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

Kerry Emanuel[1]

Michaels et al. [2006] analyze the relationship between observed tropical cyclone intensity and sea surface temperature (SST) and confirm the well-known result that SST is only one of several environmental factors that influence the intensity of individual storms. Here I point out 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. Moreover, the notion that since SST is a minor influence on individual storm intensity it must necessarily be a minor influence on aggregate storm statistics does not hold up to scrutiny.

1. Introduction

Attempts to understand and forecast the intensity of tropical cyclones have led to the identification of several environmental factors that influence storm intensity (e.g. *Gray*, [1982]). The most successful statistical forecast methods in use today confirm that the most important factors are the potential intensity (usually but improperly considered to be a function of SST alone) and environmental wind shear [*DeMaria and Kaplan*, 1999], and more recent research has also revealed the importance of factors such as ocean mixed layer thickness and storm translation speed that affect the storm's interaction with the upper ocean [*Schade and Emanuel*, 1999].

Most if not all of the environmental factors other than potential intensity serve to diminish the intensity of tropical cyclones [*Emanuel et al.*, 2004]. Analysis of large samples of historical storms show that the aggregate effect of these influences yields a universal, linear cumulative distribution of tropical cyclone maximum winds speeds normalized by potential maximum wind speeds [*Emanuel*, 2000]. This shows that there is an equal probability of any randomly selected storm to achieve any intensity up to its potential intensity, a testament to the strong influence of these other factors. Although SST is not always a good proxy for potential intensity, plots of storm maximum wind speed against SST, such as that shown in Figure 1 of *Michaels et al.* [2006] (hereafter MKD), reveal that storm intensity is nearly uniformly distributed up to an SST-dependent upper bound. Most storms fall well short of their potential intensity.

2. SST vs. potential intensity

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 ^{o}C, but the sensitivity apparently drops off markedly and may even reverse sign at higher SSTs.

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[2] show very sharp gradients near the position of the 26 ^{o}C SST isotherm, but these are almost entirely owing to sharp gradients in the outflow temperature, not 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 ^{o}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

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 discussed in the Introduction, there is an equal probability of a given storm to achieve any intensity up to its potential intensity. 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 ^{o}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 ^{o}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 dependence of tropical cyclone intensity on SST when the latter is higher than 28.25 ^{o}C is unwarranted.

4. Aggregate versus individual relationships

In the last paragraph of their paper, MKD state that since SST is only one of several influences on the

[1] Program in Atmospheres, Oceans, and Climate, Massachusetts Intitute of Technology, Cambridge, MA 02139

[2] See http://wind.mit.edu/~emanuel/pcmin/climo.html

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, SST explains 88% of the variance of 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) increases the variance explained from 88% to 88.5%. As pointed out by MKD, the sensitivity of power dissipation implied by Figure 1 exceeds that from earlier model predictions by *Knutson and Tuleya* [2004]. Given the low resolution of that model, and other issues, it is premature to throw out this very clear signal in the data in favor of the model results.

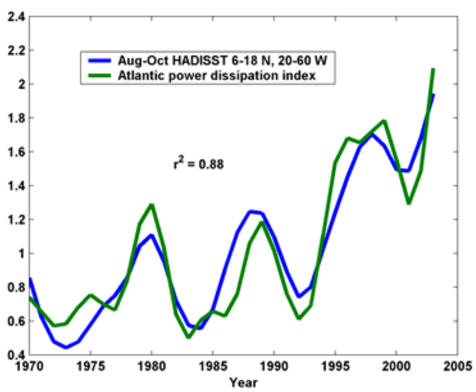


Figure 1. Time series of the August-October sea surface temperature averaged over the region 6-18 N, 20-60 W (blue), versus the power dissipation index of Atlantic hurricane activity (green). Both times series have been smoothed with a 1-3-4-3-1 filter to emphasize variability on time scales of three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

5. An illustration

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. As in *Emanuel et al.* (2006), the genesis statistics are taken from post-1970 HURDAT genesis points, monthly mean upper ocean thermal profiles from *Levitus* [1982] are used, and monthly mean potential intensity and 250 an 850 hPa wind covariances (from daily data) are derived from NCEP re-analysis data.

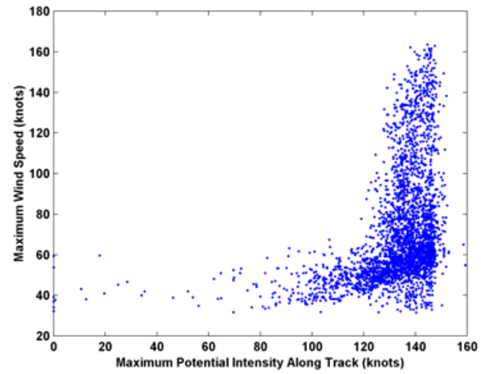
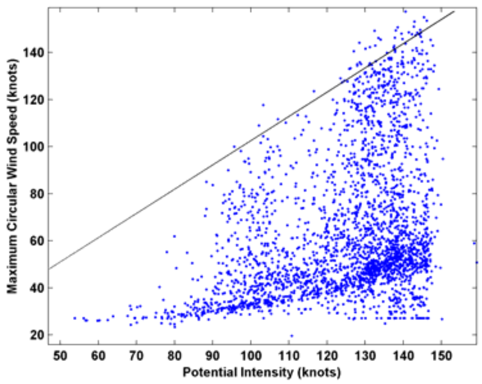


Figure 2. Scatter plot showing storm lifetime maximum wind speed (ordinate) against the maximum potential intensity that occurred along each storm track prior to the time of maximum wind speed. The data are taken from 3000 synthetic storm tracks as described briefly in the text and in more detail in *Emanuel et al.* [2005].

Figure 2 shows the storm lifetime maximum wind speed plotted against the maximum value of the potential intensity that occurred prior to the time of maximum wind speed. This can be compared to Figure 1 of MKD, though they used SST rather than potential intensity. The distributions are very similar. Figure 3, on the other hand, plots the storm lifetime maximum wind speed against the concurrent potential intensity. In order to compare to potential intensity, we here use the maximum speed of the azimuthally averaged flow, which does not account for translation speed, and omit cases of storms moving rapidly from warm to cold SSTs, for which the actual intensity transiently can greatly exceed the potential intensity. As expected, this distribution is more uniform, with a more nearly linearly increasing upper bound. Note that at the very highest end of the range of potential intensity, in both cases, the paucity of events leads to an apparently dramatic decline of the upper bound on storm intensity. *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.

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. This is consistent with the actual change in power dissipation index over the past 15 years, as shown in Figure 1, while 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.

Thus 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.

6. Summary

Long-term variability and trends of observed, basin-wide metrics of tropical cyclone activity are very well correlated with potential intensity (SST). This observation is well supported by tropical cyclone models that have sufficiently high resolution of the inner core. Other environmental factors have only a small influence on these aggregated metrics. Notwithstanding these observations and model results, individual storms are strongly affected by these other environmental factors, especially wind shear. When unaggregated tropical cyclone records are compared to potential intensity (or SST), the large, random variability introduced by these other, rapidly varying environmental factors strongly masks the underlying correlation with potential intensity and leads MKD to falsely conclude that increasing potential intensity (SST) has a negligible effect on aggregate tropical cyclone activity. Their 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.

The high correlations and high sensitivity of basin-wide, aggregated metrics of tropical cyclone activity with potential intensity (and SST) in the post-1970 North Atlantic, where tropical cyclone and sea surface temperature measurements are most robust, belie the projections by MKD that global warming will have a minor effect on tropical cyclone activity, based as they are on a poorly conceived analysis of the data and low resolution model results. The data and properly resolved models show otherwise.

References

DeMaria, M., and J. Kaplan (1999), An updated Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic and eastern North Pacific basins, *Wea. and Forecast.*, *14*, 326-337.

Emanuel, K., C. DesAutels, C. Holloway, and R. Korty (2004), Environmental control of tropical cyclone intensity, *J. Atmos. Sci.*, *61*, 843-858.

Emanuel, K.A. (1986), An air-sea interaction theory for tropical cyclones. Part I., *J. Atmos. Sci.*, *42*, 1062-1071.

Emanuel, K.A. (2000), A statistical analysis of tropical cyclone intensity, *Mon. Wea. Rev.*, *128*, 1139-1152.

Emanuel, K.A. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686-688.

Emanuel, K.A., S. Ravela, E. Vivant, and C. Risi (2006), A statistical-deterministic approach to hurricane risk assessment, *Bull. Amer. Meteor. Soc.*, *19*, 299-314.

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

Gray, W.M., Tropical cyclone genesis and intensification, in *Joint Symposium (IUTAM/IUGG) on Intense Atmospheric Vortices, Reading, Eng., July 14-17, 1981*, pp. 3-20, Springer-Verlag, N.Y., 1982.

Knutson, T.R., and R.E. Tuleya (2004), Impact of CO_2 -induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization, *J. Climate*, *17*, 3477-3495.

Levitus, S. (1982), Climatological atlas of the world ocean. National Oceanic and Atmospheric Administration,, U.S. Government. Print. Off, Washington, D.C.

Schade, L.R., and K.A. Emanuel (1999), The ocean's effect on the intensity of tropical cyclones: Results from a simple coupled atmosphere- ocean model, *J. Atmos. Sci.*, *56*, 642-651.