Sea-surface temperatures and tropical cyclones in the Atlantic basin

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[1] Whereas there is a significant relationship between overall sea-surface temperature (SST) and tropical cyclone intensity, the relationship is much less clear in the upper range of SST normally associated with these storms. There, we find a step-like, rather than a continuous, influence of SST on cyclone strength, suggesting that there exists a SST threshold that must be exceeded before tropical cyclones develop into major hurricanes. Further, we show that the SST influence varies markedly over time, thereby indicating that other aspects of the tropical environment are also critically important for tropical cyclone intensification. These findings highlight the complex nature of hurricane development and weaken the notion of a simple cause-and-effect relationship between rising SST and stronger Atlantic hurricanes. **Citation:** Michaels, P. J., P. C. Knappenberger, and R. E. Davis (2006), Sea-surface temperatures and tropical cyclones in the Atlantic basin, *Geophys. Res. Lett.*, *33*, L09708, doi:10.1029/2006GL025757.

1. Introduction

[2] Recently, *Emanuel* [2005] and *Webster et al.* [2005] have suggested that rising sea surface temperatures (SST) in the North Atlantic hurricane formation region are linked to recent increases in hurricane intensity, and that the trend of rising SSTs during the past 3 to 4 decades bears a strong resemblance to that projected to occur from increasing greenhouse gas concentrations. Higher SSTs from increased greenhouse gas concentrations have been shown to increase hurricane intensity in computer models [*Knutson and Tuleya*, 2004], although the timing and magnitude of the change that will occur is a matter of debate [*Michaels et al.*, 2005; *Knutson and Tuleya*, 2005].

[3] Neither of the recent studies [*Emanuel*, 2005; *Webster et al.*, 2005] directly linked local changes in SST to changes in hurricane intensity. Rather, they rely on trends in basin-wide averaged monthly or seasonal SST that are not necessarily representative of the local marine environment experienced by individual tropical cyclones. A closer look at the direct relationship between more local SST and tropical cyclone intensity reveals a complicated picture [e.g., *Evans*, 1993]. Using monthly-averaged SST data resolved at 2° × 2° latitude/longitude, from 1967 to 1986, *Evans* [1993] found that SST alone was an inadequate predictor of ultimate hurricane intensity, largely because the strongest storms were often not coincident with the highest temperatures that they encountered. *Evans'* [1993] general conclusion was that, while SST may provide an upper bound on tropical storm intensity, SST is not the dominant factor in determining either the instantaneous storm intensity or the actual maximum intensity attained by a tropical system. Similar results have been reported by *Merrill* [1987, 1988] and *Baik and Paek* [1998].

[4] The *Evans* [1993] study is limited by rather coarse (2° × 2°) monthly SST data. Here, we update these analyses using more recent SST data that is of a finer spatial and temporal resolution. The *Evans* [1993] study also ends before a mid 1990s shift in the Atlantic Multidecadal Oscillation [*Goldenberg et al.*, 2001] that is thought to be more conducive to tropical cyclone development.

2. Data and Methods

[5] Our SST data are the weekly-average gridded 1° latitude by 1° longitude record described by *Reynolds et al.* [2002]. Data are available from 1982 to 2005 and incorporate both in-situ and satellite measurements of SST from the world's oceans. Our primary region of interest in this analysis is the North Atlantic Ocean. The tropical cyclone data are the best track data file, HURDAT, developed by and available from the National Hurricane Center (NHC) [*Jarvinen et al.*, 1984] (and updates). The HURDAT file contains 6-hourly (0000, 0600, 1200, 1800 GMT) center locations (latitude and longitude in tenths of degrees) and intensities (maximum 1-minute surface wind speeds and minimum central pressures) for all tropical storms and hurricanes in the Atlantic basin from 1851 through 2004. Our analyses begin in 1982 coincident with the beginning of the SST data set. To include the record-setting Atlantic basin hurricane season of 2005, we interpolated the 2005 storm information issued in advisories by the NHC to the six hourly time intervals contained in the HURDAT data. While these data are preliminary, they should provide a reasonable estimation of 2005 tracks and intensities.

[6] For each 6-hourly storm report, we identified the underlying weekly-average SST from the 1° × 1° grid cell that contained the center of the tropical system. Since tropical cyclones are known to cool the SST over which they are located (through mixing and evaporation) [*Bender et al.*, 1993], we use the SST during the week prior to the time of observation to best represent the SST encountered by each storm as it traversed the ocean. The 6-hourly observations were then examined for each of the 270 named storms, from which we calculated maximum storm intensity (as measured by wind speed), SST at time of maximum intensity, and highest SST encountered prior to maximum intensity.

3. Results and Discussion

[7] A plot of wind speed versus SST for the 7,814 6-hourly observations of named tropical cyclones in the

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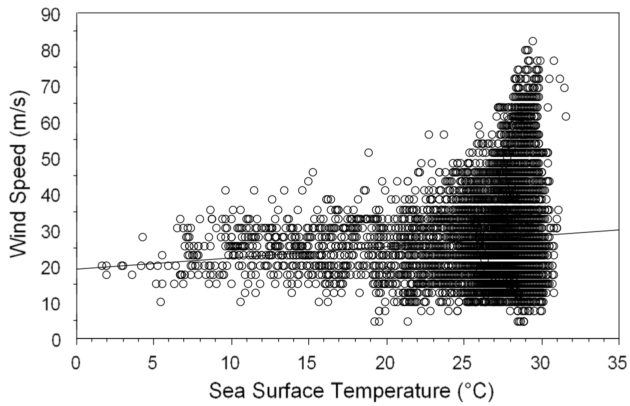

Figure 1. The relationship between wind speed and the SST (where here SST refers to the SST in the grid cell one week prior to the passage of the storm center) for the complete set of 6-hourly observations from all Atlantic basin tropical systems from 1982 to 2005. The linear least-squares regression line is statistically significant (N = 7814, $p < 0.0001$, $R^2 = 0.0089$, slope = 0.309).

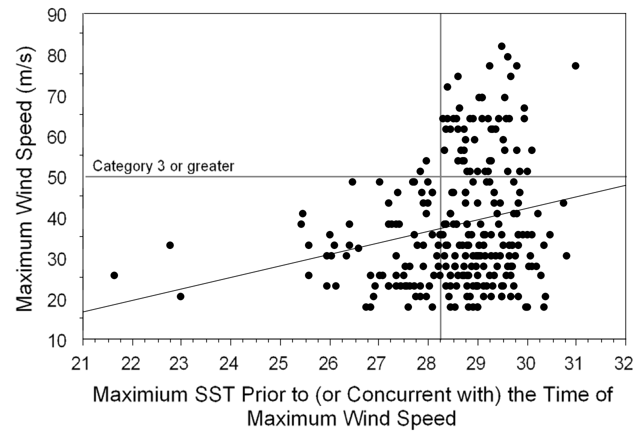

Figure 3. Maximum wind speed attained by the 270 named Atlantic tropical systems from 1982 to 2005 plotted against the maximum SST encountered prior to (or concurrent with) the maximum wind speed. Storms with sustained surface winds of at least 50 m/s are categorized as major hurricanes (category 3, 4, or 5 storms on the Saffir-Simpson hurricane scale). The regression line through all the data points is statistically significant (N = 270, p = 0.0002, $R^2 = 0.051$, slope = 2.81). (Analysis after the removal of the three low SST outliers indicates that they are not leverage points.)

North Atlantic Ocean from 1982 to 2005 yields an overall relationship that is similar in shape to that reported by *Evans* [1993] and *Baik and Paek* [1998], with the peak in intensity occurring below the maximum SST (Figure 1). Note the six points at the upper right hand portion of Figure 1 that lie outside the general envelope of data are all from 2005 hurricane Katrina, which encountered unusually high SST as it approached shore in the northern Gulf of Mexico. (Katrina attained its greatest wind speed at an SST 0.8° below the maximum SST that it encountered). A linear least-squares regression analysis indicates the existence of a statistically significant relationship between SST and wind speed (N = 7814, $p < 0.0001$, $R^2 = 0.0089$, slope = 0.309) (We also log-transformed the wind speed data to account for the heteroskadisticity and the resulting model is statistically significant; N = 7814, p = 0.0002, $R^2 = 0.0017$, slope = 0.002). Also, we note, as did *Evans* [1993] that although the overall explained variance between SST and wind speed is small, SST seems to define an upper bound to the wind speed—a bound which increases somewhat exponentially up to about 29°C but that drops off thereafter.

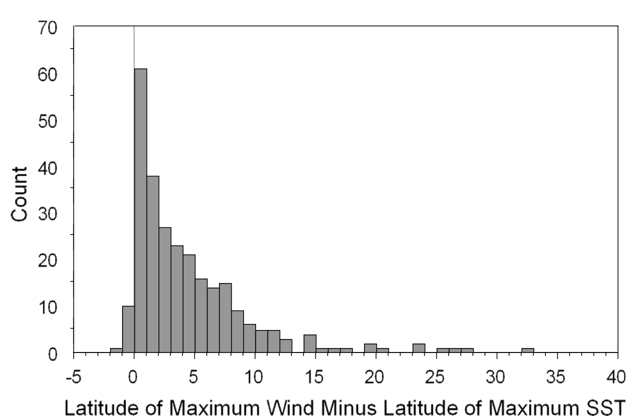

Figure 2. Difference in latitude between the location of maximum wind and the location of maximum SST for the 270 named tropical cyclones in the Atlantic basin from 1982 to 2005.

[8] The observed relationship between wind speed and contemporaneous SST can underestimate the true relationship between storm intensity and SST because hurricanes can reach their maximum intensity some distance away from the warmest waters they encounter. *Merrill* [1988] and *Evans* [1993] suggest that storms that form over the very warm waters in the deep tropics typically deflect northward around the subtropical anticyclones and then encounter extensive areas of cooler water. But, having organized under warmer waters, they can continue to intensify via convective feedbacks while over slightly cooler water.

[9] We find support for the hypothesis that life-cycle aspects of hurricanes can partially explain why the strongest storms are not found over the warmest waters. Figure 2 demonstrates that there is a considerable displacement between the latitude at which the maximum wind was reported and the latitude at which the maximum SST was encountered (prior to maximum wind). The average difference is 4.4° latitude northward. (However, owing to the skewness of the distribution, fully 67% of cyclones reached their maximum winds within 5° latitude of their maximum encountered SST).

[10] To account for the observation that maximum wind speed and maximum SST are typically not co-located (they were within 1 degree only 26% of the time), we plot in Figure 3 the maximum wind speed attained by each of the 270 named Atlantic basin tropical cyclones against the maximum SST experienced prior to or concurrent with the time of maximum wind. Here we find, as expected, that this overall relationship is somewhat stronger (N = 270, p = 0.0002, $R^2 = 0.051$, slope = 2.81). The slope indicates that for each additional degree of SST encountered, the maximum wind attained increases by 2.8 m/s (5.44 knots).

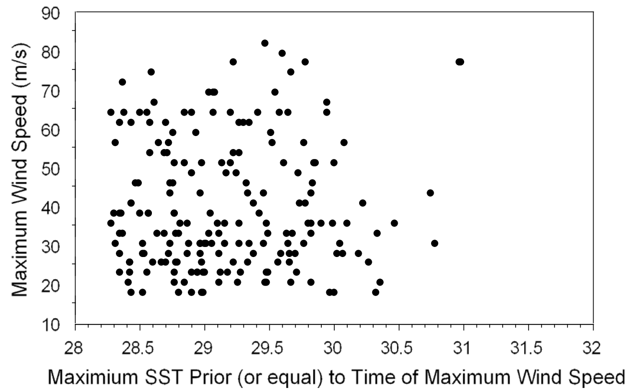

Figure 4. The relationship between maximum wind speed and the highest SST encountered prior to (or concurrent with) reaching the maximum wind speed at temperatures greater than or equal to 28.25°C. The relationship is statistically insignificant (N = 195, p = 0.513, R^2 = 0.002, slope = 1.32).

[11] There appears to be a discontinuity in the relationship depicted in Figure 3 at about 28.25°C. All but two of the storms that reached major hurricane status (sustained surface winds of at least 50 m/s) on the Saffir-Simpson hurricane scale encountered SST of at least 28.25°C. There is no significant relationship between SST and maximum winds at SST exceeding 28.25°C (N = 195, p = 0.513, R^2 = 0.002, slope = 1.32) (Figure 4). This suggests that while crossing the 28.25°C threshold is a virtual necessity for attaining category 3 or higher winds, SST greater than 28.25°C does not act to further increase the intensity of tropical cyclones.

[12] To validate the statistical robustness of our identified threshold, we progressively remove storms from our analysis in lower portion of the SST range and recalculate the regression. We first delete the three "outlier" storms with maximum SST encountered below 24°C and find that the overall relationship between SST and storm strength remains statistically significant. Then, we successively remove low SST storms in 0.25°C SST intervals and test the overall significance of the relationship between SST and storm intensity in the remaining population. We find that the relationship remains statistically significant ($p < 0.05$) up to 27.75°C. Above 27.75°C, the relationship between maximum intensity and maximum SST encountered becomes statistically insignificant. We choose 28.25°C rather than 27.75°C as our threshold because the number of major hurricanes per temperature increment becomes much greater above 28.25°C (averaging 14 storms in every 0.5°C interval) than between 27.75°C and 28.25°C (only 2 storms) and thus 28.25°C rather than 27.75°C is a more practical representation of the threshold value.

[13] Thus, observations indicate the existence of a temperature threshold necessary for the development of major hurricanes rather than a continuous positive relationship between maximum storm intensity and SST. Factors other than SST become dominant for determining the ultimate strength of storms once the 28.25°C threshold is surpassed.

[14] The existence of a threshold SST for major hurricanes has been suggested previously by *Merrill* [1987, 1988], who noted a discontinuity in the relationship between climatological average SST and maximum wind speed whereby he found few (only 2) occurrences of storms with a maximum wind that exceeded 50 m/s over SSTs below 28°C. We find that threshold is maintained when finer-scale data are used in a warmer world.

[15] To investigate recent claims that the warming that has occurred during the past several decades has been responsible for the observed increase in Atlantic tropical cyclone intensity [*Emanuel*, 2005; *Webster et al.*, 2005], we divide our study into the periods 1982–1994 and 1995–2005—years before and after a noted shift in Atlantic hurricane activity [*Goldenberg et al.*, 2001]. In the 13 years prior to 1995, a total of 71 storms encountered 28.25°C before reaching maximum intensity, and 16 (22.5%) of those storms became major hurricanes. In the 11 years since 1995, 124 storms encountered 28.25°C SST and 42 (33.8%) of those storms attained category 3 strength or greater. The doubling of the annual frequency of Atlantic tropical systems that encounter SST that exceed the 28.25°C threshold for major hurricane development is a clear indication that the SST encountered by named Atlantic tropical systems were higher in the 1995–2005 period. However, in addition to the increase in the frequency of storms exceeding the threshold, there has been a 50 percent increase in the percentage of storms above the threshold that have reached major hurricane strength. This latter increase suggests that there have been changes in the tropical environment other than SST increases that have proven conducive for the development of major hurricanes, as the average maximum SST encountered by storms that experienced SST greater than 28.25°C is similar during both periods (28.95°C vs. 29.28°C). Gaining a better understanding of these other changes is part of our ongoing research.

[16] Whether the general increase in SST in the North Atlantic tropical cyclone formation region during the past several decades is a result of global warming from an enhanced greenhouse effect, a natural change in the quasi-cyclic multi-decadal Atlantic hurricane regime, or some combination of these, the effect on Atlantic tropical cyclones has been significant. However, increased SST alone is not sufficient to explain all of the changes. Researchers [e.g., *Gray et al.*, 1997; *Landsea et al.*, 1999; *Goldenberg et al.*, 2001; *Bell and Chelliah*, 2006] have shown that in prior active periods, changes in other atmospheric characteristics, such as lapse rates, vertical wind shear, and moisture characteristics, have accompanied the SST changes. In some cases, such as for lapse rates, *Knutson and Tuleya* [2004] note that observed changes run counter to those projected by climate models to accompany an enhancing greenhouse effect.

4. Potential Implications

[17] It is tempting to speculate on what the observed relationship between SST and tropical cyclone intensity may mean for a warmed climate. One future scenario could be that SST will rise to the point that all tropical cyclones in the subtropical Atlantic encounter temperatures that exceed the 28.25°C threshold (note: *Henderson-Sellers et al.* [1998] suggest that the SST necessary for the development of major hurricanes may increase if the vertical lapse rate declines in the future as projected by climate models, but we

do not consider this effect here). This would require a general warming of SSTs in the tropical cyclone formation region of the Atlantic Ocean of about 2–3°C (Figure 3). During the period from 1982 to 2005, 195 out of 270 storms encountered SST greater than the 28.25°C threshold. A total of 58 of the 195 storms (29.7%) reached peak intensities of category 3 or greater. If we use the 1982–2005 period as an analog for the future under our scenario by assuming that all 270 storms encounter SST exceeding the 28.25°C threshold and that the same percentages hold true, 80 storms (29.7% of 270) would have attained wind speeds of category 3 or greater—a frequency increase of 37.9 percent over the number observed over the past quarter century. The peak wind speed averaged across all 270 storms would increase from 38.1 m/s (the current average of all storms observed during 1982–2005) to 40.5 m/s (the average of those storms from 1982 to 2005 that encountered SST exceeding the 28.25°C threshold)—an increase of 6.3%. Interestingly, these numbers are close to those calculated to occur by *Knutson and Tuleya* [2004], who modeled the effects on tropical cyclone intensity of a SST increase of about 2°C.

[18] Both our calculations and those of *Knutson and Tuleya* [2004] indicate that the effect of higher SST on tropical cyclone intensity is far less than could possibly explain the post-1994 changes in tropical cyclone characteristics relative to prior decades. Together, these findings indicate that the observed rise in Atlantic basin SST encountered by tropical systems during the past several decades (a rise of several tenths of a degree Celsius) as reported by *Emanuel* [2005] and *Webster et al.* [2005] would change storm characteristics by an amount generally too small to reliably measure (roughly an increase in the peak wind attained in storms of 1–2%). Furthermore, since a large portion of the observed SST rise in the Atlantic could be caused by factors other than greenhouse changes [see *Knight et al.*, 2005] it is not possible to state that anthropogenic activity has detectably influenced the observed pattern of Atlantic hurricane frequency and severity.

5. Conclusions

[19] We investigated the relationship between SSTs and tropical cyclone intensity in the North Atlantic Ocean for the period from 1982 through 2005, applying much higher resolution data than in previous studies, and tracked the relationship through a significant change in the Atlantic climatic regime. Typically, peak storm wind speeds do not occur over the location of the highest SST along the storm track. Instead, the peak wind occurs on average about 4.4 degrees latitude northward of the highest SST. A better indicator of the ultimate intensity reached by tropical cyclones is the highest SST encountered prior to the time of peak wind. However, within this relationship, there exists an apparent threshold SST that must be exceeded for a tropical system to attain wind speeds in excess of 50 m/s—the wind speed that defines a major hurricane (a storm of category 3 or greater). Once this threshold is exceeded, we find no relationship between storm intensity and SST. This suggests that rising SST will act to increase the percentage of major hurricanes but not change the ultimate intensity of these storm systems.

[20] Our results show that SST plays a relatively minor role in the observed characteristics of tropical storms and hurricanes in the North Atlantic Basin. As such, other factors must be involved in the increase in tropical cyclone activity recorded during the post-1994 Atlantic hurricane seasons. The full reason behind these observed changes remain an area of active scientific inquiry. We therefore recommend a cautious approach to assigning an underlying cause in this complex system.

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