Balancing the early observational problems was a tendency for ships to provide better information on tropical cyclones, as they were less apt to avoid storms being without the excellent warning system that is now available (Holland 1981; Mann & Emanuel 2006).

Although it is impossible to quantify the absolute errors in the database, we have adopted the following guiding principles. First, we focus our analysis on periods when there has been a major shift in tropical cyclone characteristics in a short period of time, which is less likely to be attributable to a known observing or analysis changes. Second, different periods in the data record are chosen to

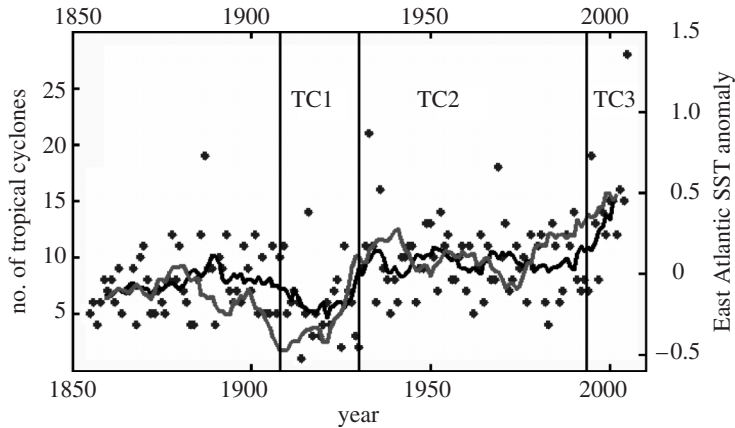


Figure 1. Tropical cyclone occurrence (dots indicate annual totals and the black line is a 9-year running mean) in the North Atlantic together with East Atlantic sea surface temperature (SST) anomalies for the hurricane season (grey line) from 1855 to 2005. TC1–TC3 refer to climate regimes discussed in the text.

emphasize cyclone numbers and intensities in recognition of the varying quality in observing these parameters.

The period 1855–2005 was used to enable a long-period assessment of general variability of tropical cyclone frequency. Before 1945, the overall statistic of total tropical cyclones numbers contains useful information. However, for the period prior to 1945, we consider that intensity estimates are too uncertain for definitive analysis, especially for differentiating between hurricane classes. Since the advent of aircraft reconnaissance in 1945, we consider that intensities are sufficiently accurate to provide a reasonable differentiation between major (category 3–5) and minor hurricanes (category 1 and 2), and between hurricanes collectively (from category 1 to 5) and tropical storms. From 1970 onwards, the use of satellites to complement aircraft reconnaissance has aided further in the differentiation between the classes of storms, especially in regions not routinely covered by aircraft reconnaissance. In this regard, we concur with the assessment of Neumann *et al.* (1993), Landsea *et al.* (1999), Goldenberg *et al.* (2001) and Owens & Landsea (2003) and who conclude that the period of reliable and accurate records for the determination of hurricane intensity in the NATL commenced in 1944. The exception to this conclusion is subtropical developments, which were not analysed prior to 1965 due to analysis practice (e.g. Spiegler 1971; Simpson & Pelissier 1971). These systems are therefore not included in this analysis. Kossin *et al.* (2006) also used a coherent satellite analysis to show that the variability in overall tropical cyclone intensities since 1983 in the North Atlantic database was accurate.

In summary, we consider that the veracity of the NATL tropical storm database is sufficient to enable the broad brush analysis that we undertake in this study. Prior to 1945, we concentrate on the total number of tropical cyclones, irrespective of intensity. After 1945, we extend the analysis and consider a broad categorization of total number of cyclones, minor hurricanes (categories 1 and 2) and major hurricanes (categories 3–5).

Questions have been raised over the quality of the NATL data even for such a broad brush accounting. For example, a recent study by Landsea *et al.* (2006) claimed that long-term trends in tropical cyclone numbers and characteristics cannot be determined owing to the poor quality of the database in the NATL, even after the incorporation of satellite data into the database. We have carefully examined the data record and considered as yet unpublished analyses by other investigators. Our conclusion is that the number of earlier missed storms most likely lies between 1 and 3 per year prior to 1900, less than 2 in the early nineteenth century and dropping off to essentially zero by 1960. The conclusion by Landsea (2007) of much higher numbers of missing storms is considered to be based on a false premise of an assumed constancy of landfalling storms ratio (Mann *et al.* submitted *a, b*; Holland in press). Landsea *et al.* (2006) also state unequivocally that there is no trend in any North Atlantic tropical storm characteristics (frequency or intensity) after 1960. This is at odds with several other studies (Emanuel 2005; Webster *et al.* 2005; Curry *et al.* 2006), which found a strong trend similar to that in figure 1. To remove the upward trend since 1960 would require the implausible conclusion that up to 5 tropical cyclones were missed prior to 1995.

(b) *Sea surface temperature data*

The SST analyses are derived from the extended reconstructed SST set archived at the NOAA Climate Data Center. Averages are compiled over the main hurricane season from July to September and for four geographical regions: eastern Atlantic (5–25° N, 55–20° W); western Atlantic (10–25° N, 90–55° W); Gulf of Mexico; and eastern North Pacific (5–20° N, 120–90° W). The eastern and western Atlantic regions include both the main cyclone development region defined by Goldenberg & Shapiro (1996) and the area of tropical SST fluctuations associated with the Atlantic Multidecadal Oscillation (e.g. Bell & Chelliah 2006).

Historical SST data have also varied in quality due to changing observing practices and especially with the implementation of satellite observing techniques (e.g. Rayner *et al.* 2006). Estimates by Kent & Challenor (2006) indicate that the random errors in monthly tropical SST data are of order 1°C and there may be a cool bias during periods of high aerosol loading, such as arising from major volcanic eruptions. The eastern tropical NATL has particular problems due to the low ship traffic before the satellite era and later with satellite algorithm errors caused by the large areas of Saharan dust that are advected over the region. However, Rayner *et al.* (2006) show that SST trends in the tropical regions are accurate to within 0.1°C at 95% confidence level and this concurs with 100-year trend differences between archived SST datasets of up to 0.25°C (Santer *et al.* 2006). We consider that our averaging over the full tropical cyclone season and further smoothing of the data in time have reduced random error influences to levels below these estimates. As a result, the large trends of order 0.5–1°C found by Webster *et al.* (2005) and used in this study are beyond the bounds of known errors.

3. Atlantic tropical cyclone changes

Spectral analysis of the tropical cyclone database (not shown) reveals distinct peaks at 2- to 3-, 5-, 9-year and multidecadal time periods. As longer period variations and trends are the focus of this paper, we require the removal of short-

term variations, such as associated with the El Niño–Southern Oscillation (ENSO) and quasi-biennial oscillation (QBO), which are both of order 2–3 years in period. We tested filters and averaging periods between 3 and 15 years. The averaging showed considerable sensitivity to smoothing period out to 5 years but relatively stable at longer averaging periods. All data are therefore smoothed by a simple 9-year running mean.

Standard statistical tests are used throughout. Unless otherwise indicated, all variance and correlation coefficients are valid at the 95% level using the *t*-statistic with correction for serial correlation by assuming the degrees of freedom are given by the number of observations divided by the averaging period.

(a) *Climatic regimes*

Atlantic tropical cyclone numbers since 1855 (figure 1) display several climatic regimes separated by sharp transitions, upon which is superimposed substantial interannual variability. The interannual variability is associated with El Niño and other short period phenomena (e.g. Gray 1984) and not relevant to this study. The tropical cyclone climatic regimes are also closely associated with similar transitions between climatic SST regimes (figures 1 and 2) and are characterized by distinctive annual ranges as well as mean changes in both cyclone frequency and SST. Between 1855 and 1900 cyclone numbers averaged 7–9 per year and the SST anomaly remained around -0.1 to -0.2°C . This period was followed by a marked decrease of 30% to an average of six tropical cyclones per year from 1905 to 1930, which we designate climate regime TC1. Annual numbers then increased to a new stable regime averaging around 10 tropical cyclones per year from 1931 to 1994 (climate regime TC2). This increase was accompanied by a rise in SST of 0.2 – 0.3°C and an upward shift of the annual variability to typically 6–14 named storms. Since 1995, the NATL has experienced a sustained upward trend in tropical cyclone numbers which may not as yet have settled into a stable regime. Accompanying this increase in tropical cyclone numbers is a marked SST warming to unprecedented anomaly levels exceeding $+0.7^{\circ}\text{C}$. We suggest that this trend may represent a transition to a third, and as yet undefined, climatic regime (TC3) in which cyclone frequency could stabilize at significantly higher numbers than characteristic of any previous period.

As shown in table 1, each of these climate regimes has distinctly different characteristics as well as some similarities. Tropical cyclone frequency increased by more than 50% between each regime; the variance was steady between TC1 and TC2, but then jumped by over 60% during TC3. Furthermore, both the annual minimum and maximum numbers of cyclones have increased substantially between each regime. The overall proportion of hurricanes to total tropical cyclone number has remained remarkably constant, especially since 1945. The higher proportion of hurricanes in the early record (figure 3b) was probably due to a tendency to miss weaker systems in earlier years. Since 1905, 80% of the variance in hurricanes is explained by tropical cyclone frequency. For TC1–TC3, eastern NATL SSTs were cool, normal and warm, respectively, and there has been a net 0.8°C increase in SST from TC1 to TC3. The annual variance in SSTs has remained constant, and the warming trend arose from a combination of increased low and high seasonal mean SSTs. Figure 1 also shows that superimposed on the climate regimes is a distinct shorter-term variability.

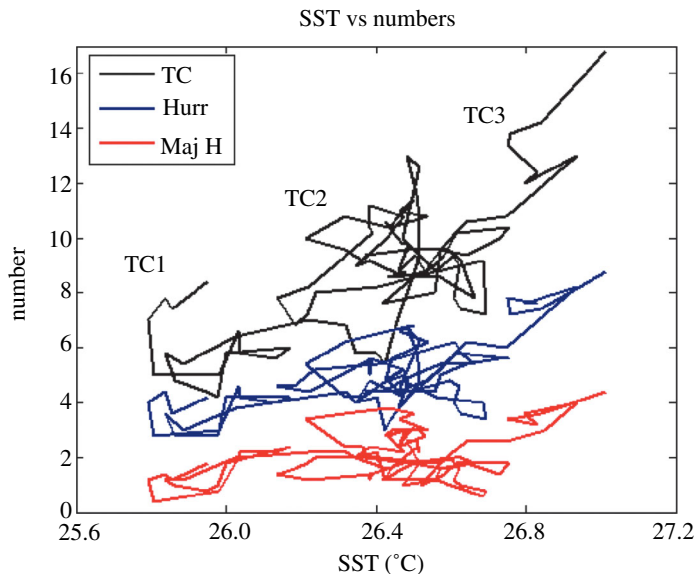


Figure 2. Phase diagram showing relationship between 5-year filtered annual tropical cyclone, hurricane and major hurricane numbers and SST in the East Atlantic Ocean. The three climate regimes discussed in the text are indicated and the changeover between the regimes occurs in the short joining contours. Note that regime 3 has not yet settled into a stable pattern.

Table 1. Summary of statistics for tropical cyclone, hurricane proportion and eastern NATL SST anomaly (from the 1905–2005 mean) for the three climate regimes, TC1–TC3 (shown in figure 1). (The standard deviations and min/max are for annual seasonal means.)

regime	period	tropical cyclones			hurricane proportion			east NATL SST anomaly		
		mean	s.d.	min/ max	mean	s.d.	min/max	mean	s.d.	min/max
TC1	1905–1930	6.0	3.2	1/14	0.58	0.25	0/1	−0.34	0.29	−0.7/+0.3
TC2	1931–1994	9.4	3.2	4/21	0.54	0.16	0.13/0.86	0.06	0.25	−0.5/+0.7
TC3	1995–2005	14.8	5.0	7/27	0.57	0.12	0.33/0.71	0.42	0.28	−0.1/+0.8

Taken together the overall trend in unadjusted tropical cyclone numbers is significant at the 95% level for all time periods prior to 1920 and is significant from 1890 onwards when the time series is increased by 2.5 cyclones per year prior to 1900 and by a decreasing amount to zero by 1960. The trend in major hurricanes is significant at the 95% level for all time periods prior to 1920 (R. Smith 2007, personal communication).

We have noted the uncertain quality of the tropical cyclone database in early years, and certainly, there will have been a number of unreported systems. However, we are aware of no known change in analysis or observing methodology that can explain the quite sharp changes between the relatively stable climatic regimes in figures 1 and 2; and table 1, especially since these have been associated

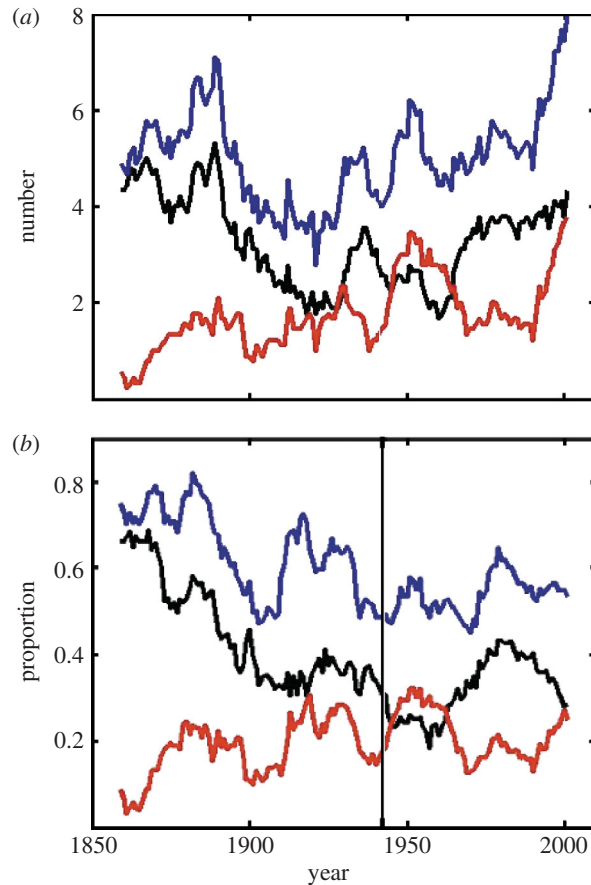


Figure 3. Variations in hurricanes (blue), and major (red) and minor (black) hurricanes from 1855 to 2005: (a) annual number and (b) proportion relative to all named storms. All data have been smoothed by a 9-year running mean and the vertical line indicates the commencement of reliable intensity data.

with stable hurricane to total tropical cyclone proportions, which have varied by less than 3% over the three regimes. Of particular importance is the way in which changes in the number of tropical cyclones have been accompanied by systematic changes in seasonal mean SSTs over the eastern Atlantic (figures 1 and 2; table 1). There has been an average of one additional tropical cyclone for each 0.1°C increase in SST and one hurricane for each 0.2°C increase. As the SST and tropical cyclone datasets are completely independent, the coincidence of trends and steady periods in both datasets offers support to the veracity of each.

Variations in major and minor hurricane numbers and their relative proportions (figure 3) are quite different from those found between all tropical cyclones and hurricanes. Specifically, the proportion of major and minor hurricanes has a distinct out-of-phase oscillation, which is not reflected in the more steady hurricane proportions. This oscillation becomes quite marked after the commencement of reliable intensity measurements in 1945, with a correlation of -0.79 between the proportions of major and minor hurricanes. The changeovers around 1945, 1962 and 1995 correspond closely with the change

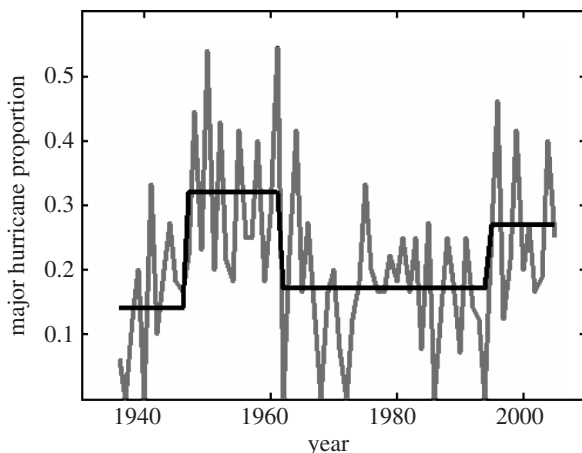


Figure 4. Unsmoothed annual variation in annual major hurricane proportions (relative to all named storms) from 1935 to 2005 (grey line) showing the sharp transition between regimes. The black lines show the means for each regime.

points identified by [Elsner *et al.* \(2004\)](#) using a more elegant statistical approach than used here. The oscillation in major to minor hurricane proportions extends over the entire record with little variation in amplitude or period (approx. 0.16 and 40 years, respectively).

The proportionality relationship between major and minor hurricanes is relatively insensitive to the choice of intensity grouping used; for example, taking the separation either half way through category 2 or halfway through category 3 hurricanes results in essentially the same relationship. Thus, an error of one full category in intensity observations has minimal effect on the overall statistics. We therefore suggest that, while the period prior to 1900 is substantially affected by data deficiencies, the upward trend in major hurricanes since 1900 may be real. Certainly the trend since 1945 is not significantly affected by data deficiencies.

The 9-year averaging period hides the fact that the changes between the climatic regimes for major hurricanes are extremely rapid, typically occurring across 1–2 years ([figure 4](#)). This sharp transition from one climatic state to another is a feature of nonlinear time series ([Lorenz 1963](#)) and the 1995 change in hurricane numbers has been previously noted by [Kimberlain & Elsner \(1998\)](#) and [Elsner *et al.* \(2001\)](#). Since the SSTs do not change so abruptly and tend to lead the cyclone changes (e.g. [figures 1 and 2](#)), there is an implication of a rapid phase transition in response to relatively steady SST increases.

The substantial oscillations in proportions of major and minor hurricanes during TC2 were in a period when the numbers of all tropical cyclones and hurricanes remained relatively stable (compare [figure 1](#) with [figure 3a](#) and note [table 1](#)). Thus, the period of enhanced hurricane activity and resultant damage during the 1950s and 1960s was due entirely to changes in proportions of major and minor hurricanes. The current record level of major hurricane activity ([figure 3a](#)) has also arisen from the coincidence of increasing cyclone numbers in TC3 ([figures 1 and 2](#)) and an increase in proportion of major hurricanes ([figure 3b](#)).

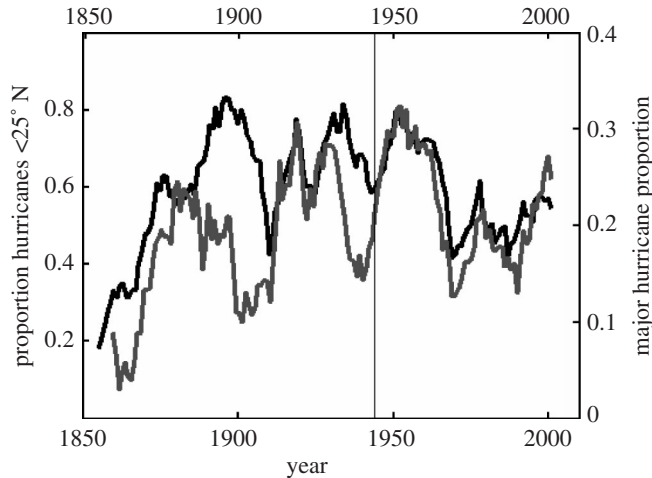


Figure 5. Variations in proportions relative to all named storms of major hurricanes (grey) and hurricanes forming equatorward of 25° N (black). All data have been smoothed by a 9-year running mean and the vertical line indicates the commencement of reliable intensity data.

As shown in figure 5, variations in the proportion of hurricanes forming equatorward of 25° N are almost entirely responsible for the variations in proportions of major hurricanes. These equatorial developments explain 53% of the variance in proportion of major hurricanes since 1905 and 83% since 1945. By comparison, minor hurricane variations arise mostly from developments poleward of 25° N, which explain 65% of the variation in minor hurricane proportions since 1945.

In summary, we suggest that there have been three distinct climatic regimes for NATL tropical cyclones since 1900 (TC1–TC3), which are distinguished by long periods of consistent tropical cyclone and hurricane activity separated by relatively sharp transitions. Net tropical cyclone and hurricane frequency increased by 50% from TC1 to TC2 and again from TC2 to TC3, and these changes occurred in conjunction with a sharp warming in eastern NATL SSTs of 0.44 and 0.38°C , respectively.

Superimposed on these climate regimes has been a marked out-of-phase oscillation in the proportion of major and minor hurricanes, which has a sharp changeover phase of one or two seasons and occurs in the absence of any associated changes in hurricane frequency. This changeover in proportional dominance by major and minor hurricanes is defined almost entirely by the proportion of hurricanes that form in equatorial ($<25^{\circ}$ N) versus mid-latitude ($>25^{\circ}$ N) regions. For example, the proportion of equatorial developments explains well over 80% of the variance in major hurricanes. There has been no real trend in the amplitude of the oscillation in major hurricane proportion, but when combined with the substantial trend in tropical cyclone numbers, a trend in the number of major hurricanes also emerges.

The transition phase since 1995 has seen the NATL experience an unprecedented increase in major hurricanes and associated impacts. This has arisen from an increase in both the numbers of tropical cyclones and the proportion of major hurricanes and is closely associated with a concomitant

unique increase in eastern NATL SSTs. This transition implies a move towards a climatic regime with substantially higher tropical cyclone, hurricane and major hurricane frequency than has hitherto been experienced in the historical record.

(b) *SST relationships*

(i) *Prior studies*

Several studies of global tropical cyclone activity have shown that SSTs explain a substantial part of the variance in tropical cyclone variability. Longer period changes in NATL hurricane characteristics were attributed by Gray (1990) and Landsea *et al.* (1999) to SST variations in the eastern Atlantic and Caribbean region. Emanuel (2005) found a close relationship between the sum of the cube of the maximum winds and SSTs, with 65% of the variance explained in the NATL from 1950 to 2004. Webster *et al.* (2005) noted a strong relationship between global changes in category 4 and 5 hurricanes and SST for the period from 1970 to 2004. A more comprehensive global study by Hoyos *et al.* (2006) used Bayesian statistics to confirm that there is a strong global relationship between SSTs and category 4–5 hurricanes for the period from 1970 to 2005. Hoyos *et al.* also found that other atmospheric variables, such as vertical wind shear, did not contribute substantially to the long-term trend for an increase in major hurricane numbers but only to shorter-term interannual variability. Goldenberg *et al.* (2001) concluded that there is a strong relationship between vertical wind shear over the major Atlantic cyclone development region and *in situ* SSTs. They also examined tropical cyclone and hurricane variability since 1944 and found a strong relationship with equatorial Atlantic SSTs. Vitart & Anderson (2001) conducted a general circulation modelling assessment that found a strong impact of varying eastern NATL SSTs on tropical cyclone characteristics, apparently related to vertical wind shear changes which also resulted from the SST variations.

In contrast, Shapiro & Goldenberg (1998) found that direct SST–cyclone relationships explain only a small part of the annual cyclone variance (10%) compared with approximately 50% for vertical shear, and suggested that the SSTs were a secondary influence on cyclone development after the larger-scale environment had been established by other mechanisms. However, their study was based on the period from 1968 to 1992, which only matches the period of TC2 and one-half cycle on major hurricane proportion and included no regime changes. Their signal was also dominated by the ENSO cycle, which impacts vertical wind shear, but for which there is essentially no NATL SST relationship. There are also questions about the method used for calculating the vertical shear, which was done on monthly mean winds instead of the more correct daily winds and their variance.

Klotzbach (2006) disputed the Emanuel (2005) and Webster *et al.* (2005) studies. Using a limited data period from 1986 to 2005, he suggested that there were only small global changes, and that these could be explained by variations in observing practice. Klotzbach did support a large increase in the NATL activity; however, the short period used in his study brings question and doubt to the generality of his overall conclusions.

Bell & Chelliah (2006) have found that, when a 5-year filter is passed over the data, two leading modes, which they refer to as tropical multidecadal modes (designated TMM and TMM2), define much of the variability in atmospheric factors thought to influence tropical cyclone genesis and development, including West African monsoon variability (Grey 1990; Goldenberg & Shapiro 1996), vertical wind shear (Grey 1968; Goldenberg *et al.* 2001) and the Atlantic Multidecadal Oscillation (AMO; Folland *et al.* 1986; Delworth & Mann 2000; Goldenberg *et al.* 2001). These so-called TMM and TMM2 modes are highly correlated with the tropical eastern NATL SSTs and combining the two explains 41 and 73% of the 5-year filtered SST observations for 1950–2002 and 1970–2002, respectively.

We concur with the conclusion of Bell & Chelliah (2006) and Kossin & Vimont (*in press*) that the observed relationship between SST and tropical cyclones arises from their mutual association with coherent large-scale patterns. However, we consider that the conclusion by Bell and Chelliah that the TMM2 mode is oscillatory on multidecadal time scales is difficult to defend using a dataset that is only half the length of the proposed oscillation. More likely, as discussed in §4*a*, the TMM2 is a trend associated with greenhouse warming. The more recent study by Kossin & Vimont (*in press*) has shown a quite strong relationship of tropical cyclones with the Atlantic Multidecadal Mode (AMM), which incorporates a combination of oceanic and atmospheric variations and includes the latitudinal shifts in tropical cyclone occurrence identified here. Kossin and Vimont conclude that the current warm phase of the AMM could be responding to warming associated with anthropogenic causes.

(ii) *Relationship between SSTs and tropical cyclones*

Figures 1 and 2 clearly show that the transitions between the three main climatic regimes are closely aligned with changes in eastern NATL seasonal SST anomalies. The SST anomalies explain over 60% of the tropical cyclone variance since 1905 and tend to lead the changes in cyclone frequency. Similar results have been found by Mann & Emanuel (2006). This correlation arises entirely from the regime changes defined earlier. As shown in figure 2, the regimes are clustered within East Atlantic SST ranges of 25.8–26.2°C (TC1, 1900–1930), 26.2–26.7°C (TC2, 1940–1994) and 26.7–27°C (TC3, 1995–2005). Within each regime, the variations in SST are weakly correlated negatively with tropical cyclone frequency. Hurricanes follow a very similar clustering, though with a slightly lower explained variance (56%) by eastern NATL SST anomalies.

The oscillation in proportion of major and minor hurricanes (figure 3*b*) bears no relationship with eastern NATL SST anomalies ($R=0.08$ for the period 1945–2005); however, it is highly correlated with SST anomalies in the Gulf of Mexico ($R=0.8$, or 64% of the variance since 1945). There is no evidence of the clustering found for tropical cyclones and eastern NATL SSTs.

The out-of-phase relationship between major and minor hurricanes and SSTs also extends somewhat into interannual time scales. Removing the low-frequency variability to isolate the interannual variability leaves a weak, but still significant, relationship between the proportions of major and minor hurricanes (10% variance explained) and between the proportions of major hurricanes and Gulf of Mexico SSTs (9% variance explained).

An intriguing feature is the way that eastern Atlantic SST tends to lead tropical cyclone frequency, especially for the regime changes (figure 1). Taking lagged correlations indicate that even at 5-year lag, the eastern NATL SSTs explain over 50% of the variance in longer-period tropical cyclone frequency. A clue for this may lie in the manner in which sustained ENSO activities may extend over a sufficiently long period to map onto the longer period changes. For example, a sustained and record period of warm central Pacific anomalies that occurred between 1990 and 1995 (Trenberth & Hoar 1996) may have suppressed the tropical cyclone response to the East Atlantic SST warming in this period (Goldenberg *et al.* 2001).

To summarize, there is a strong relationship between the long-period frequency of tropical cyclone and hurricanes, and SSTs in the main genesis region over the eastern NATL. This relationship appears to arise entirely from the transition between climate regimes. The oscillation between major and minor hurricanes is not related to SSTs in the genesis region, but has a strong association with SST variations in the Gulf of Mexico. Our findings are in agreement with other NATL and global studies (e.g. Emanuel 2005; Webster *et al.* 2005; Hoyos *et al.* 2006; Kossin & Vimont *in press*). We concur with previous studies (e.g. Bell & Chelliah 2006; Kossin & Vimont *in press*) that the SST/cyclone number relationship is not entirely direct and that a substantial component arises from the mutual association with atmospheric features that influence tropical cyclone characteristics.

4. Natural variability or climate trend?

Considerable public debate has developed following the record 2005 hurricane season on whether we are experiencing a peak in a long-term cycle of natural variability, or whether the above-average tropical cyclone and major hurricanes activity is part of a trend associated with greenhouse warming. This is an important question and requires serious consideration. The main issue lies with how to differentiate a forced trend from natural variability using the limited available historical information and given the unknown level of uncertainty in this information. The only relationship for which there are reasonable data over a long period is that between tropical cyclones and SST, so we use this as the basis for our discussion here.

(a) *Natural variability*

Bell & Chelliah (2006) provide a detailed summary of natural variability arguments in previous studies for long-period tropical cyclone changes, to which the reader is referred for full information. There are several views on the role of natural variability, most of which overlap. Landsea *et al.* (1999) concluded that there were no trends in any characteristics of NATL tropical cyclones, and that the only signal arises from multidecadal oscillations. However, their analysis covered only the period 1944–1996, or TC2, which we have shown to be dominated by no net trend and a strong oscillation in major hurricane proportion. Goldenberg *et al.* (2001) and Kossin & Vimont (*in press*) associate the observed changes, including the current enhanced activity, with the Atlantic Multidecadal Mode, which includes a strong correlation between SSTs and cyclone activity in the NATL. All of our climatic regimes are considered to be

included in this mode, though we note that Goldenberg *et al.* fail to differentiate between TC1–TC3 and the independent oscillations in major and minor hurricanes. Elsner & Kocher (2000) used a common factor model to combine the tropical cyclone activity in each ocean basin. They showed that the NATL was out of phase with all other regions, having low activity when others were high and vice versa. They also found a significant relationship with the North Atlantic Oscillation (NAO) which appears to have a decadal period. However, their data extended from 1966 to 1998, and thus covered only part of TC2 and one major/minor hurricane cycle.

Thus, the limited periods used by all of the above studies mean that they could not possibly have captured the trend from TC1 to TC3. These studies also typically covered only one major/minor hurricane cycle.

The major thesis proposed by Bell & Chelliah (2006) is that much of the tropical cyclone variability arises from the TMM and TMM2 leading tropical multidecadal modes, which have been derived from the period 1950–2002, and thus include TC2, a part of TC3 and just over two major/minor hurricane cycles. They found that the enhanced major hurricane activity from 1950 to 1960 was associated with TMM, while the increased tropical cyclone and major hurricane activity after 1995 was associated with TMM2. Their TMM2 was an atmospheric mode, which is strongly correlated with SSTs in the eastern NATL, implying that the observed increases in cyclone frequency since 1995 are primarily caused by environmental changes associated with increases in these SSTs. We may draw the inference that the TMM is associated with the observed variations in major and minor hurricane proportions. However, TMM does not predict the increase in major hurricane proportions around 1995.

We are in agreement with the findings of Bell & Chelliah (2006), with one major exception. They imply that both TMM and TMM2 are natural modes of variability of the tropics. Yet their data only extend over 55 years which is not even a complete oscillation and is less than the Nyquist frequency for the supposed multidecadal oscillations. Further, the TMM2 mode has only recently appeared and Bell and Chelliah indicate that it seems to be invalid before 1970. It is not possible for their analysis to differentiate between a sustained trend that rose above the noise level around 1970 and an oscillation that will reach some maximum amplitude and then return sometime in the future. A more comprehensive study by Kossin & Vimont (*in press*) arrived at a strong relationship between changes in the AMM and tropical cyclones from TC1 to TC3 and noted that this could not be distinguished from global warming.

Several studies have examined seasonal relationships with tropical cyclone occurrence (e.g. Hess & Elsner 1994; Lehmiller *et al.* 1997; Elsner & Jagger 2006). Statistical forecasting techniques have also been developed for the NATL (Gray 1984; Klotzbach & Gray 2003; Saunders & Lea 2005). These studies identify five main indicators associated with increased genesis frequency: warm SST anomalies and/or El Niño changes, low surface atmospheric pressures, weak vertical wind shear, variations in the low-level tropical flow and the phase of the stratospheric QBO. Of these, the El Niño and QBO are interannual processes that are not of interest here. Hess & Elsner (1994) have shown that these predictors work best for tropical cyclones developing from easterly waves. The apparent success of the statistical seasonal forecasts has led to unpublished claims that this implies a dominance of natural variability in NATL tropical

cyclones (<http://typhoon.atmos.colostate.edu/forecasts/2005/nov2005/>). However, these studies are based largely on the period from 1944 and prior to 1995, and thus are only from TC2. All techniques listed above have consistently underpredicted all tropical cyclone parameters in the active period since 1995 and the seasonal forecasts of total tropical cyclone activity have marginal or no skill compared with a simple time-series average and trend. We conclude that such seasonal forecast techniques contain little useful information for detecting the transitions between the climatic regimes identified here.

(b) *Climate trend*

Given the clear and strong relationship between East Atlantic SSTs and tropical cyclone frequency, we examine the potential for a climate trend in tropical cyclones by first considering SST changes. Variations in global surface temperatures over the past century and a half have arisen from a combination of natural variability and anthropogenic addition of greenhouse gases to the atmosphere. Meehl *et al.* (2004) have undertaken an extensive investigation of these global temperature changes using an ensemble of 22 different climate models. They found that known natural forcing mechanisms (including both internal oscillations and external forcing from solar and volcanic effects) can explain much of the variability up to around 1970. However, natural forcing alone would have led to a slight cooling over the period since 1970; the observed upward trend in global temperatures since 1970 can only be explained by greenhouse warming. This is quite similar to the findings of Knutson *et al.* (2006) using an ensemble approach with the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) model.

Knutson *et al.* (2006) and Santer *et al.* (2006) have narrowed this analysis to the tropical cyclone development regions in the NATL and western North Pacific. Santer *et al.* found that anthropogenic changes in greenhouse gases were the major drivers of observed SST changes in both regions, and that there was an 84% probability that 67% of the observed trend since 1906 is due to greenhouse warming. In other words, 42% of the observed 0.67°C increase in hurricane season SSTs in the NATL since 1906 can be attributed with a high degree of confidence to anthropogenic gases introduced into the atmosphere. Warming by greenhouse gases dominates the anthropogenic impact, but this can be slowed by radiative cooling associated with anthropogenically introduced sulphates as noted by Mann & Emanuel (2006). The overall proportional contribution between natural variability and greenhouse warming is very similar to that found by Mann & Emanuel (2006) and Trenberth & Shea (2006) using quite different approaches.

An important result of the Santer *et al.* (2006) study is that the greenhouse gases have had an impact since the beginning of the twentieth century. While their impact has accelerated since 1950, greenhouse gases also contributed substantially to the sharp warming that occurred around 1930, with the other main contribution being from solar forcing.

The Santer *et al.* (2006) results are in conflict with other studies (e.g. Goldenberg *et al.* 2001) that attribute the Atlantic signal in tropical cyclone activity and SST variability primarily to local responses associated with the AMO, which is poorly replicated by the climate models used by Santer *et al.* We have already noted that the Goldenberg *et al.* study was confined to a single

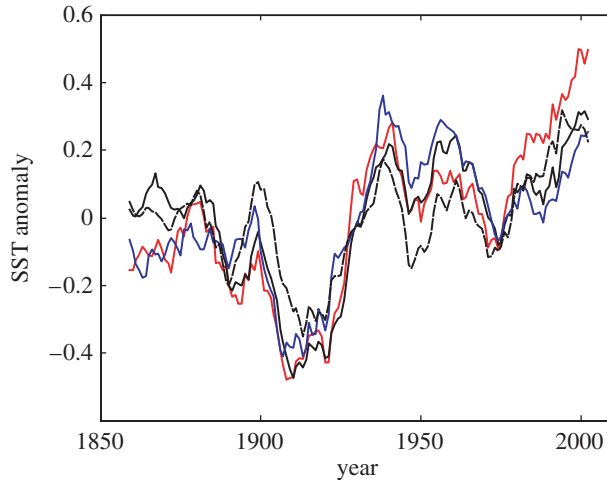


Figure 6. Variation of hurricane season SST anomalies (from the 1855–2005 mean) for the eastern Atlantic (red), western Atlantic (black), Gulf of Mexico (blue) and eastern Pacific (black dashed). All series have been smoothed with a 9-year running mean.

climate regime and did not include the major shifts shown in figures 1 and 2. Several recent studies also argue against such a dominant role by the AMO. The variation in tropical SSTs under the AMO is closely related to changes in the Atlantic Thermohaline Circulation (THC; e.g. Knight *et al.* 2005). Mann & Emanuel (2006) have analysed NATL SSTs from the late nineteenth century, and concluded that there is ‘no apparent role of the AMO’ and that the observed warming is global in nature and associated with a combination of greenhouse warming and a partially compensating cooling from sulphate aerosols.

The AMO is an Atlantic phenomenon, with the major signal in the eastern Atlantic region. There is some disagreement on its global characteristics: Knight *et al.* (2005) found a negligible global signal, while Enfield *et al.* (2001) and Sutton & Hodson (2005) find a global signal, particularly in the North Pacific. Trenberth & Shea (2006) showed that removal of the global warming trend left very little contribution by the AMO to recent warming of the North Atlantic, and this is supported by recent modelling results from Santer *et al.* (2006). Since eastern North Pacific SST variations have been shown to be unassociated with the AMO (Sutton & Hodson 2005), we can use this region to check the potential AMO contribution to the SST trend in figure 1. Figure 6 contains the anomaly series for the eastern Atlantic, western Atlantic, Gulf of Mexico and eastern North Pacific regions. All regions exhibit the same major features and the eastern North Pacific (black dashed line) explains 76% of the variance in the eastern NATL (red line). Importantly, both the overall trend and the sharp transitions in eastern NATL SST associated with regimes TC1–TC3 are also present in the eastern North Pacific. However, there are also notable differences: the 9-year mean eastern Atlantic SSTs have warmed by 0.55°C compared with the 1850–1900 average and by 0.85°C since the coldest period around 1910–1920, whereas the eastern Pacific has warmed up by 0.3 and 0.6°C over corresponding periods. We next isolate a potential regional signal for the eastern Atlantic by taking differences with each of the other series (figure 7). This reveals a distinct

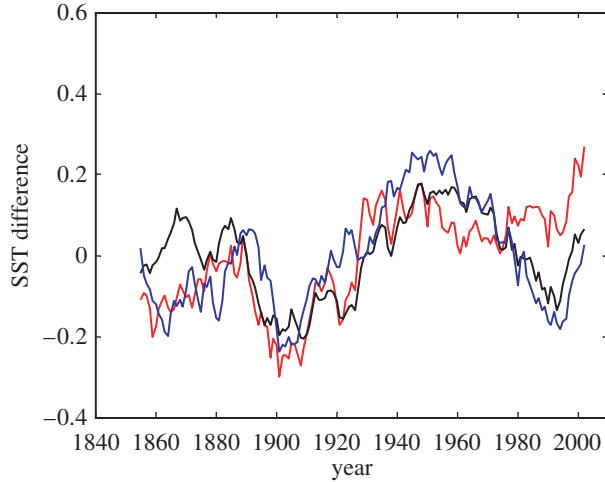


Figure 7. Differences of hurricane season SST anomalies after subtracting off the eastern Pacific anomaly for: eastern Atlantic (red); western Atlantic (black); and Gulf of Mexico (blue). All series have been smoothed by a 9-year running mean and the scale is the same as in figure 6. Note that the sharp upturn after 1995 arose from an anomalous cooling of the eastern North Pacific.

multidecadal oscillation in the residual eastern NATL, western NATL and Gulf of Mexico SSTs with a period of 40–50 years and amplitude of 0.2°C . Compared with the full SST anomaly shown in figure 6, the amplitude is approximately 50% and the distinct upward trend has disappeared. Care needs to be taken in interpreting this simple analysis, as there are certain to be other factors involved and the analysis cannot distinguish between natural and forced variability. Nevertheless, these results are in good agreement with the findings of Trenberth & Shea (2006) and Santer *et al.* (2006) and imply that the slow variations in equatorial Atlantic SSTs are dominated by global effects.

We can now develop the following causal chain.

- SSTs in the main hurricane development regions of the NATL ocean have increased over the past century, particularly in the past 30 years, due primarily to greenhouse warming associated with anthropogenically introduced gases.
- There is a strong and statistically significant relationship between SSTs and tropical cyclone activity at longer periods, with eastern NATL SSTs explaining over 60% of the variance in overall cyclone frequency and Gulf of Mexico SSTs explaining a similar level of variance in the proportion of major hurricanes.
- The SST/cyclone relationships are primarily due to transitions between distinct climate regimes and are independent of known data uncertainties.

Collectively, this causal chain leads to the strong conclusion that the current level of tropical cyclone activity in the North Atlantic is largely a response to climate change from anthropogenic causes.

We note that there has been no marked trend in the proportion of major hurricanes over the past century. Rather, figure 3*b* shows that the out-of-phase

oscillation in major and minor hurricanes has held a remarkably stable phase and amplitude since 1900. This implies an internal oscillation of the climate system, one that is associated with meridional changes in hurricane genesis locations between mid-latitude and equatorial regions (figure 5). Although the relationship between major hurricane proportion and SSTs in the Gulf of Mexico is indicative of a response to potential internal North Atlantic oscillations, it is not definitive. Given that this is a nonlinear process, the rapid changeovers in figure 4 could also be the result of random changes. Also, it is not possible to rule out other global influences particularly with regard to atmospheric processes that are not examined here. A more thorough investigation of these interesting transitions is required.

As mentioned previously, Landsea *et al.* (2006) have argued that it is not possible to find a hurricane global warming signal because theory and modelling studies (e.g. Henderson-Sellers *et al.* 1998; Knutson & Tuleya 2004) predict only a small increase of approximately 5–10% in maximum winds for a 1°C increase in SST, and that this trend cannot be resolved above errors in the observing system. Our analysis completely agrees with these studies in that the mean peak intensity of all storms has not changed, as shown, for example, by the proportion of major hurricanes to all tropical cyclones during the last 50 years (figure 3b). However, the theory and modelling studies assumed no change in distribution with greenhouse warming. The oscillatory changes in severe storms that have occurred have been a result of a very similar oscillation in equatorial developments (figure 5) and the observed increasing trend in major hurricanes has arisen entirely from an increase in all tropical cyclones. Furthermore, equatorial developments increased sharply in 1995 in association with the marked increase in Atlantic SSTs since 1970, which Santer *et al.* (2006) have demonstrated to be largely due to greenhouse warming. Kossin & Vimont (in press) have related this to a warming phase of the AMM, which included the equatorward shift in formation and which they conclude could be influenced by greenhouse warming.

Since over 80% of all major hurricanes occur from equatorial developments, we arrive at the conclusion that increases in intense hurricanes in the NATL are associated with both a direct effect (as identified in the modelling and theoretical studies) and a change in the population distribution of storms. The increase in equatorial developments places a substantially larger number of cyclones in a region that is conducive to sustained intensification, and this has been the dominant cause of both the trend in major hurricanes and the recent heightened activity. This conclusion is consistent with that of Oouchi *et al.* (2006) who found a definite increase in both numbers and intensity of NATL tropical cyclones in a high-resolution global climate modelling study of the impact of greenhouse warming. Future modelling and theoretical studies should take into account such changes in population distribution.

5. Summary

We have identified a marked trend in NATL tropical cyclones and hurricanes since 1900 that has arisen from sharp transitions between three distinct climatic regimes as shown in figure 1. Regime TC1 consisted of a period of suppressed activity (six tropical cyclones and four hurricanes per year) up to 1930. This was followed by a

sharp increase to regime TC2, which was relatively constant at around 10 tropical cyclones and 5 hurricanes per year, and lasted up to 1994. From 1995 to the present, we have seen a further sharp increase in tropical cyclone and hurricane frequency. We define this period as TC3, though this would be more properly assigned to the transition to another, as yet undefined, regime. TC3 has experienced an average of 15 tropical cyclones and over 8 hurricanes per year. Superimposed on these regimes is a marked out-of-phase oscillation between proportions of major and minor hurricanes (figure 3b) with amplitude 0.2 that occurs with no related changes in total hurricane numbers. As shown in figure 3b, a period of low major hurricane proportion from 1930 to 1944 was followed by a high period from 1945 to 1961, then a low period from 1962 to 1994, and a transition to a new high period starting in 1995. The oscillations in proportion of major and minor hurricanes are closely related to SSTs in the Gulf of Mexico and the formation of hurricanes equatorward of 25° N, whereas the changes between TC1, TC2 and TC3 are closely related to eastern Atlantic SSTs.

We have given careful consideration to the quality of the data and particularly to changing observing system and analysis practices. We have noted with some concern the contradictory conclusions reached in a number of papers that, on the one hand, describe the data as being of high quality sufficient to determine natural variability in hurricane characteristics (Landsea *et al.* 1999; Goldenberg *et al.* 2001; Owens & Landsea 2003) but, on the other hand, of insufficient quality to determine trends that are demonstrably of similar magnitude (Landsea *et al.* 2006). We concur with Emanuel (2005), Webster *et al.* (2005) and Hoyos *et al.* (2006) that the trends since 1900 shown in figure 1 are substantial and the related linear trend is significant at the 95% level (R. Smith 2007, personal communication). We are of the strong and considered opinion that data errors cannot explain the sharp high-amplitude transitions between the climatic regimes in the NATL, each with an increase of approximately 50% in cyclone and hurricane numbers, and the close relationship of these regime changes with SSTs.

There has been a marked warming trend approaching 1°C in eastern Atlantic SSTs since 1905, and this has occurred primarily in sharp transitions, with a 0.4°C increase around 1930 and a similar increase since 1970. The intervening periods were marked by relatively stable SSTs. We have cited substantial work from other studies that conclude that anthropogenically produced greenhouse gases have contributed to this trend throughout the entire period, and that their effect has accelerated since 1970 (e.g. Santer *et al.* 2006). In particular, global change due to greenhouse warming is responsible for around two-thirds of the current record high Atlantic SSTs. While there is strong evidence for a contribution by internal variations in the climate system, such as the AMO, there is no persuasive evidence for this to be the dominant signal. In particular, the second leading tropical multidecadal mode (TMM2) proposed by Bell & Chelliah (2006) can be more properly ascribed to an accelerating trend associated with greenhouse warming than to an actual mode of oscillation.

The variability in major hurricanes is quite different from that for tropical cyclones and hurricanes. The proportion of major hurricanes relative to all tropical cyclones has undergone a steady oscillation in both amplitude and period for the last 100 years and one with no distinct trend. This has been matched by an out-of-phase oscillation in minor hurricanes and is independent of the changes in either hurricane or tropical cyclone numbers. This oscillation in major hurricanes

also has no apparent relation to East Atlantic SSTs, but it is very closely related to the proportion of hurricanes that form equatorward of 25° N (correlation of 0.92 since 1945) and to SSTs in the Gulf of Mexico (correlation of 0.80 since 1945).

However, while the *proportion* of major hurricanes appears to be dominated by cyclic behaviour, the *number* of major hurricanes has a distinct and statistically significant trend that arises from the increasing numbers of tropical cyclones. The elevated level of activity since 1995 has arisen from the unfortunate correspondence of the trend in the number of tropical cyclones and a peak in the oscillation in proportion of major hurricanes to all tropical cyclones. It remains to be determined whether these relationships will be maintained or will change with increasing global warming.

In conclusion, the observed eastern Atlantic SST changes are driven by a combination of natural variability and anthropogenic effects, with the greenhouse warming (partially offset by cooling from sulphate gases) being the dominant process. Given the strong relationship between East Atlantic SST anomalies and tropical cyclone variability presented here and corroborated by several independent studies (e.g. Kossin & Vimont *in press*), we are led to the confident conclusion that the recent upsurge in tropical cyclone frequency is due in part to greenhouse warming, and this is most likely the dominant effect. Earlier variations, such as the sharp increase in the 1930s, were also probably impacted by greenhouse warming. This trend in overall tropical cyclone frequency is mirrored by hurricane frequency, with the proportion of hurricanes remaining constant at 0.55 ± 0.03 since the beginning of the twentieth century.

We have also found that the proportion of major and minor hurricanes to all tropical cyclones exhibits a distinct, trendless oscillation. But the combination of this oscillation with the increasing number of tropical cyclones also results in a strong trend in major hurricane numbers that is directly associated with greenhouse warming. These conclusions are robust to known errors in the available data.

This study has raised several questions, which are the subject of ongoing investigations.

- (i) *What maintains the remarkably steady proportion of hurricanes to all tropical cyclones?* Maximum potential intensity theories (Emanuel 1995; Holland 1997) imply that an increase of SSTs should lead to a net shift in population towards higher intensities. It may be that this theoretical shift is simply too small to be discerned at this stage above the general noise level. But it may also be that there are more fundamental processes that lead to an increase in weaker systems, which may balance the general trend towards higher intensity.
- (ii) *What drives the steady oscillation in proportion of major and minor hurricanes relative to all cyclones?* Previous work on natural variability does not provide an adequate explanation. For example, the first leading mode of Bell & Chelliah (2006) can explain the peak in major hurricane proportion in the 1950s, but not the most recent increase. We have shown a distinct relationship with SSTs in the Gulf of Mexico, but consider this to be more of an indicator of other processes than an answer in itself. Perhaps the major clue lies in the close relationship between oscillations in proportions of major and minor hurricanes and the proportion of hurricanes that develop equatorward and poleward of 25° N. Understanding the latter question may

lead to an understanding of the former. An intriguing aspect of this oscillation is the remarkably sharp manner in which the reversal occurs (figure 4), which raises several questions on the type of nonlinear processes involved and their intrinsic predictability.

- (iii) *What are the projections of tropical cyclone and hurricane frequency and intensity, given an accelerating increase in SSTs associated with greenhouse warming?* We have noted that the current climate regime seems more indicative of a transition phase than the settling into a new steady regime. Whether this will stabilize soon or continue to increase is a matter of great scientific interest and a matter of considerable concern for coastal communities in the impacted regions. If we project past increases forward, then an increased SST over the next 50 years of, say, 1–2°C could lead to an average of 20–25 cyclones and 10–15 hurricanes per year. This conclusion raises another question; are there inhibiting factors that will impede this potential increase?

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