Reply to comment by K. Emanuel on "Sea-surface temperatures and tropical cyclones in the Atlantic basin"

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1. Introduction

[1] Most recent studies of tropical cyclones and their relationship to changing environmental conditions, including sea surface temperatures (SST), have examined regional-scale seasonal averages in comparison with basin-wide seasonal tropical cyclone characteristics [e.g., *Emanuel*, 2005; *Webster et al.*, 2005; *Hoyos et al.*, 2006]. In our recent paper [*Michaels et al.*, 2006], we took a different approach. We examined the *local* SST (weekly averages contained in 1 × 1° degree gridcells) associated with each named tropical cyclone as it traversed the North Atlantic Ocean during the period 1982–2005. Aggregating the SST associated with the maximum storm intensity (as measured by wind speed) attained in each storm, we found that while overall (across the full range of SST) there exists a positive relationship between maximum storm intensity and SST, this relationship breaks down above 28.25°C. We identified this temperature (28.25°C) as both a threshold necessary to be reached for a tropical cyclone to reach major hurricane status (category 3 or higher on the Saffir-Simpson hurricane scale, sustained surface winds of at least 50 m/s), as well as the SST beyond which there is no longer a statistically significant relationship between maximum storm intensity and local SST in the collection of Atlantic tropical cyclones that make up our data set. We proposed that in a warming climate, higher SST would lead to a modest increase in mean maximum tropical cyclone wind speeds as an increasing number of storms encountered SST necessary to develop into major hurricanes. We noted that while we expected an increase in the number of major hurricanes, we did not expect to see an increase in the intensity of these storms.

[2] In his comment to our paper, *Emanuel* [2007] has concerns as to whether spatial patterns of storm tracks may have led us to overestimate the SST/intensity relationship at low SST, and that the available sample size may be insufficient to allow us to detect a significant relationship between SST and storm intensity at higher SST. New analysis presented here, along with the discussion and analysis provided by Emanuel, have led to a better understanding of these issues.

2. Space/Time Relationships

[3] *Emanuel* [2007] demonstrates that northward-moving tropical cyclones in the open waters of the North Atlantic Ocean eventually encounter unfavorable SST, and, at the same time, increasingly unfavorable atmospheric conditions. Emanuel proposes that this superposition leads to a greater apparent dependence of storm intensity on SST in these regions than actually exists, and the inclusion of this effect in our basin-wide climatology leads to an overestimation of the strength of the SST/intensity relationship at low SST. He suggests that this demonstrates the imprecision of using current SST/intensity relationships derived over space and time to project future behavior under changing climate conditions.

[4] In the projections made by *Michaels et al.* [2006], we assumed that the current SST/intensity relationship (as aggregated over the Atlantic basin during the period 1982–2005) would be representative of future conditions. However, a continued rise in SST will likely lead to a northward expansion of the region of critical SST for tropical cyclone formation as well as an expansion of the region containing critical SST for major hurricane development. However, as *Emanuel* [2007] points out, atmospheric conditions favorable for tropical cyclone development rapidly deteriorate at latitudes north of about 30°N—as the subsiding branch of the Hadley cell leads to drier and more stable conditions aloft. Therefore, SST/intensity relationships derived from the current climate may actually *overestimate* the tropical cyclone intensity increases expected from a northward expansion of higher SST. Unfavorable atmospheric conditions in the northern portion of the Atlantic basin would likely lead to a retardation of tropical systems in a region that, based upon SST considerations alone, would otherwise support tropical cyclone development and intensification.

3. Sample Size and Statistical Significance

[5] *Emanuel*'s [2007] other major concern is that the total number of storms in our study period (270) is too small, which is the reason behind our finding that no statistically significant relationship between SST and intensity exists above 28.25°C. To address this concern, Emanuel simulates the development and motion of 3,000 tropical cyclones across the North Atlantic based upon climatological derivations of observed storm characteristics as well as atmospheric conditions. From this population of synthetic

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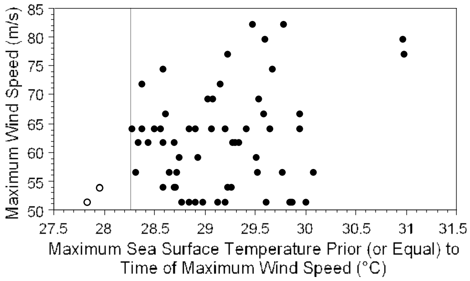

Figure 1. Scatterplot of maximum wind speed and the highest SST encountered prior to (or concurrent with) reaching the maximum wind speed for all Atlantic basin major (category 3, 4, 5) hurricanes. The two storms in the lower left (open circles) did not encounter the 28.25°C threshold (vertical line) that is typically a prerequisite for major hurricane development.

tropical cyclones, he repeats our analysis and finds much as we reported—that the correlation of storm intensity with SST, or in his case, potential intensity (which is strongly related to SST), is statistically *insignificant* at the upper end of the range. Emanuel writes "This lack of correlation, as stated by MKD [*Michaels et al.*, 2006], is owing to the large scatter of storm intensities for a given potential intensity, reflecting the influence of other environmental factors such as wind shear." This was indeed our conclusion. Despite running a simulation with a sample size that was more than 10 times greater than ours, Emanuel still reports the relationship between tropical cyclone intensity and SST (or potential intensity) to be insignificant at high SSTs. This finding lends support to our contention that SST does not strongly determine the ultimate intensity of major tropical cyclones in the Atlantic basin.

4. Future Projections

[6] *Emanuel* [2007] then reruns his 3,000 synthetic tropical cyclones in an environment in which the potential intensity is increased by 10 percent. From this analysis, he reports that the mean wind speed in all storms is 17% greater than in the original runs. He concludes that this refutes our central hypothesis that temporally increasing SST (or potential intensity) "will have no significant effect on tropical cyclone activity." However, we never make this claim. A careful reading of *Michaels et al.* [2006], reveals that, in fact, we found nearly the opposite. In *Michaels et al.* [2006], we ran an analysis very similar, in effect, to the one run by Emanuel—we consider what impact a SST rise of 2–3°C across the active tropical cyclone regions of the North Atlantic will have on future storm characteristics based upon the observed relationships that we established. We projected that average maximum wind speeds would increase by about 6% and that the frequency of major hurricanes would increase by nearly 40%—findings similar to model-based projections [e.g., *Knutson and Tuleya*, 2004] and also comparable to those reported by Emanuel.

[7] *Emanuel* [2007] further notes that the absolute maximum wind speed in his synthetic storm sample, as well as the average maximum wind speed of the most intense 10% of events, is higher in his enhanced potential intensity experiment, and goes on to state that there isn't "any indication that maximum wind speed achievable in hurricanes levels off at high sea surface temperatures; both theories and models show a smooth, continuous increase." However, actual *observations* are not as persuasive. To demonstrate this, we examine the relationship between SST and maximum wind speed within the collection of the 60 major hurricanes that formed in the Atlantic basin between 1982–2005 that encountered SST above the 28.25°C threshold prior to reaching maximum wind speed (Figure 1). A simple least-squares linear regression line through all 60 of these major hurricanes when plotted against SST is statistically insignificant ($N = 60$, $p = 0.0713$, $R^2 = 0.047$, slope = 3.14 m/s/°C). However, there were also two Atlantic tropical cyclones that reached major hurricane strength without passing over water that reached the 28.25°C threshold. With the inclusion of these two events, the regression slope does become statistically significant at the $p = 0.05$ level ($N = 62$, $p = 0.0347$, $R^2 = 0.072$, slope = 3.71 m/s/°C). This demonstrates the sensitivity of the analysis to outlier events and suggests that the estimated regression slope is not robust. To better account for this instability, we ran a 10,000 replication bootstrap procedure in which we randomly drew, with replacement, 62 events from the existing population and then regressed storm intensity with SST. The result of this procedure was an average slope of 3.55 m/s/°C that was statistically insignificant at the 1-in-20 level. Thus, our conclusion is that during the past 24 years, observations do not indicate that the intensity of major hurricanes is strongly and/or clearly dependent on SST.

[8] That other factors besides SST are responsible for the recent increase in Atlantic tropical storm activity is further evidenced by *Emanuel*'s [2007] own results. He reports that when he increases the potential intensity by 10% and then reruns all 3,000 modeled tropical cyclones, the average intensity in the modeled storms increases by 17% while the average power dissipation index (PDI) increases by 66% "consistent with the actual change in PDI over the past 15 years." However, he goes on to state that the observed potential intensity in the main development region of the tropical Atlantic ocean has increased by 10% since 1980, or during the past *twenty-five* years. As Figure 1 of Emanuel shows, the PDI calculated from actual (rather than modeled) storms since 1980 has nearly tripled. The observed tripling of the PDI accompanying an observed increase of potential intensity of 10% is far beyond the response predicted by Emanuel's modeling exercise, and is strong indication that factors other than potential intensity (SST) have played major roles in enhancing the frequency and intensity of Atlantic tropical cyclones during the past several decades.

5. Conclusions

[9] We thank *Emanuel* [2007] for analyses that provide further detail about the complex relationship between SST and tropical cyclone intensity in the Atlantic basin. In agreement with *Michaels et al.* [2006], Emanuel's model-based findings confirm the lack of a strong, statistically significant SST signal in the average intensity of tropical cyclones encountering high SST (i.e., above the 28.25°C threshold). There is, however, some indication that higher SST may lead to more intense strong storms. Currently,

observations can neither confirm nor refute that relationship. We do not contend that increasing SST has not, or will not, influence the intensity or frequency of Atlantic tropical cyclones. We have demonstrated in our initial findings [*Michaels et al.*, 2006], and Emanuel has furthered in his comments, that a modest impact is likely. However, the overall weakness in the relationship between SST and storm intensity indicates that SST is only one of myriad determinants of tropical cyclone strength. This complicates clear attribution of observed or future changes. These results reaffirm our original conclusions that the full reason for the observed changes in tropical cyclone activity in the North Atlantic has yet to be established, and that "we therefore recommend a cautious approach to assigning an underlying cause in this complex system [*Michaels et al.*, 2006]."

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