2.4 SEA-SURFACE TEMPERATURES AND TROPICAL CYCLONES: BREAKING THE PARADIGM

Patrick J. Michaels*
University of Virginia, Charlottesville, Virginia and Cato Institute, Washington DC

Paul C. Knappenberger
New Hope Environmental Services, Inc., Charlottesville, Virginia

Robert E. Davis
University of Virginia, Charlottesville, Virginia

1. INTRODUCTION

There is a commonly-held belief that there is a direct and strong cause-and-effect linkage between sea-surface temperature (SST) and hurricane intensity. While, to a certain degree, this is true when examined over the entire range of SSTs encountered by tropical cyclones, the relationship is much less clear in the upper range of SSTs normally associated with these storms. Early modeling studies such as Emanuel (1987) indicated that warmer ocean waters, projected under conditions of increasing carbon dioxide, would increase the maximum possible hurricane intensity that could be attained and move the potential for stronger storms further to the north. He also introduced the notion of "hypercanes" into popularized science (Emanuel, 1988).

Indeed, as planetary temperatures have warmed, there is strong evidence for a perceived increase in hurricane strength (Figure 1), as indicated by the number of news stories relating hurricanes to global warming (Lexis-Nexis, 2004).

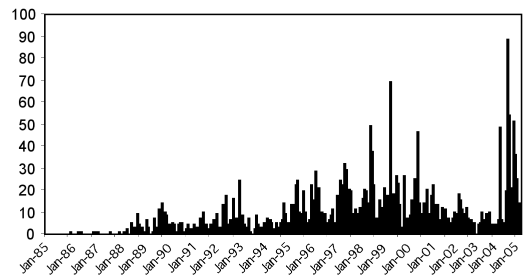

Figure1. Number of stories per month in major English language newspapers from around the world that included the terms "hurricanes" and "global warming."

2. BACKGROUND

The most prominent recent study examining the relationship between tropical cyclone strength and SSTs was conducted by Knutson and Tuleya (2004) who, using state-of-the-art modeling techniques, projected "a 14% increase in central pressure fall, a 6% percent increase in maximum surface wind speed, and an 18% increase in average precipitation rate" after eighty years, with models run with increasing carbon dioxide. In this study, the average correlation coefficient between SST and intensity (measured by central pressure) was -0.74, resulting in an explained variance of 55%.

Michaels et al. (2005) noted that the actual explained variance between SST indices and hurricane intensity (peak wind in the strongest storms, or number of strong storms) was much lower (around 10%), a result more consistent with Landsea et al. (1999) who found the explained variance between local SSTs and storm intensity measures to be between 3% and 10%. This is less than the variance explained between storm intensity and more global and teleconnected influences such as ENSO, stratospheric QBO, and Sahelian rainfall. Michaels et al. (2005) also noted that the Knutson and Tuleya result was dependent upon an unrealistic growth rate in atmospheric carbon dioxide and the assumption of no changes in vertical wind shear surrounding model-evolved hurricanes.

Corresponding author address: Patrick J. Michaels, Univ. of Virginia, Dept. of Environmental Sciences, P.O. Box 400123, Charlottesville, VA 22904-4123; e-mail: pjm8x@virginia.edu

In addition, while Michaels et al. (2005) found a statistically significant overall relationship between the peak wind speed in the strongest storms and SST anomalies, the result became statistically insignificant when they examined only the subset of higher than average SSTs, which are surely more representative of the potential state of future SST.

Michaels et al. (2005) also cautioned that the Knutson and Tuleya result was generated with an unrealistically large (1%/year) increase in carbon dioxide. Hansen (2001) and Michaels (2002, 2005) have commented that this must lead to overprediction of warming rates, at least in the next fifty years, and have concluded, given first-derivative trends in major emissions, that the global average warming during the coming half-century is likely to be approximately 0.8°C because of reduced emissions. Further, Covey et al. (2003) have stated that "the CMIP2 increasing-CO2 scenario…is also not a good estimate of future anthropogenic climate forcing, except perhaps as an extreme case in which the world accelerates its consumption of fossil fuels while reducing its production of anthropogenic aerosols."

Evans (1993), using monthly-averaged SST data resolved at 2 X 2° latitude/longitude, from 1967-86, 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. However, the use of monthly temperatures may have obscured some more transient relationships. Her general conclusion was that, "while SST may well provide an upper bound on tropical storm intensity, it is by no means the dominant factor in determining either the instantaneous storm intensity or the actual maximum intensity attained by a storm."

Evans hypothesized that the observation that hurricanes consistently reach their maximum intensity some distance away from the warmest waters they encounter is a result of the life cycle of many of the classic severe Cape Verde cyclones. These storms form over the very warm waters (29-30˚C) in the deep tropics and then as they increasingly deflect northward around the subtropical anticyclones, they encounter extensive areas of cooler water (although still above 27˚C). Having organized under warmer waters, they can continue to intensify via convective feedbacks while over slightly cooler water.

Here we examine the relationship between SST and Atlantic tropical cyclone intensity using weekly sea-surface temperatures as described in Reynolds et al. (2002), applicable to the period from 1982-2003, and a concurrent set of tropical cyclone data with little overlap with Evans (1993) whose analysis ended in 1986. Our analysis uses higher resolution SST data (both in space and time) and a tropical cyclone history occurring solely in a period of planetary warming that is largely thought to be of human origin. Evans (1993) data was equally divided between the Northern Hemisphere cooling, which ended around 1975, and the subsequent warming. Our study allows us to see if there have been any systematic changes in the intensity/SST relationship as the planet has warmed.

3. DATA AND METHODS

The Reynolds et al. (2002 and updates) data are resolved at 1 X 1˚ latitude/longitude, 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. Our hurricane data is the 'best track' file, HURDAT, from the National Hurricane Center (Jarvinen et al., 1984 and updates). This file contains six-hourly (0000, 0600, etc…) center locations and intensities. Location is given in tenths of a degree, and intensities are estimated one-minute surface wind speeds and minimum central pressure.

For each six-hourly storm report contained in HURDAT, we identified the corresponding Reynolds SST. These observations were generated originally from 229 tropical storms and hurricanes, from which we extracted maximum storm intensity, SST at time of maximum intensity, and highest SST encountered prior to, or concurrent with, maximum intensity.

4. RESULTS AND DISCUSSION

The shape of the overall relationship between SST and concurrent wind speed is very similar to that in Evans (1993), with an obvious peak in intensity below the maximum SST (Figure 2). This is also clear in Table 1 which aggregates the data in Figure 1 into 1°C-wide bins and within each bin (starting with 25°C) compares the number of observations of major hurricanes (Saffir-Simpson Category 3 or greater) with the total number of observations. Note that the percentage of strong cyclones peaks in the 28.0-28.9°C bin (1739 observations), despite the fact that eight percent of the observations (569 out of 6761) were under warmer conditions.

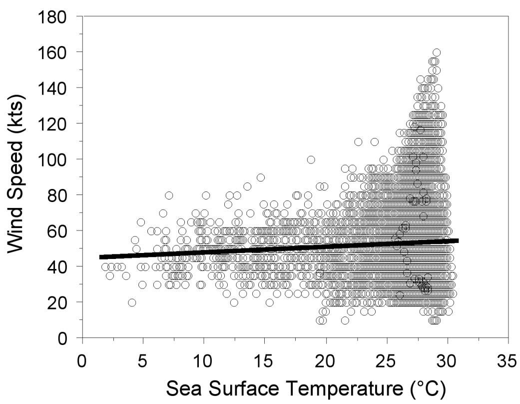

Figure 2. The relationship between wind speed and SST for the complete set of 6-hourly observations from an Atlantic basin tropical systems from 1982-2003. The regression line is statistically significant (N=6761, p<.0001, R-sq = 0.0024, slope=0.286)

Temp. Bin (°C)	Total Obs.	Cat. 3, 4, or 5	% Cat. 3, 4, or 5
25.0-25.9	534	7	1.31
26.0-26.9	905	31	3.43
27.0-27.9	1587	149	9.39
28.0-28.9	1739	225	12.94
29.0-29.9	519	30	5.78
30.0-30.9	17	0	0.00

Table 1. The results of aggregating the data in Figure 2 into 1°C-wide bins and within each bin (starting with 25°C) comparing the number of observations of major hurricanes (Category 3 or greater) with the total number of observations.

Similar results were obtained when we examined the 6-hourly observations aggregated into individual storm systems. In the case of Figure 3, we plot the maximum wind speed attained within each of the 229 identified Atlantic basin tropical cyclones against the maximum SST experienced prior to or concurrent with the time of maximum wind. These results are further aggregated into 1°C-wide bins in Table 2.

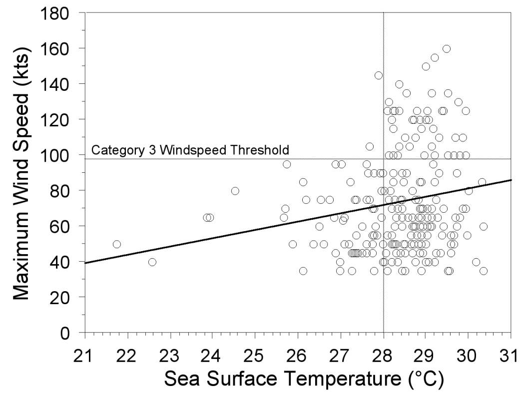

Figure 3. The relationship between maximum wind speed and the highest SST encountered prior to (or concurrent with) reaching the maximum wind speed for each of the 229 tropical cyclones studied. The regression line is statistically significant (N=229, p<.0032, R-sq = 0.0377, slope=4.64)

Temp. Bin (°C)	Total Obs.	Cat. 3, 4, or 5	% Cat 3, 4, or 5
25.0-25.9	4	0	0.00
26.0-26.9	14	0	0.00
27.0-27.9	43	2	4.65
28.0-28.9	101	26	25.74
29.0-29.9	57	21	36.84
30.0-30.9	5	0	0.00

Table 2. The results of aggregating the data in Figure 3 into 1°C-wide bins and within each bin comparing the number of observations of major hurricanes (category 3 or greater) with the total number of observations.

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. There is a considerable displacement between the latitude at which the maximum wind was reported versus the latitude at which the maximum SST was encountered in each of the 229 cyclones (Figure 4). The average difference was 4.9° latitude northward. (However, owing to the skewness of the relationship, fully 65% of cyclones reached their maximum winds within 5° latitude of their maximum encountered SST).

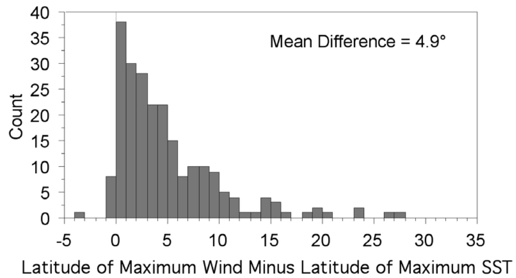

Figure 4. Difference in latitude between the location of maximum wind and the location of maximum SST for each of the 229 identified tropical cyclones in the Atlantic basin from 1982-2003.

Obviously the relationship between SST and intensity is not as straightforward or surely not as statistically strong as implied in the modeling studies of Knutson and Tuleya (2004). In fact, when we stratify the data in Figure 3 into Category 3, ,4 or 5 (major) hurricanes we find that while nearly all (47 out of 49) of the major hurricanes encountered SSTs that equaled or exceeded 28˚C, there is no significant relationship between maximum wind speed and SST above 28˚C (Figure 5). This suggests 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.

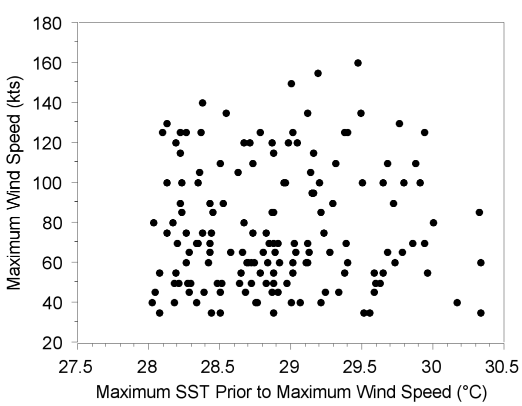

Figure 5. The relationship between maximum wind speed and the highest SST encountered prior to (or concurrent with) reaching the maximum wind speed at temperatures greater than or equal to 28ºC. The relationship is statistically insignificant (N=163, p=0.5471, R-sq = 0.002, slope=0.0009).

We can use these observed relationships to investigate how Atlantic tropical cyclones may evolve in a future in which the SSTs are higher than today's. Consider a scenario in which there is no water in the Atlantic hurricane basin cooler than 28˚C (this roughly represents a 2˚C average rise in basin temperature, similar to what was assumed in Knutson and Tuleya (2004)). A reasonable assumption is that, under this scenario, the same statistical breakdown between weak and strong storms would hold as today, as there is no other trend in intensity versus maximum encountered SST beyond this apparent 28°C threshold.

Under current conditions, 71% (163) of all (229) storms experience SST ≥ 28˚C prior to reaching their maximum intensity (as measured by wind speed). Of these storms, 29% attain a strength of Category 3 (wind speeds ≥96 knots) or higher. Thus, under a scenario where all storms encounter SSTs that exceed 28˚C, an additional 8% (29% x 29%) of storms would reach Category 3 or higher.

It is important to note, however, that while crossing the 28˚C threshold acts to increase the likelihood of attaining Category 3 or higher, moving beyond 28˚C does not act to further strengthen tropical cyclones.

Despite the large differences between modeled hurricanes and reality in the tightness of fit between intensity and SST, both modeled and observed increases in wind speed and frequency of major hurricanes are similar under a scenario of a 2˚C basin-wide SST increase. Knutson and Tuleya argued that an average warming of approximately 2˚C in the Atlantic Basin would increase average intensity "by roughly half a category."

In our sample, 49 of the 229 tropical cyclones reached Category 3 at some time in their life cycle. If we assume that there are *no* SSTs <28˚C encountered by storms in our sample, then they all move to the right of the "threshold," and if similar proportions obtain, then 8% of the total number of storms, or 18 of the 229 storms that hadn't reached Category 3, would indeed do so. Taking into account the number of observed storms during the period 1982-2003 that reached a maximum intensity of between Category 2.5 (>89kt and <96kt) and 3.0 (≥96kt), Knutson and Tuleya would suggest an increase of 16 major hurricanes over a 22-year period where basin temperatures average about 2˚C higher than today (effectively raising temperatures throughout the basin to 28˚C or higher).

A similar correspondence holds between the empirical data and the model results for potential wind speed changes. Again, if we assume that all temperatures in the hurricane formation and growth region of the Atlantic Basin exceed 28˚C, the average maximum wind speed attained would increase from the 1982-2003 average of 73.2 kts to the above 28˚C average of 77.0 kts, or 5.2%. Using their cyclone model, Knutson and Tuleya report an increase in the maximum surface wind of 6% under their 2˚C warming scenario.

How likely is a 2˚C rise in basin temperatures in the foreseeable future? Knutson and Tuleya arrive at this change in basin temperatures around model year 80 (circa-"2080") based upon the assumption of a 1% annual compound increase in carbon dioxide. However, for the last three decades, the increase rate has less than half of that, at 0.45%/year. Hansen et al. (2001, 2005) and others have argued that most of the warming in the next half-century is "in the pipeline" because of historical emissions; in other words much, of the realized forcing for at least half of the Knutson and Tuleya timeframe is in the range of half of their assumed value. If this graduated to 1%/year by year 40, then, at best, the overall warming would be 75% of the assumed total of 2˚C. If the same rate of emissions as observed now continued through model-year 80 (which is certainly more likely than a 1%/year increase starting in the first decade of the model period), the warming would by 1˚C. Consequently, it appears that our mutual estimates of change in wind speed or the number of major storms by year 80 are overestimates of tropical cyclone changes.

5. SUMMARY

We investigated hurricane behavior from 1982 through 2003, a period of human-induced warming, and found no systematic changes in the SST-intensity relationship described by Evans (1993). The explained variance between encountered SST and intensity was much lower in our studies than in a prominent modeling study of Knutson and Tuleya (2004).

We also found that 28˚C is an important threshold for the development of major hurricanes (Categories 3, 4, or 5) but, above that threshold there is no increase in intensity that is proportional to SST.

If we assume, as did Knutson and Tuleya (2004), an average warming of 2˚C in the Atlantic basin, a threshold analysis indicates 8% more major hurricanes, similar to their finding. However, their GCM was tuned with too large an increase in carbon dioxide, at least for the first half of its 80-year timeframe. The resultant average SST warming in this timeframe, when adjusted to more realistic levels, gives a basin warming of between 1˚C and 1.5˚C, resulting in changes in intensity and frequency of between _ and _ of their published values.

6. REFERENCES

Covey, C., K. M. AchutaRao, U. Cusbasch, P. Jones, S. J. Lambert, M. E. Mann, T. J. Phillips, and K. E. Taylor, 2003: An overview of Results from the Coupled Model Intercomparison Project (CMIP). *Global and Planetary Change*, **37**, 103-133.

Emanuel, K., 1987: The dependence of hurricane intensity on climate. *Nature*, **326**, 483–485.

Emanuel, K.,1988: Toward a general theory of hurricanes. *American Scientist*, **76**, 370-79.

Evans, J.E., 1993: Sensitivity of tropical cyclone intensity to sea surface temperature. *Journal of Climate*, **6**, 1133-1140.

Hansen, J. E., and M. Sato, 2001: Trends of measured climate forcing agents. *Proceedings of the National Academy of Sciences*, **98**, 14778-14783.

Hansen, J.E., et al., 2005. Earth's energy imbalance: confirmation and implications. *Sciencexpress*, April 28, 2005.

Jarvinen, B.R., Neumann, C.J., and M.A.D. Davis, 1984: A Tropical Cyclone Data Tape for the North Atlantic Basin, 1886-1983: Contents, Limitations, and Uses. *NOAA Technical Memorandum NWS NHC 22*, and updates. (http://www.nhc.noaa.gov/tracks1851to2004_atl.txt)

Knutson T. R., and R. E. Tuleya, 2004: Impact of CO2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterization. *Journal of Climate*, **17**, 3477-3495.

Landsea, C.W., Pielke, Jr., R.A., Mestas-Nuñez, A.M., Knaff, J.A., 1999: Atlantic basin hurricanes: Indices of climatic changes, *Climatic Change*, **42**, 89-129.

Lexis-Nexis, 2005. http://web.lexis-nexis.com/universe.

Michaels, P. J., P. C. Knappenberger, O. W. Frauenfeld, and R. E. Davis, 2002: Revised 21st century temperature projections. *Climate Research*, **23**, 1-9.

Michaels, P.J., Knappenberger, P.C., and C.W. Landsea, 2005: Comments on "Impacts of CO2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Scheme", *Journal of Climate*, in press.

Reynolds, R.W., N.A. Rayner, T.M. Smith, D.C. Stokes, and W. Wang, 2002: An Improved In Situ and Satellite SST Analysis for Climate. *Journal of Climate*, **15**, 1609-1625. (Available on-line at http://ingrid.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.weekly/)