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CLIMATOLOGY

The Current Debate on the Linkage Between Global Warming and Hurricanes

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Abstract

Following Hurricane Katrina and the parade of storms that affected the conterminous United States in 2004–2005, the apparent recent increase in intense hurricane activity in the Atlantic basin, and the reported increases in recent decades in some hurricane intensity and duration measures in several basins have received considerable attention. An important ongoing avenue of investigation in the climate and meteorology research communities is to determine the relative roles of anthropogenic forcing (i.e., global warming) and natural variability in producing the observed recent increases in hurricane frequency in the Atlantic, as well as the reported increases of tropical cyclone activity measures in several other ocean basins. A survey of the existing literature shows that many types of data have been used to describe hurricane intensity, and not all records are of sufficient length to reliably identify historical trends. Additionally, there are concerns among researchers about possible effects of data inhomogeneities on the reported trends. Much of the current debate has focused on the relative roles of sea-surface temperatures or large-scale potential intensity versus the role of other environmental factors such as vertical wind shear in causing observed changes in hurricane statistics. Significantly more research – from observations, theory, and modeling – is needed to resolve the current debate around global warming and hurricanes.

1 Introduction

Hurricanes are one of nature's most awe-inspiring natural systems. Hurricanes are just one manifestation of the generic tropical cyclone, a nonfrontal synoptic scale low-pressure system over tropical or subtropical waters with organized convection (i.e., thunderstorm activity) and definite cyclonic surface wind circulation (Holland 1993). The tropical cyclone is called a "tropical storm" when winds surpass 17 m/sec for a sustained period of time. Beyond wind speeds of 33 m/sec, they are called:

- "hurricane" (the North Atlantic Ocean, the Northeast Pacific Ocean east of the dateline, or the South Pacific Ocean east of 160°E),
- "typhoon" (the Northwest Pacific Ocean west of the dateline),

- "severe tropical cyclone" (the Southwest Pacific Ocean west of 160°E or Southeast Indian Ocean east of 90°E),
- "severe cyclonic storm" (the North Indian Ocean), and
- "tropical cyclone" (the Southwest Indian Ocean).

These storms typically form in environments with (1) warm ocean waters (> 26.5 °C) throughout a sufficient depth, (2) a potentially unstable atmosphere to moist convection, (3) a moist mid-troposphere, (4) sufficient distance from the equator, (5) a preexisting near-surface disturbance with adequate spin and convergence, such as tropical easterly waves, and (6) low values of vertical wind shear or magnitude of wind change with height. Zehr (1992) hypothesizes that genesis of the tropical cyclones occurs in two stages. Stage 1 occurs when a large cluster of thunderstorms produces a mesoscale circulation or vortex. Stage 2 occurs when a secondary outbreak of convection at the vortex initiates the intensification process that leads to central pressure reduction and wind speed intensification. Yet, the exact nature and tendency for tropical cyclogenesis is still an area of intensive research. Ultimately, the warm ocean is the primary fuel source, however (Figure 1).

Hurricanes are as dangerous as they are awe-inspiring. The recent suffering and economic losses caused by Hurricane Katrina and the parade of Atlantic basin storms that affected the United States in 2004–2005 have energized a debate on what may be causing such anomalous hurricane activity and to what extent the activity is even anomalous in the context of longer (century-scale) records. The estimated economic damage from the 2004 Atlantic hurricane season alone was nearly $40 to 42 billion according to a recently published article by Halverson (2006) and U.S. National Hurricane Center and some estimates place the damage from the 2005 Atlantic season well over $100 billion (Beven 2006). The question of whether global warming is having an important impact on hurricanes has become a topic of debate in the wider community of decision-makers, stakeholders, scientists, and citizens. Within the climate and hurricane research communities, an important scientific debate of this issue is ongoing – specifically to determine the relative roles of anthropogenic forcing (e.g., global warming) and natural variability in causing the observed changes. The apparent increase recently in intense hurricane activity in the Atlantic basin and the reported increases in recent decades in some hurricane intensity and duration measures in several basins are receiving considerable attention.

Pielke et al. (2005) note that research on possible links between greenhouse gas-induced global warming and hurricane *frequency* is ambiguous, with most studies suggesting that future changes in frequency will be regionally dependent, and with different studies lacking consistency in projecting even the sign of the change in the total global number of storms (Henderson-Sellers et al. 1998; Royer et al. 1998; Sugi et al. 2002). Past and current studies give such contradictory results as to suggest that the state of understanding of tropical cyclogenesis provides too poor a foundation to

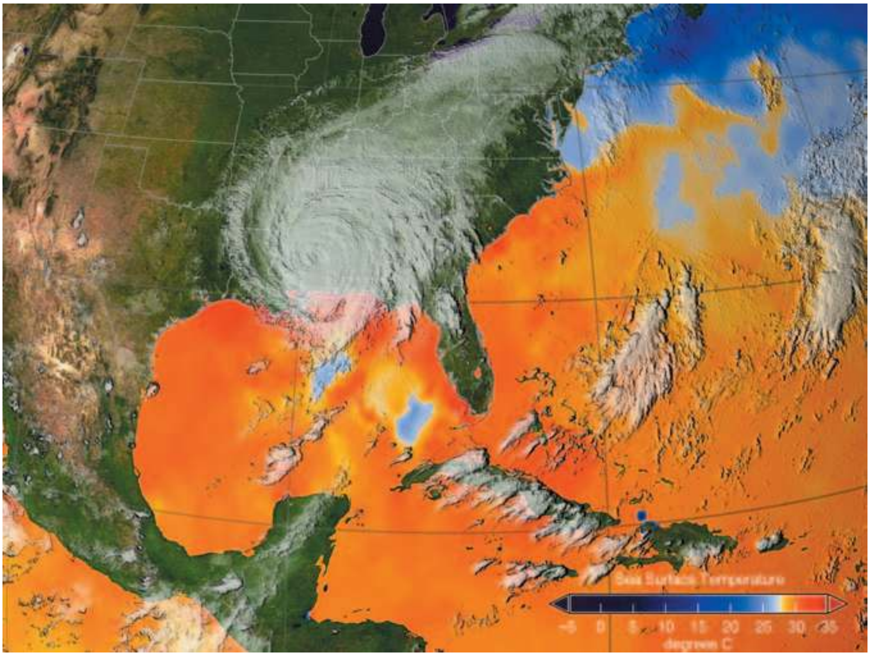

Fig. 1. Satellite-derived sea-surface temperatures showing the warm ocean waters and a cold water wake (light blue) mixed up by Hurricane Katrina (courtesy of the NASA SVS).

base any projections about the future (Pielke et al. 2005). In addition to these difficulties with frequency trends, intensity trends present additional challenges.

In their recent assessment, Pielke et al. (2005, p. 1574) concluded the following:

1. “. . . no connection has been established between greenhouse gas emissions and the observed behavior of hurricanes (Houghton et al. 2001; Walsh 2004). The study of Emanuel (2005a) is suggestive of such a connection, but is by no means definitive. In the future, such a connection may be established or made in the context of other metrics of tropical cyclone intensity and duration that remain to be closely examined . . .”
2. “. . . peer-reviewed literature reflects that a scientific consensus exists that any future changes in hurricane intensities will likely be small in the context of observed variability (Henderson-Sellers et al. 1998; Knutson and Tuleya 2004), while the scientific problem of tropical cyclogenesis is so far from being solved that little can be said about possible changes in frequency . . .”
3. “. . . under the assumptions of the Inter-governmental Panel on Climate Change (IPCC), expected future damages to society of its projected changes in the behavior of hurricanes are dwarfed by the influence of

> its own projections of growing wealth and population (Pielke et al. 2000) . . .”

Although current research appearing in the literature is beginning to challenge some of the aforementioned statements, the body of literature and dissenting opinions suggest that more historical, observational, and modeling studies will be required to address this problem. In this review article, the most provocative and relevant arguments on both sides of the issue are presented. Although the emphasis will be on Atlantic hurricane activity, we also review some findings related to tropical cyclone activity in other basins. The Atlantic basin typically accounts for about 12 percent of the global number of tropical cyclones (Neumann 1993) and one should not generalize trend results obtained solely from the Atlantic to the other tropical cyclone basins. For example, in the Western Pacific (north and south), much of tropical cyclogenesis occurs within the monsoon trough, whereas in the Atlantic many tropical cyclones evolve from easterly waves. To read more discussion on tropical cyclogenesis in different basins, see Ritchie and Holland (1999) and Molinari and Vollaro (2000).

2 Theoretical and modeling arguments for a link between global warming and hurricanes

Early studies of the impact of global warming on hurricanes focused on the frequency of occurrence of weak tropical storm-like features in global climate models for present-day and high carbon dioxide levels (e.g., Bengtsson et al. 1996; Broccoli and Manabe 1990; Haarsma et al. 1993). These studies showed inconsistent results among different models, even as to the sign of the simulated change. Emanuel (1987) introduced the concept of potential intensity of hurricanes and pointed out its relevance in the context of climate change. Potential intensity refers to an upper-limit intensity that a tropical cyclone can attain for a given set of thermodynamic conditions (sea-surface temperature (SST), large-scale atmospheric temperature, and moisture) and does not consider effects of dynamical (e.g., related to motion or wind) influences such as wind shear on the intensity. Emanuel’s (1987) paper in *Nature* was the first analysis linking greenhouse gas-induced warming to a possible future increase in the potential intensity of tropical cyclones. His theory predicts roughly a 5 percent increase in potential intensity per degree Celsius SST warming (e.g., Emanuel 2005a). His conclusions were later supported by a similar potential intensity theory proposed by Holland (1997) as applied to several climate model of greenhouse warming scenarios (Tonkin et al. 1997). Holland’s theory also predicted increased tropical cyclone potential intensities in greenhouse-gas-warmed climates. Caveats to these theory-based assessments were summarized in Henderson-Sellers et al. (1998), and included concerns about sea spray effects and other neglected processes.

In reality, actual intensity is of greater interest than potential intensity for societal concerns. Actual intensity includes the effects of dynamical influences, land influences, and other negative impacts on storm intensity. Emanuel (2000), in a statistical analysis of observed hurricane intensities and potential intensities, found that once a storm reaches minimal hurricane intensity, it has roughly an equal chance of eventually achieving any intensity in the range between that minimum hurricane intensity and its upper-limit (potential) intensity. Another observational study by Goldenberg et al. (2001) noted a strong statistical relation between major hurricane counts in the Atlantic basin and a vertical wind shear index in the tropical Atlantic "Main Development Region" for tropical cyclones. A debate continues in the hurricane research community over the relative importance of thermodynamic factors (e.g., the potential intensity) and dynamical factors (e.g., wind shear), particularly in affecting the low-frequency behavior of hurricanes in the Atlantic.

In the late 1990s, Knutson, Tuleya, and Kurihara at the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration (GFDL/NOAA) began simulating samples of hurricanes both from the present-day climate and from a greenhouse-gas-warmed climate using the high-resolution GFDL hurricane prediction system. Their approach was to nest samples of coarsely resolved tropical storms from GFDL's global climate model into the same high-resolution regional hurricane prediction model used for operational hurricane prediction. The manuscript first describing this work was published in *Science* (Knutson et al. 1998), followed by a more detailed report in *Climate Dynamics* (Knutson and Tuleya 1999). All of these studies, including the potential intensity assessments mentioned above, include the moderating effect of atmospheric stabilization aloft under high carbon dioxide conditions, rather than simply increasing the SST alone. That is, greenhouse warming experiments for all global climate models examined to date show a warming of the upper troposphere (near 300 hPa) that exceeds the surface warming. This profile of atmospheric temperature change reduces, but does not eliminate, the increase of storm intensity in models and theory that results from the SST increase alone (e.g., Shen et al. 2000).

In a follow-up study, Knutson et al. (2001) explore the climate warming/hurricane intensity issue using a hurricane model coupled to a full three-dimensional ocean model. The coupled model was used to simulate the "cool SST wake" generated by the hurricanes as they moved over the simulated ocean. Tropical cyclones can reduce SST up to 6 °C along their tracks due to a combination of upwelling, turbulent mixing, and heat transport (Nelson 1998). These "cool wakes," which are visible in satellite-derived SST fields in real storm cases, act to reduce the intensity of tropical cyclones – particularly slower moving ones. The model simulations including this additional feedback on intensity simulated weaker storms in general, yet still showed a similar percentage increase of hurricane intensity under warm climate conditions as the original model without ocean coupling.

To test the robustness of the global warming–storm intensification link, Knutson and Tuleya (2004) performed a comprehensive set of tests using future climate projections from nine different global climate models and using four different versions of the GFDL hurricane model. The GFDL hurricane model used for these studies was a research resolution version of the model used to predict hurricanes operationally at NOAA's National Centers for Environmental Prediction. According to their study, an 80-year buildup of atmospheric carbon dioxide at 1 percent per year (compounded) leads to roughly a one-half category increase in potential hurricane intensity on the Saffir-Simpson scale (Figure 2) and about a 20 percent increase in precipitation near the hurricane core. The Saffir-Simpson Hurricane Scale is a 1–5 rating based on a hurricane's intensity, with 5 being the most intense and corresponding to sustained maximum surface winds exceeding 249 km/hour. The scale is used to provide an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale (Smith, 1999). The 1 percent per year carbon dioxide increase scenario they used is an idealized scenario of future climate forcing. As noted by the IPCC Special Report on Emissions Scenarios (Houghton et al. 2001), there is considerable uncertainty in projections of future radiative forcing of Earth's climate.

A criticism of Knutson and Tuleya (2004) by Michaels et al. (2005) was recently published in the *Journal of Climate*. Michaels et al. (2005) challenged the 1 percent per year carbon dioxide scenario in Knutson and Tuleya (2004) as an "unrealistically large carbon dioxide growth rate." Knutson and Tuleya (2005) responded by noting that when a more complete set of radiative forcing is considered, as in the set of six scenarios from the IPCC Special Report on Emissions Scenarios (Houghton et al. 2001), the resulting total radiative forcing by 2100 spans a range lying both above and below the 1 percent per year carbon dioxide scenario in terms of global radiative forcing. Michaels et al. (2005) also argued that the correlations between SST and hurricane intensity in the simulations of Knutson and Tuleya (2004) are higher than those obtained in their real-world analysis (e.g., their figure 1). Knutson and Tuleya (2005) acknowledged that this apparent relation is as expected, because the idealized experimental design does not include weather noise, wind shear effects, and other factors that can prevent storms from reaching their potential intensity. However, they point to several studies (Baik and Paek 1998; DeMaria and Kaplan 1994; Emanuel, 2000; Whitney and Hobgood 1997), which positively correlate tropical cyclone intensity with SST. Finally, Michaels et al. (2005) suggested that the model used in Knutson and Tuleya (2004) has no intensity forecasting skill and therefore is of limited utility in studies of future climate change impacts on hurricane intensity. Knutson and Tuleya (2005) clarified this point by noting the important distinction between the operational hurricane forecasting problem (a classical initial value problem) and the boundary value problem addressed in Knutson and Tuleya (2004), where one is concerned with the maximum

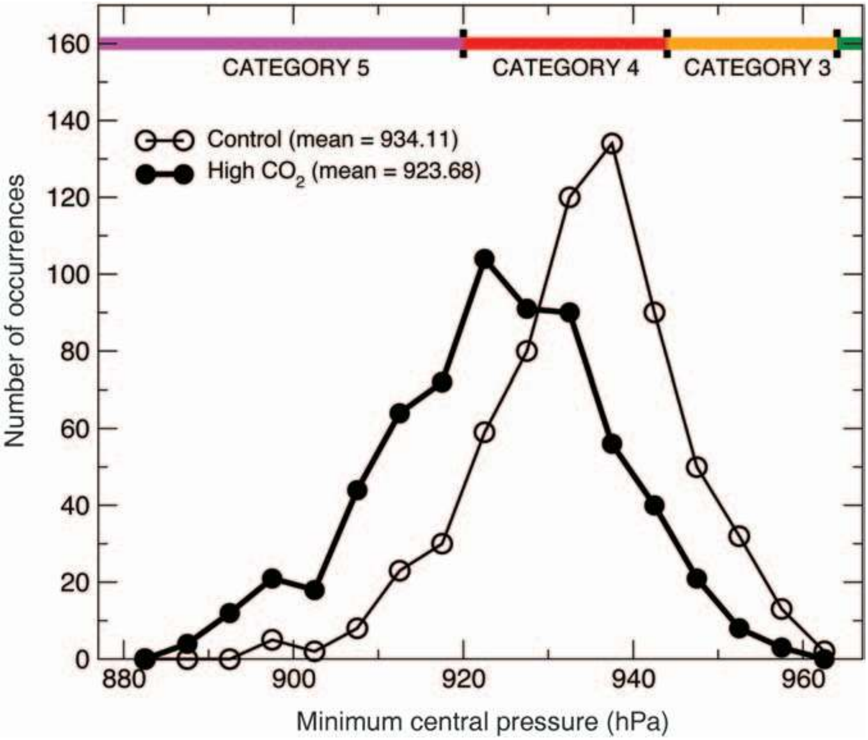

Fig. 2. Comparison of simulated hurricane intensities for present-day (thin line) and future (thick line) climate conditions assuming an 80-year buildup of atmospheric carbon dioxide at 1 percent per year compounded. The results are aggregated from sets of experiments using nine different global climate model projections and four different versions of a high-resolution hurricane prediction model (following Knutson and Tuleya 2004).

hurricane intensity that is possible for a given set of large-scale environmental conditions (i.e., a climatological or statistical distribution of maximum intensities).

The notion, based on the theoretical and modeling studies discussed above, that tropical cyclone intensities will increase in a warmer climate has received some support from other recent modeling studies – particularly those using relatively high-resolution models. Walsh et al. (2004) downscaled a large sample of tropical cyclones in the region east of Australia using a model with a grid spacing of 30 km. They reported little change of storm frequency for 3× carbon dioxide conditions, but a 26 percent increase in the number of intense storms, which in their model referred to storms with minimum central pressures below 970 hPa. Oouchi et al. (2006) recently reported on the highest resolution global model assessment of this issue to date, using a 20-km grid global model. They found a substantial decrease in overall numbers of tropical storms, yet the number of very intense storms and the intensities of those storms increased (although increases did not occur independently in all basins). Other lower-resolution global modeling studies report mixed tropical cyclone intensity results in high carbon dioxide experiments, although these comparatively low-resolution models have even greater difficulties simulating realistic intensities than the Walsh et al. (2004) or Oouchi et al. (2006) models, which have substantial low biases in tropical cyclone maximum intensities despite their use of relatively high-resolution grids.

Regarding the prospects for detection in the observations of an increased tropical cyclone intensity signal forced by greenhouse-gas-induced warming, Knutson and Tuleya (2004) speculated that the detection of such a signal would be very unlikely in the historical data and would be unlikely to emerge for several decades in the future. They interpreted their model results as indicating that the hurricanes occurring near the end of the twenty-first century are expected to be roughly one-half category stronger and have significantly more intense rainfall than under present-day climate conditions. This expectation was based on an anticipated enhancement of energy available to the storms due to higher tropical SSTs projected by that time by global climate models, assuming a substantial continued buildup of carbon dioxide levels in the atmosphere.

3 The hurricane–global warming debate heats up: recent observational studies

Commenting on the state of the science as of June 2005, Trenberth (2005) argued that long-term trends in several environmental measures were becoming evident in hurricane regions. For example, he noted that tropical SSTs and atmospheric water vapor were increasing, apparently due to anthropogenic forcing, and that those factors are believed to affect hurricanes. He also noted the increase of 1.3 percent per decade in total column water vapor over the tropical oceans since 1988 and the apparent increases in convective available potential energy in the tropics in recent decades.

A month or so following Trenberth's article, Emanuel (2005a) reported on a stunning apparent multidecadal increase in a tropical cyclone "power dissipation index" (PDI) for the North Atlantic and western North Pacific basins. PDI is a measure of the accumulated power dissipated by the cyclones (proportional to the cube of wind speeds summed over the life cycles of storms). Emanuel's PDI approximately doubled since about 1950, with most of the increase occurring over the past 30 years. According to Emanuel, increases in both intensity and duration of tropical cyclones contributed roughly equally to this apparent increase. Emanuel's PDI is strongly correlated with SSTs in the basins he examined, which have also increased markedly over the same period. As discussed in his article and supplemental materials, substantial bias adjustments were made to the tropical cyclone data in an effort to account for inhomogeneities in the data sets. An update of Emanuel's PDI for the Atlantic, Northeast Pacific, and Northwest Pacific combined is available on his Web site and was most recently retrieved on October 6, 2006, at http://wind.mit.edu/~emanuel/anthro2.htm.

Landsea (2005) raised several concerns about Emanuel's (2005a) article. He noted that in figures 1–3 of Emanuel (2005a), the smoothed time series of PDI are plotted following two passes of a 1-2-1 filter, but (unfiltered) end-points of the series are also plotted, whereas they should have been deleted. Plotting the unfiltered end-points makes an important difference to the interpretation of the Atlantic PDI series because the last data point plotted is far larger than any other portion of the time series, suggestive of a strong rise to unprecedented levels in the past few years. With the unfiltered points removed, the final few years of the filtered index are comparable with earlier values from the 1950s. Landsea (2005) also criticized the bias-removal scheme Emanuel used to alter the data for the Atlantic for 1949–1969. Emanuel's bias-removal scheme reduced the tropical-cyclone winds by 2.5–5.0 m/sec for the 1940s-1960s because of an inconsistency in the pressure–wind relation during those years compared with subsequent (and presumably more accurate) data. However, Landsea (2005) argued that recent research now indicates that it is better to use the original hurricane database than to apply a general adjustment to the data. Landsea's third concern was that it is difficult to identify an anthropogenic signal in the Atlantic, especially given the "substantial natural multidecadal oscillations" (Goldenberg et al. 2001; Gray et al. 1997; Landsea et al. 1999) and relatively short reliable record of tropical cyclone activity in the basin (Figure 3). He presented an annual PDI time series for the period 1901–2004 – restricted to U.S. landfalling tropical cyclones – that showed little evidence of any long-term trend (Figure 4).

Pielke (2005) criticized Emanuel's conclusions from the perspective of hurricane damage data. He contended that if hurricanes are indeed becoming more destructive over time, then this trend should be apparent in the damage statistics. His analysis of a long-term data set of hurricane losses in the United States showed no upward trend once the data are normalized to remove the effects of societal changes. Pielke found that the average per-storm loss in 1900–1950 is not statistically different from that in 1951–2004, and that his overall conclusion is not changed even with the addition of Hurricane Katrina of 2005. He suggested that these loss data indicate two possibilities with respect to Emanuel's analysis: that the trend in PDI identified by Emanuel was an artifact of the data and/or methods, or that the trend in PDI is realistic, but PDI is a weak indicator of hurricane destructiveness.

In a reply to both Landsea and Pielke, Emanuel (2005b) stood by his original conclusions concerning trends in the tropical cyclone PDI. He noted that the trends are large and have about the same value in all major ocean basins, despite different measurement techniques – and that they are well correlated with SST, which is a relatively well-measured variable. He also noted that the PDI for the Atlantic basin, which is accumulated over all storms and over their entire lives, contains about 100 times more data than an index related only to wind speeds of hurricanes at U.S. landfall. Emanuel (2005b) countered Pielke's assertions by noting that when global tropical cyclone activity is considered, and not just the 12 percent of activity that

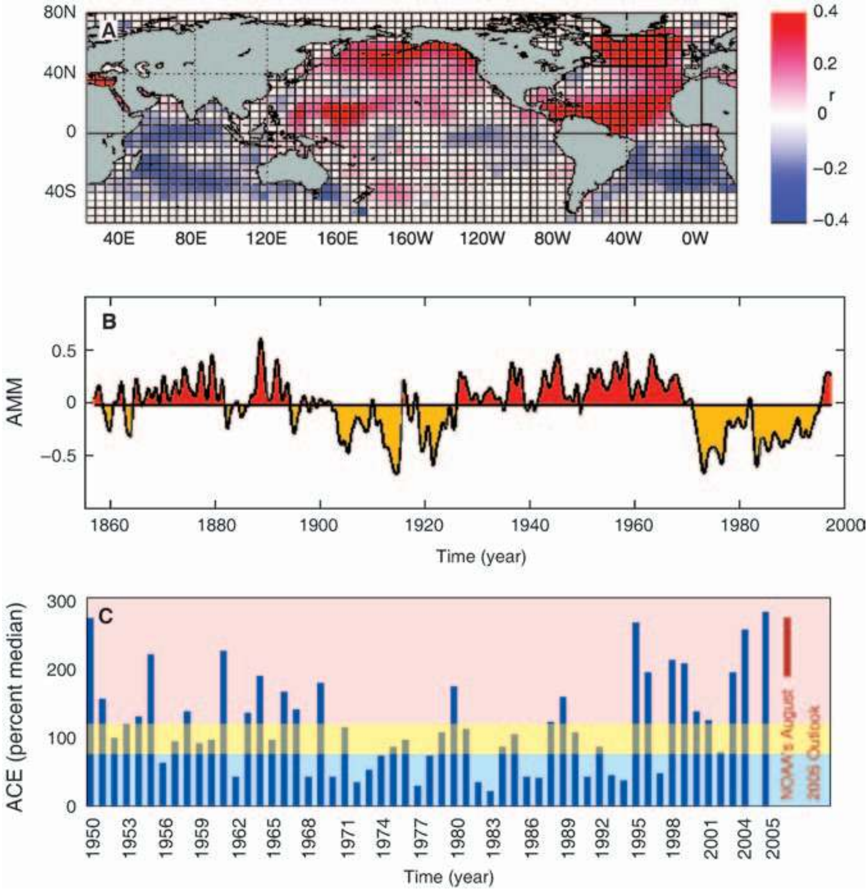

Fig. 3. (A) Distribution of correlations for the years 1857 to 1996 between local monthly sea-surface temperature (SST) anomalies versus the "Atlantic Multidecadal Mode." (B) Temporal realization of the Atlantic Multidecadal Mode (unitless) computed from temporal amplitude time series and the area-average spatial loadings over the rectangular area in the North Atlantic. The Atlantic Multidecadal Mode is based on the third empirical orthogonal function of detrended, non-ENSO-related SST variability (Enfield and Mestas-Nunez 1999). (C) Accumulated cyclone energy values, given as a percentage of the 1951–2000 median value (following Landsea et al. 1999 (A, B) and Bell et al. 2006 (C)).

occurs in the Atlantic, a trend in intensity is already apparent, and that even in the Atlantic one would expect the signal, if it continues, to emerge from the background noise in a few decades.

Emanuel (2005b) accepted Landsea's (2005) corrections to the bias-removal scheme for the Atlantic tropical cyclone data. However, Emanuel cautioned that the high correlation between hurricane activity and tropical SST is remarkable (and largely unaffected by the corrections discussed), and that the SST record is long enough to show the influence of global warming. In summary, Emanuel (2005b) concluded, even given Landsea's and Pielke's

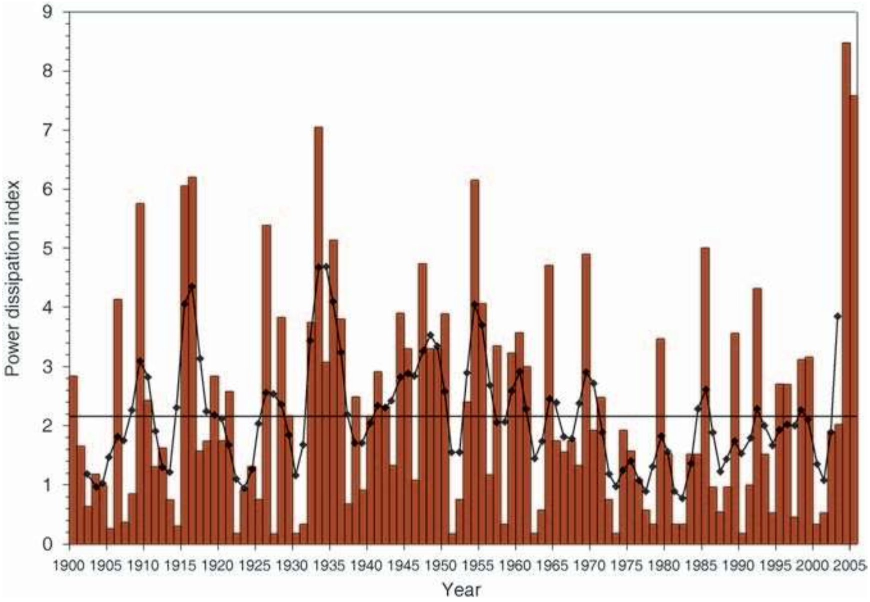

Fig. 4. The continental U.S. power dissipation index at the time of impact for the reliable period of record of 1900 – 2005 (updated figure through 2005 courtesy of Chris Landsea, National Hurricane Center, National Oceanic and Atmospheric Administration). The black line represents the data (black curve), data after smoothing with two passes of a 1-2-1 filter. The reader is referred to Landsea (2005) for more information on how power dissipation index was computed.

arguments, 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.

As noted by Emanuel (2005a), the rate of increase of hurricane intensities implied in his data (per degree Celsius of SST warming) is much greater than that simulated in projections by Knutson and Tuleya (2004) or by simple application of Emanuel's potential intensity theory. Investigators are not yet able to reconcile these large differences in apparent sensitivity of the tropical cyclone intensities. Our speculation is that these discrepancies could arise from three sources: (i) possible overestimation of the observed intensity trends; (ii) possible underestimation by models and theory of the sensitivity of tropical cyclone intensities to SST changes; or (iii) possible influence of related environmental variables such as trends in atmospheric temperatures (lapse rates), moisture, or surface wind speeds (Emanuel, personal communication, 2006). Further investigation is ongoing.

A second highly visible study was that of Webster et al. (2005), published in *Science* in September 2005, which reported further evidence for strong upward trends in tropical cyclone intensity statistics. They first noted that tropical ocean SSTs have increased by approximately 0.5 °C between 1970 and 2004. In their statistical assessment of SST trends for the tropical cyclone season in each ocean basin, they found that according to the Kendall trend test, the SST trends in each of the ocean basins are significantly different from zero at the 95 percent confidence level or higher, except for the Southwest Pacific Ocean. They then examined the hurricane characteristics for each ocean basin and found that the number of category 4 and 5 hurricanes has almost doubled globally over the past three decades (Figure 5). Although their analysis spans a shorter time period than Emanuel's, due to their decision to limit their analysis to the satellite era, their results indicated that a substantial increase has occurred in each of the six individual tropical cyclone basins.

Hoyos et al. (2006) extended the work of Webster et al. (2005) by examining the statistical relations between changes in global hurricane intensity since 1970 and other environmental parameters. They examined the joint distribution of hurricane intensity together with several variables believed to contribute to the intensification of hurricanes, using a methodology based on information theory, and isolating the trend from the shorter-term natural modes of variability. Their results show that the trend of increasing numbers of category 4 and 5 hurricanes for the period 1970–2004 is statistically linked to the trend in SST. Other aspects of the tropical environment, such as vertical wind shear, were not found to contribute strongly to the observed global trends in category 4 and 5 hurricanes, although other factors do influence shorter-term variations in hurricane intensity.

In a critique of the Webster et al. study focusing on the western North Pacific, Chan (2006) reported that by extending the analysis of Webster et al. back to earlier years, the "trend" in that basin actually appears to be part of a large interdecadal variation. Chan noted that the tropical-cyclone-related trend in western North Pacific has actually reversed since 1998. For his analysis, Chan used unadjusted data from the earlier part of the record, in contrast to the adjustments for this period proposed by Emanuel (2005a) for that basin. Chan (2006) suggested that the recent increase in occurrence of intense typhoons, being part of a large interdecadal variation in the number of intense typhoons, is related to similar temporal fluctuations in several aspects of the atmospheric environment. He argued that parameters such as atmospheric rotational flow, vertical wind shear, and thermodynamic energy, as opposed to SST, are likely to be the most important determinants of typhoon intensity in the western North Pacific.

Webster et al. (2006) acknowledged that vorticity, wind shear, and moist static energy show a positive correlation with numbers of category 4 and 5 storms, but caution that there is no statistically significant trend in any of these parameters that could be associated with a trend or multidecadal variability in the storm metrics.

Michaels et al. (2006) presented empirical evidence arguing against as strong a linkage between global warming and Atlantic hurricane activity as implied by Emanuel (2005a). They examined SSTs along the paths of storms and estimated that increased SSTs account for only about half of the increase

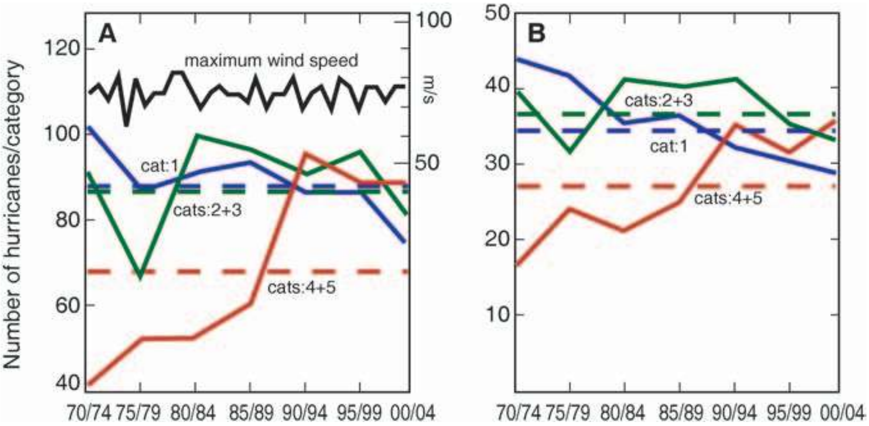

Fig. 5. Intensity of hurricanes according to the Saffir-Simpson scale (categories 1 to 5). (A) The total number of category 1 storms (blue curve), the sum of categories 2 and 3 (green), and the sum of categories 4 and 5 (red) in 5-year periods. The bold curve is the maximum hurricane wind speed observed globally (measured in meters per second). The horizontal dashed lines show the 1970–2004 average numbers in each category. (B) Same as (A), except for the percentage of the total number of hurricanes in each category class. Dashed lines show average (following Webster et al. 2005).

in strong hurricanes over the past 25 years. Michaels et al. (2006), noting the step-like – as opposed to monotonic – relation between SST and cyclone strength found by Evans (1993), proposed that there exists an SST threshold that must be exceeded before tropical cyclones can develop into major hurricanes. They hypothesized that once this threshold is crossed, other factors (e.g., wind shear, moisture gradients) become dominant. Michaels et al. argue that since maximum wind speeds in a hurricane are rarely collocated with maximum SSTs, other environmental factors must be important for storm intensity. As discussed earlier, Emanuel (2000) argues similarly that for individual storms, the potential intensity of the environment sets an upper limit, which actual storms only occasionally reach, although he found that there nonetheless appears to be a monotonic (not step-like) relation between potential intensity and the entire distribution of intensities.

Klotzbach (2006) evaluated observed tropical cyclone data from all ocean basins for the limited time period 1986 to 2005. He justified limiting his analysis to those years by arguing that only during the post-1985 years were the data homogeneous enough to permit reliable trend analysis. He argued that a significant portion of the dramatic increasing trend of Webster et al. (2005) and Emanuel (2005) is due to poor data quality before the mid-1980s. He concluded that there is not likely a link between global warming and hurricanes, since the climate has warmed over the years 1986 to 2005 without a discernible trend in tropical cyclone activity during the same period. As with Michaels et al. (2006), Klotzbach (2006) concluded that other factors such as the state of El Niño–Southern Oscillation, the strength of the vertical wind shear, and the amount of mid-level moisture, etc., play a critical role in determining the level of expected seasonal tropical cyclone activity.

Using a completely different analysis technique, Sriver and Huber (2006) derived a tropical cyclone PDI from global analyses of wind data obtained from the operational weather forecasting community – the ERA-40 reanalysis – for the period 1958 to 2001. Because of the relatively coarse resolution of their data set, they normalized both their index and Emanuel's PDI index by the respective standard deviations of the indices for comparison over equivalent domains. Their normalized PDI curve (Figure 6) agrees very well with Emanuel's result after 1978, when compared for the same regions. They regard the pre-1979 data as less reliable than post-1978 data, and differences are more apparent with Emanuel's results in earlier years. Deriving an empirical relation between SST and their global PDI, using only post-1978 data, they found that a 0.25 °C increase in mean annual tropical SST corresponds to about a 60 percent increase in their global PDI statistic, suggesting that global tropical cyclone activity may be highly sensitive to SST.

In a recent commentary, Landsea et al. (2006) maintain that the current tropical cyclone databases are simply insufficient in quality and reliability to be used for detecting trends in the frequency of extreme cyclones. They provide as examples satellite imagery from five North Indian Ocean tropical cyclones from the 1970s and 1980s, all of which were apparently significantly underestimated in terms of intensities. They allude to work underway suggesting at least 70 additional previously unrecognized category 4 and 5 tropical cyclones in the Eastern Hemisphere during 1978–1990, which is roughly the first half of the analysis period used by Webster et al. (2005). Landsea et al. argue that several operational changes would be expected to contribute to a bias over time in tropical cyclone statistics such that trends would be likely to be substantially overestimated compared to reality.

4 Atlantic SSTs and hurricanes: trends or cycles?

Globally, tropical cyclone basins around the world have been active as evident by typhoon seasons affecting Asia in 2005 and 2006. However, the Atlantic basin has received particular scrutiny regarding the global warming hurricane issue for several reasons. First, the hurricane data sets in the Atlantic are generally believed to be the best among all basins, owing to the more continuous use of aircraft reconnaissance in the basin over the years, compared to other basins. Additionally, recent Atlantic hurricanes such as Andrew and Katrina have led to remarkable economic losses as they impacted upon heavily populated and developed regions along the U.S. coast, which has raised considerable concern and awareness among insurance companies, policymakers, and the general U.S. public.

The notion of Atlantic hurricane activity as essentially a multidecadal cyclical phenomenon, having no detectable upward trend corresponding to

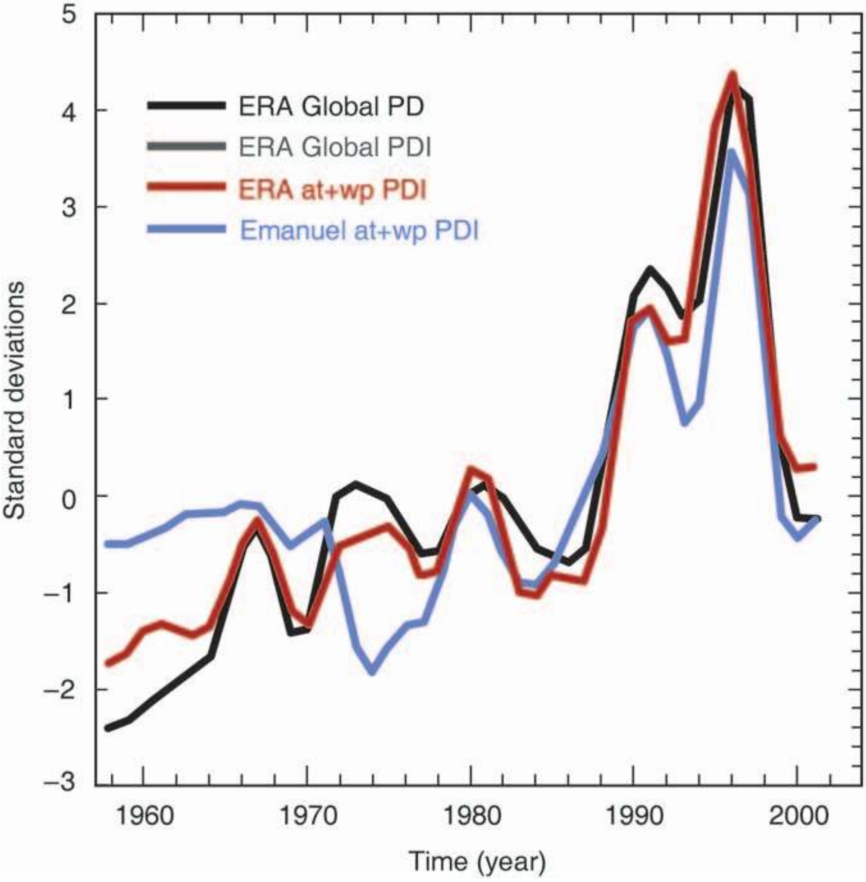

Fig. 6. Integrated power dissipation (PD) quantities for the ERA-40 project period, 1958–2001. ERA-40-derived quantities include global PD (black curve), global power dissipation index (PDI; gray curve), and PDI for the Atlantic and northwestern Pacific regions (red curve). Also shown is the Atlantic and northwestern Pacific PDI derived from data of Emanuel (2005) and filtered using the technique discussed in the methods section (blue curve). All curves are normalized with the respective standard deviations of the detrended time series (following Sriver and Huber 2006).

that of global temperatures, is exemplified in the study of Goldenberg et al. (2001). They showed that similar pronounced multidecadal variations occur in Atlantic major hurricane counts, in a vertical wind shear index for the tropical Atlantic, and in a large-scale mode of variation of Atlantic SSTs (with expressions elsewhere around the globe as well) known as the Atlantic Multidecadal Oscillation (AMO) (e.g., Figure 3).

Multidecadal oscillations related to Atlantic hurricane activity were analyzed in a similar vein by Bell and Chelliah (2006). Based on an empirical analysis of observed large-scale atmospheric variability, predominantly in the tropics, they inferred that interannual and multidecadal extremes in Atlantic hurricane activity are related to a coherent and interrelated set of atmospheric and oceanic conditions associated with three leading modes of climate variability in the tropics. All three modes are related to fluctuations in tropical convection, with two representing the leading multidecadal modes of convective rainfall variability, and one representing the leading interannual mode (i.e., El Niño–Southern Oscillation). Bell and Chelliah (2006) found that the tropical multidecadal modes are statistically linked to known multidecadal fluctuations in Atlantic hurricane activity, West African monsoon rainfall, and Atlantic SSTs. They noted that the above-normal hurricane activity since 1995 does not reflect an exact return to conditions seen during the 1950s-1960s. Rather, they found that the period 1950–1969 was characterized by a very active West African monsoon conditions and relatively normal SST, while the period 1995–2002 is associated with an only moderately active West African monsoon and exceptionally high Atlantic SSTs.

Knutson et al. (2006) used climate model simulations to assess whether regional twentieth-century trends in surface temperature exceed the levels expected from natural or internal climate variability alone. They compared the observed trends with those obtained from climate models forced by a range of factors, including anthropogenic increases in greenhouse gas concentrations and aerosols. In terms of the tropical Atlantic "Main Development Region," their analysis indicates that a significant century-timescale warming is already detectable, and that the twentieth-century trends in that region are much more realistically simulated by models that include anthropogenic forcing than by models that include only natural variability.

Mann and Emanuel (2006) statistically modeled SSTs in the tropical North Atlantic using global SSTs together with an index of radiative forcing from anthropogenic aerosols. Using these predictors, they infer the tropical Atlantic (late summer) SST multidecadal variations and trends as being primarily a response to the long-term changes in anthropogenic radiative forcing. The AMO, which they estimated as a residual, has only a relatively minor impact on late summer SSTs in the tropical Atlantic according to their analysis (Figure 7). They also examined a time series of tropical cyclone counts for the Atlantic, extending back into the late 1800s, and showed that the tropical cyclone counts closely tracked SSTs in the basin, with both showing a similar century-scale upward trend (Figure 7). They justified examining the tropical cyclone data for the whole basin back to the late 1800s by arguing that ships likely encountered storms by accident in the days before basin-wide aircraft reconnaissance was available. They concluded that the trend toward more Atlantic tropical cyclones over time is being driven by anthropogenically forced increases in Atlantic SSTs, and therefore that tropical cyclones in the basin have a long-term upward trend as opposed to a naturally occurring cycle linked to the AMO. In their analysis, anthropogenic production of aerosols (e.g., pollution) induces much of the regional cooling in the Atlantic during the 1970s and 1980s – a cooling that they contend was misinterpreted in previous studies as being primarily a natural oscillation. This work is

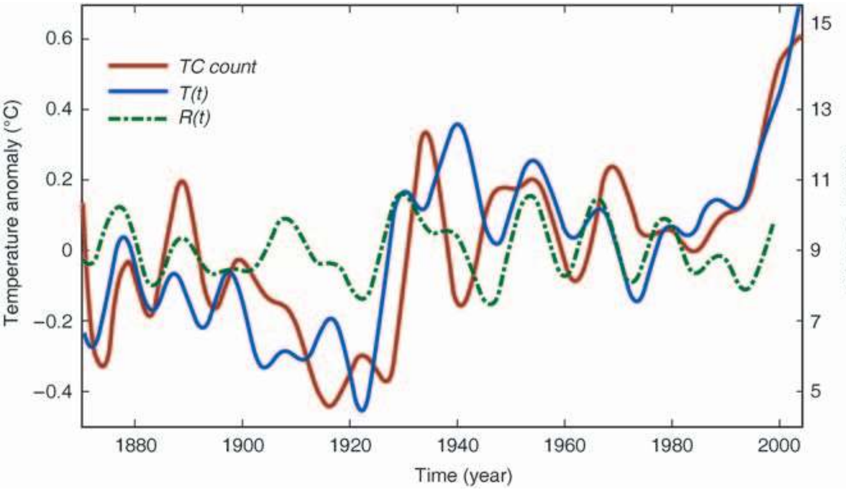

Fig. 7. Comparison of decadally smoothed Atlantic basin tropical cyclone numbers (red curve) with decadally smoothed August-September-October (ASO) main development region sea-surface temperatures (SST) (blue) and decadally smoothed residuals (dashed curve). The residuals are an estimate of SST natural variability based on the variability that remains unresolved by regression of the full SST series on both global mean SST and Northern Hemisphere anthropogenic tropospheric aerosol forcing (following Mann and Emanuel 2006).

certain to stimulate new research into the relative roles of greenhouse gases, aerosols, other forcings, and internal variability in the region. Unfortunately, reliable aerosol data from satellites and other monitoring networks have only become available in the last few decades, and the indirect forcing of aerosols through their effects on clouds and precipitation processes is still so uncertain as to not even be included in many recent climate-modeling experiments (e.g., Knutson et al. 2006).

Another statistical analysis of tropical Atlantic SSTs was proposed by Trenberth and Shea (2006). They argued against the common practice of deriving an AMO signal by first removing a linear trend (as was done, for example, in the analysis for Figure 3B), since this can lead to artificial apparent low-frequency variability in the residual series if the true trend in the data is not linear. Trenberth and Shea's analysis indicates that a substantial fraction of the 2005 warm SST anomaly in the Atlantic was linked to global warming, being in common with global SST changes. They attribute a smaller contribution to remote effects of El Niño. Their results thus support the notion of a substantial tropical Atlantic warming arising from increased greenhouse gases.

Santer et al. (2006) find that observed SST increases in the Atlantic and North Pacific tropical cyclogenesis regions during the twentieth century are unlikely to be due solely to unforced variability of the climate system, but are more realistically simulated in experiments using estimated historical climate forcing. Their internal climate variability assessment and external forcing results agree with those of Knutson et al. (2006) but are made more robust by their use of 22 different climate models and two observed SST reconstructions. In one of the models, in which individual forcing experiments were available, they find that the human-induced change in greenhouse gas forcing is the main cause of the twentieth-century warming, and particularly of the late-twentieth-century warming (Figure 8).

While these studies make a stronger case that tropical Atlantic SSTs have a strong warming trend, as shown earlier (Figure 4) the U.S. landfalling PDI index of Landsea (2005) shows no strong evidence at this time for a trend in hurricane activity affecting the U.S. coasts since 1900. Emanuel (2005b) views this discrepancy as arising from the fact that U.S. landfalling hurricane data, being a relatively limited sample, is probably too noisy for reliable trend detection at this time. Mann and Emanuel's (2006) argument that Atlantic tropical cyclone counts from the late 1800s can provide useful information on trends is certain to stimulate more discussion and debate.

5 Where is the debate headed?

In reviewing the debate so far, it seems clear that several unresolved questions will be taken up in further studies, as scientists attempt to understand this complex but important set of issues. The first of these is the question of the quality of the tropical cyclone data sets. This is crucial, since problems in the data can lead to exaggerated or erroneous trend estimates, especially if the problems are in the form of a bias that changes over time. Landsea et al. (2006) clearly view this as the case for tropical cyclones, whereas Mann and Emanuel (2006) argue otherwise for the Atlantic tropical cyclone count data stemming back to the late 1800s. Further analyses are underway in an attempt to address this critical question.

A second major theme to address will be the relative importance of the thermodynamic state (e.g., potential intensity, SST, atmospheric temperature and moisture, ocean heat content) versus the role of dynamical factors such as vertical wind shear in affecting low-frequency variations of tropical cyclone activity. For example, are the increases in Atlantic PDI and major hurricane counts from the 1970s and 1980s to the present driven more by changes in the thermodynamic background state or in the wind shear? This may have important implications for future projections, because, for example, while climate models appear unanimous in projecting future increases in tropical SSTs and potential intensity, they are much less in agreement about the future direction of vertical wind shear in the Atlantic and other basins (Knutson and Tuleya 2004). The answers to this major issue appear to conflict among current studies.

The relative roles of natural variability and anthropogenic forcing in causing the recent increases and multidecadal variations in tropical Atlantic SSTs will likely attract more vigorous debate, because the answers have implications for the likely future trajectory of tropical Atlantic SSTs and hurricane activity in the coming decades.

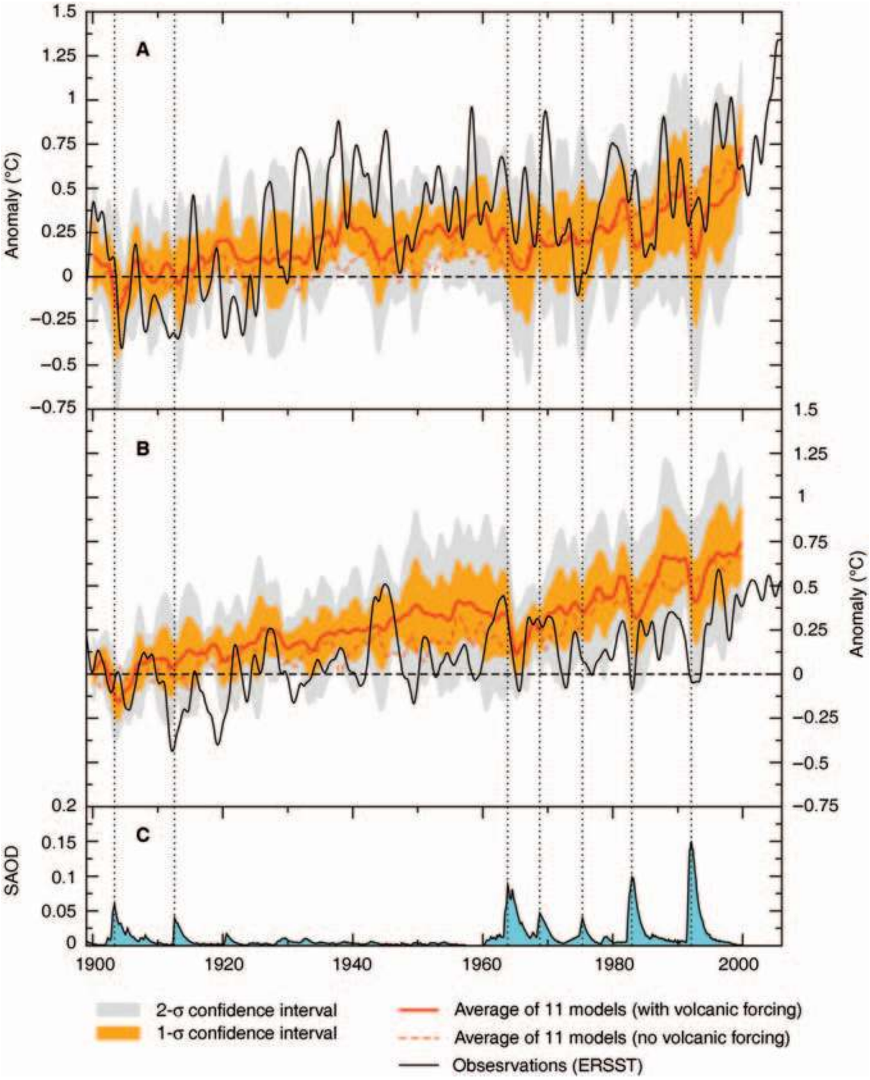

Fig. 8. Modeled and observed (ERSST) low-pass filtered SST anomalies relative to 1900–1090 in the Atlantic and Northwest Pacific tropical cyclogenesis regions. Model results are from twentieth-century climate model simulations using 22 different climate models forced by estimated past radiative forcing and are grouped according to whether volcanic forcing was or was not included. Yellow and gray envelopes denote 1- and 2-sigma confidence intervals for the volcano runs. Estimated stratospheric optical depth is denoted by the blue shading, with major eruptions denoted by dashed vertical lines (following Santer et al. 2006).

6 Concluding remarks

Our review of the existing literature indicates that significantly more research – from observations, theory, and modeling – is needed to resolve the current debate around global warming and hurricanes. Even as the debate continues recent articles published during the 2006 hurricane season add more support to the notion that human activities are contributing to increased SSTs in the Atlantic basin hurricane formation region (see Elsner 2006; Santer et al. 2006). As noted by Pielke et al. (2005), there are many possible metrics of intensity (e.g., maximum potential intensity, average intensity, average storm lifetime, maximum storm lifetime, average wind speed, maximum sustained wind speed, maximum wind gust, accumulated cyclone energy, power dissipation, and so on), and not all such metrics have been closely studied from the standpoint of historical trends, due to data limitations among other reasons. Additionally, while much of the debate has tended to focus on SSTs, other environmental factors must be considered. For example, the tropical cyclone heat potential (TCHP, a measure of the oceanic heat content from the sea surface to the depth of the 26 °C isotherm) may be a better indicator of the potential for hurricane intensification than SST (Scharroo et al. 2005). New satellite altimetry products are beginning to provide estimates of TCHP and will continue to be valuable for future assessment of TCHP–storm intensity relations (Figure 9). Emanuel (2005a) has emphasized the importance of considering the potential intensity and not just SST, while numerous studies have emphasized the importance vertical wind shear and other dynamical factors (Bell and Chelliah 2006; Goldenberg et al. 2001).

Long-term studies and re-analysis of atmospheric and oceanic data sets will be needed to begin to address some of these issues. Additionally, improvements in modeling technology should provide some new insights and advancements as well. For example, a model at NASA Goddard Space Flight Center called the Finite Volume General Circulation Model (fvGCM) is beginning to show promise at representing hurricanes and their behavior at unprecedented spatial resolutions for a GCM (Atlas et al. 2004). Furthermore, new satellite or enhanced and *in situ* observing capabilities can provide rich new observational capabilities for hurricane internal and external environments that will increase understanding of past and current events as well as aid in assessing the plausibility or likelihood of future projections.

For the Atlantic basin, regardless of whether the underlying cause of increased hurricane activity is a natural multidecadal cycle, a longer-term radiatively forced trend, or some combination of the two, it appears likely that continued high levels of hurricane activity will persist in the basin overall while SSTs remain anomalously warm there. The data for U.S. landfalling hurricanes are less compelling regarding presence of trends or pronounced multidecadal variations (e.g., Figure 4). There is currently no demonstrated ability to reliably forecast the duration of the current period of high basin-wide activity, and even less so for U.S. landfalling hurricanes. From

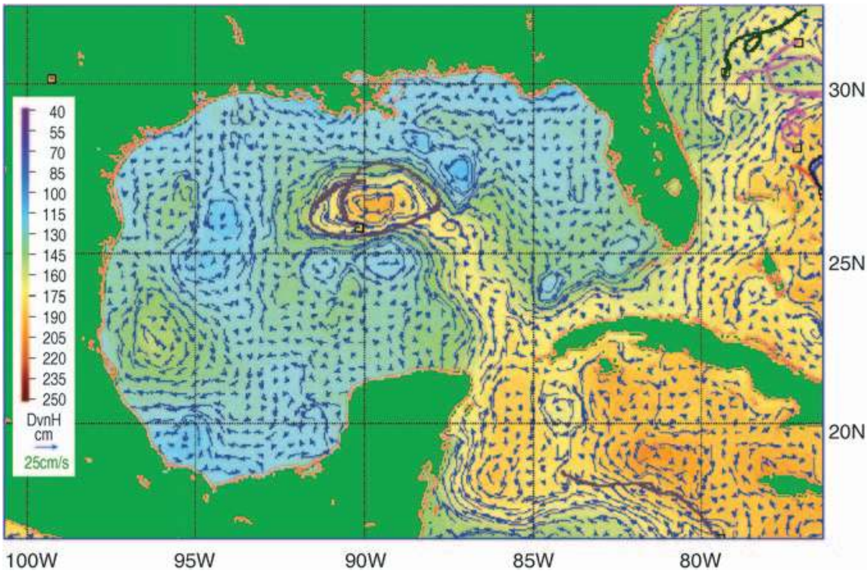

Fig. 9. Assessment of Tropical Cyclone Heat Potential 7 days prior to the landfall of Hurricane Katrina. Altimetry-derived sea surface height (cm) (color, yellows are higher and blues are lower) and surface current directions (arrows) highlight the Loop Current and a warm ring (around 89°W, 27°N) in the Gulf of Mexico. The trajectory over the warm ring corresponds to a surface drifter and confirms the altimetry estimates (courtesy of NASA/Jet Propulsion Laboratory).

the viewpoint of Goldenberg et al. (2001) predicting basin-wide activity involves predicting the future state of the AMO, whereas the scenario arising from Mann and Emanuel's (2006) study is more pessimistic, with Atlantic hurricane activity continuing to increase in coming decades as global warming proceeds (e.g., Houghton et al. 2001), with little near-term prospect for a return to the "quiet" hurricane conditions of the 1970s and 1980s.

Scientists will continue to carefully and methodically analyze past and emerging data sets and model results, and to debate relevant research questions, in order to provide objective and sound information to the public and various stakeholders in the public and policy sectors on these important issues.

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Note

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