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Comment on "Sea-surface temperatures and tropical cyclones in the Atlantic basin" by Patrick J. Michaels, Paul C. Knappenberger, and Robert E. Davis

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1. Introduction

[1] *Michaels et al.* [2006] (hereinafter referred to as MKD) analyze the relationship between observed tropical cyclone intensity and sea surface temperature (SST) and reaffirm the well-known result that SST is only one of several environmental factors that influence the intensity of individual storms. But they make two errors of inference, one physical and the other statistical, that lead them to overestimate the true dependence of storm intensity on SST when the latter is low, and to seriously underestimate it when it is high. They further deduce that since SST is a minor influence on individual storm intensity, it must necessarily be a minor influence on aggregate storm statistics, and that the average maximum intensity of hurricanes would be unaffected by climate change. Here I show that both these deductions are false.

2. SST Versus Potential Intensity

[2] MKD analyze the relationship between observed Atlantic tropical cyclone maximum wind speed and SSTs. As in previous such analyses (e.g. [*Evans*, 1993]), both the mean and upper bound of the maximum winds speeds are strongly dependent on SST when the latter is in the range of ~23–28°C, but the sensitivity apparently drops off markedly and may even reverse sign at higher SSTs.

[3] MKD assume that this SST dependence is universal and is independent of whether the SST variations are spatial or temporal. A close inspection of the data, however, belies this assumption. It is first important to recognize that the actual thermodynamic control of tropical cyclone intensity is exercised through the potential intensity, which depends mostly on SST and the entropy-weighted mean temperature of the storm's outflow. Climatological spatial distributions of potential intensity (available at http://wind.mit.edu/~emanuel/pcmin/climo.html) show very sharp gradients near the position of the 26°C SST isotherm, but these are almost entirely owing to sharp gradients in the outflow temperature, not to SST gradients per se [*Emanuel*, 1986]. (This results from the fact that in the subtropics, boundary layer air reaches buoyant equilibrium at the level of the Trade inversion, far lower, and therefore warmer, than the tropopause.) Since outflow temperatures are themselves highly correlated with SST, one is easily led to the false conclusion that potential intensity is highly sensitive to SST in the range centered at 26°C. The strong gradient of potential intensity with respect to SST in this range is owing to strong gradients in outflow temperature and would not translate, for example, to an equally strong dependence of potential intensity on temporal variations of SST when the outflow temperature is held constant.

3. Empirically Deduced Dependence of Storm Intensity on SST When the Latter is High

[4] An equally serious but different problem arises in inferences made by MKD about the dependence of storm intensity on SST near the upper range of the latter. As shown by *Emanuel* [2000], there is an equal probability that a given, randomly selected storm will achieve any intensity up to its potential intensity; this is owing to the myriad environmental processes that act to reduce the intensity of real storms. In any real sample of storms, there will be only a finite number of storms in any given interval of SST. For certain intervals, such as 26–27°C in the present climate, there is a large population of events and the distribution all the way to the potential intensity is well populated. But as one moves toward the highest observed SSTs, which occupy only a very small portion of the area, the population diminishes and the probability of finding a storm near its potential intensity correspondingly declines. For example, there may be a very small patch of ocean whose temperature is above 31°C, but the probability of any Category 5 storm passing over this is very small. Thus the small sample of events at very high SSTs yields a decided negative bias in estimates of the upper bound of the wind speed distribution and introduces a random element in attempts to detect trends in the mean intensity at very high SST. In addition to this problem, MKD plot peak storm intensity against the maximum SST that the storm encountered any time up to the time of peak intensity; given that this time lag may be many days and that the response time of tropical cyclones to changes in their environment is of order 15 hours, this is unphysical. Thus the conclusion of MKD that there is little

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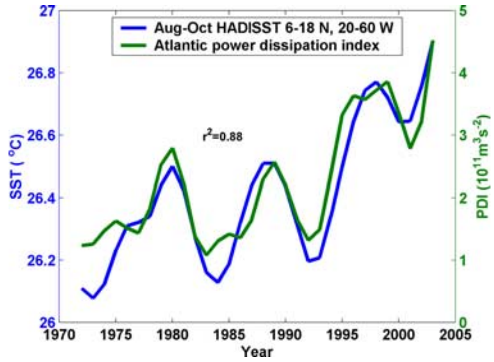

Figure 1. Time series of the August–October sea surface temperature averaged over the region 6–18 N, 20–60 W (blue), versus the power dissipation index of Atlantic hurricane activity (green). Both times series have been smoothed with a 1-3-4-3-1 filter to emphasize variability on time scales of three years and longer. Sea surface temperatures are from the Hadley Centre (HadISST1), and tropical cyclone power dissipation is from HURDAT data.

dependence of tropical cyclone intensity on SST when the latter is higher than 28.25°C is unwarranted.

4. Aggregate Versus Individual Relationships

[5] In the last paragraph of their paper, MKD state that since SST is only one of several influences on the behavior of individual tropical cyclones, it follows that factors other than SST must have been responsible for the post-1994 increase in aggregate tropical cyclone metrics, such as those reported by *Emanuel* [2005]. This conclusion is demonstrably false. We have already seen that factors other than potential intensity act in the aggregate to reduce actual storm intensity, but that peak storm intensity, normalized by potential intensity, obeys a universal cumulative frequency distribution. This implies that a fractional increase in the potential intensity will lead to the same fractional increase in the intensity of a sufficiently large sample of events. The key physical effect that explains this is that whereas potential intensity varies slowly in time and space, other environmental factors such as wind shear vary rapidly and have a variance large compared to any temporal trends in their average values. In point of fact, as shown in Figure 1, temporally smoothed SST explains 88% of the variance of smoothed tropical cyclone power dissipation in the period 1970–2005, when the Atlantic hurricane data is considered most robust; adding as a predictor the 850-250 hPa vertical shear over the same region (derived from NCEP re-analysis data) only increases the variance explained from 88.2% to 88.5% (Shear, by itself, explains 52% of the variance of *PDI*, but shear and SST are also correlated with an r^2 of 53%.).

5. An Illustration

[6] Recently, the author and colleagues presented a new technique for deriving tropical cyclone climatologies from a combination of space-time genesis statistics, atmospheric general circulation statistics, potential intensity, and upper ocean thermodynamic profiles [*Emanuel et al.*, 2006]. The genesis and atmospheric circulation statistics are used to generate a large sample of synthetic tropical cyclone tracks, and a very high resolution, coupled atmosphere-ocean model is then run along each track to generate time-evolving wind fields. Both the track direction and speed statistics and the intensity statistics derived from this method compare very well to equivalent statistics from post-1970 hurricane data, as contained in the HURDAT record. We here use a sample of 3000 North Atlantic events to generate key statistics to compare and contrast to the technique presented by MKD.

[7] Figure 2 plots the storm lifetime maximum wind speed against the concurrent potential intensity. This can be compared to Figure 1 of MKD, who used instead the maximum SST up until the time of peak intensity. As expected, the distribution in Figure 2 is more uniform, with a more nearly linearly increasing upper bound. There is no tendency for the slope of the upper bound to decrease at high intensity, but note that at the very highest end of the range of potential intensity, there are too few events to populate the whole range of intensity up to the upper bound. *In either case, the correlation of storm intensity with potential intensity when the latter exceeds 120 knots is statistically insignificant*, in agreement with MKD. This lack of correlation, as stated by MKD, 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.

[8] To test MKD's inference from the above result that temporally increasing potential intensity will cause no appreciable increase in actual storm intensity, we re-ran all 3000 events with a single change: the potential intensity was increased everywhere by 10%. (All other factors, including the storm tracks and shear, were left unchanged.) This results in a 17% increase in the mean wind speed of all storms and a 66% increase in the power dissipation index, a measure of total energy generation by tropical cyclones over their lifetimes. When changes in the observed frequency of

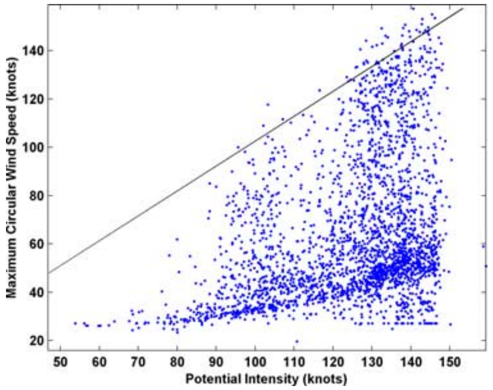

Figure 2. Scatter plot showing the storm lifetime maximum circular component of the wind speed, with the translation velocity removed, against the potential intensity at the time of maximum wind speed. Storms moving rapidly from warm to cold water have been omitted. The black line shows maximum wind speed equal to potential intensity. The data are taken from 3000 synthetic storm tracks as described briefly in the text and in more detail in the work of *Emanuel et al.* [2006].

Atlantic tropical cyclones are accounted for, this is consistent with the actual change in power dissipation index over the past 15 years shown in Figure 1, given that the August–October mean potential intensity of the main development region of the tropical North Atlantic (6–18 N, 20–60 W) has increased about 10% since 1980, according to NCEP re-analysis data. Moreover, the maximum wind velocity in each sample of 3000 events increases from 160 knots to 180 knots, while the average storm lifetime maximum wind of the most intense 10% of the events increases from 129 knots to 148 knots. By contrast, increasing the magnitude of the shear by 10% decreases the power dissipation index by only 12%.

6. Summary

[9] MKD's central hypothesis is refuted: Lack of correlation of high intensity events with SST (or potential intensity) in a particular climate does not imply that temporally increasing potential intensity (SST) will have no significant effect on tropical cyclone activity; indeed observed time trends in tropical cyclone energy are highly significant and strongly correlated with SST, as observations clearly show. Nor is there any indication that the maximum wind speed achievable in hurricanes levels off at high sea surface temperature; both theories and models show a smooth, continuous increase. MKD's conclusion that tropical cyclone intensity depends on SST only in a certain range of the latter is likewise false, arising from a confusion between spatial gradients of potential intensity, that depend mostly on the very large increase of outflow temperature from the tropics to the subtropics, with variability within the tropics, where the outflow temperature is less variable.

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