On the Increasing Intensity of the Strongest Atlantic Hurricanes

James B. Elsner and Thomas H. Jagger

Abstract The past three decades have seen a significant upward trend in the intensity of the strongest hurricanes worldwide that is most pronounced over the North Atlantic. Questions remain about this trend especially its relevance to coastal communities in the United States and elsewhere. This chapter focuses on observed changes in the intensity of the strongest hurricanes over the North Atlantic basin and on the spatial pattern of these changes. Results show that the upward trend is significantly related to rising sea-surface temperature (SST) after accounting for El Niño. The trend peaks at 16 m s^{-1} per $^\circ$C at the 75th percentile with a 90% confidence interval of between 7 and 20 m s^{-1} per $^\circ$C. The consequences of increasing intensity of the strongest hurricanes is not confined to the open ocean as nearly 70% of all hurricanes that occur over the basin reach a lifetime maximum intensity west of 60°W longitude. The largest intensity increases are occurring over the Gulf of Mexico and the Caribbean Sea, where ocean temperatures are warmest and hurricanes are strongest. Decreases in intensity are noted along most of the United States coastline consistent with a hypothesis that continental aerosols act to decrease hurricane intensity. This might help explain why, despite the increasing intensity of basin-wide hurricanes, there is no detectable upward tend in damage costs in the United States.

1 Introduction

Hurricanes are getting stronger on average with a recent trend that is related to an increase in ocean temperatures over the Atlantic and elsewhere (Emanual 2005, Webster et al. 2005). Indeed our paper entitled "The increasing intensity of the strongest tropical cyclones" published in September of 2008 (Elsner et al. 2008) generated

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considerable attention in the hurricane research community. The purpose of this chapter is to examine the evidence for trends in the strongest Atlantic hurricanes in more detail and to provide rejoinders to some of concerns that were raised about our methods and findings on blogs and especially on the *tropical storms mailing list*.

In particular here we show three new aspects of our original result. (1) The strongest hurricanes are getting stronger and the increase is related to an increase in sea-surface temperature (SST) after statistically controlling for the El Niño cycle. (2) Hurricanes often have a lifetime maximum intensity relatively near the coast of the United States. (3) The largest increase in the intensity of the strongest hurricanes is occurring over the Caribbean Sea and Gulf of Mexico where ocean temperatures are the warmest in the basin and where hurricanes tend to be the strongest.

At present hurricanes cannot be resolved in climate models, and the complex relationships between climate and hurricane frequency, intensity, and location are not well understood. Moreover, hurricanes and climate processes extend over a broad range of spatial and temporal scales making it difficult to model the potential relationships with a low-order numerical model. Thus in order to shed light on questions concerning the relationships between hurricanes and climate it is necessary to rely on the available historical data while keeping in mind data limitations and what we might expect to see in the data from theory.

As an example, there is no empirical evidence, modeling result, or theoretical argument that indicates the number of hurricanes will increase in a warmer world. On the other hand, relying on the notion of *ceteris paribus*, we can say that warmer oceans should lead to stronger hurricanes. To detect this signal in historical records, it is necessary to separate hurricane frequency from hurricane intensity. Our approach is to use quantiles of lifetime maximum hurricane intensity and to quantify trends and examine statistical significance of quantile intensities using quantile regression.

This chapter is outlined as follows. A brief description of the hurricane and climate data is provided in Sect. 2. Here we use the HURDAT data hourly interpolated over the period 1943–2008, inclusive. In Sect. 3 a short introduction to quantiles is given followed in Sect. 4 by the results of a quantile regression of hurricane intensity on SST and El Niño. Results from the regression model verify that the strongest hurricanes are getting stronger as SST increases after statistically controlling for El Niño. The geographic distribution of lifetime maximum intensities are considered in Sect. 5. Areas near the Gulf coast and Florida are relatively more frequently visited by hurricanes near the time of their lifetime maximum than areas farther east over the open ocean. In Sect. 6 changes over time in the geographic distribution of maximum intensity of hurricanes are examined. The Gulf of Mexico and the Caribbean Sea are regions where some of the strongest Atlantic hurricanes occur and where the trend toward stronger hurricanes is most notable. The summary and conclusions are given in Sect. 7. The chapter ends with replies to comments made about our earlier research on this topic.

2 Data

As is customary in this kind of research, tropical cyclone wind speed estimates are obtained from the HURricane DATa base (HURDAT or best-track) maintained by the US *National Ocean and Atmospheric Administration* (NOAA) *National Hurricane Center* (NHC). HURDAT is the official record of tropical cyclone information for the Atlantic Ocean, Gulf of Mexico and Caribbean Sea, including those that have made landfall in the United States. HURDAT consists of the 6-hr position and intensity estimates for tropical cyclones back to 1851 (Jarvinen et al. 1984, Neumann et al. 1999). Here a natural spline interpolation is used to obtain positions and wind speeds at 1-hr intervals from the 6-hr values based on the work of Jagger and Elsner (2006).

For the present study we consider only tropical cyclones at hurricane intensity or above ($\geq$ 33 m s^{-1}) over the period 1943–2008, inclusive. The period is long enough to examine temporal changes but not too long that it includes data from the pre-aircraft reconnaissance era (prior to 1943). There are $N = 409$ hurricanes over the 66-year period. The raw wind speed values are given in 5 kt (2.5 m s^{-1}) increments. Although knots (kt) are the operational unit used for reporting tropical cyclone intensity to the public in the United States, here we use the MKS units of m s^{-1} . Throughout this chapter we use the term “intensity” as shorthand for “maximum wind speed,” where maximum wind speed refers to the estimated fastest wind velocity somewhere in the core of the hurricane. Lifetime maximum refers to the highest maximum wind speed throughout the lifetime of the hurricane.

On the seasonal time scale and to a first order a warm ocean and a calm atmosphere (low wind shear) allows hurricanes to intensify. Some of the wind shear is related to the El Niño-Southern Oscillation (ENSO) cycle. Here we include data on the Southern Oscillation Index (SOI) as an indicator of ENSO and data on Atlantic SST as an indicator of ocean warmth. ENSO is characterized by basin-scale fluctuations in sea-level pressure between Tahiti and Darwin. The SOI is defined as the normalized sea-level pressure difference between Tahiti and Darwin. The SOI is strongly anti-correlated with equatorial Pacific SST so that an El Niño warming event is associated with negative values of the SOI. Units on the SOI values are given in standard deviations indicating they are standardized by the long-term mean and standard deviation. The relationship between ENSO and hurricane activity is strongest during the hurricane season, so we use an August–October average of the SOI as our covariate (explanatory variable). The monthly SOI values (Ropelewski and Jones 1997) are obtained from the Climatic Research Unit (CRU).

The United Kingdom Hadley model SST and U.S. NOAA optimal interpolated SST datasets were used to compute Atlantic SST anomalies in $^{\circ}$C north of the equator. Anomalies are computed by month using the base period 1951–2000. Data are obtained from the NOAA-CIRES Climate Diagnostics Center back to 1871. For this study we average the SST anomalies over the peak hurricane season months of August through October. Monthly global temperature anomalies (1961–90 base period) from the Intergovernmental Panel on Climate Change (IPCC) values are obtained from the CRU (Folland et al. 2001).

3 Quantiles and hurricane intensity

Quantile regression, introduced by Koenker and Bassett (1978), extends the ordinary least-squares regression model to conditional quantiles of the response variable. It is used in Elsner et al. (2008) and Jagger and Elsner (2008) to examine trends in the intensity of tropical cyclones. Before considering our application of quantile regression using hurricane intensity we say a few words about quantiles and hurricane intensity.

Quantiles are points taken at regular intervals from the cumulative distribution function of a random variable. The quantiles mark a set of ordered data into equal-sized data subsets. For example, of the 409 hurricane intensity values in our North Atlantic data set, 25% of them are less than 39 m s^{-1}, while 50% are less than 47 m s^{-1}. Thus there is an equal number of hurricanes with intensities between 33 and 39 m s^{-1} as there is between 39 and 47 m s^{-1}. When we say that the median maximum hurricane intensity is 47 m s^{-1}, we mean that half of all hurricanes have intensities less than this value and half have intensities greater than this value. Similarly, the quartiles (deciles) divide the sample of hurricane intensities into four (ten) groups with equal proportions of the sample in each group. The quantiles, or percentiles, refer to the general case of dividing the intensities into any number of groups.

Quantiles values of hurricane intensity are not directly tied to the frequency of hurricanes. This is important to understand before examining how the quantiles might be changing over time. Suppose for instance that in some earlier year there occur 4 hurricanes with maximum wind speeds of 33, 38, 48, and 53 m s^{-1}, and that in some later year there occur 3 hurricanes with maximum wind speeds of 33, 43 and 61 m s^{-1}. Then using only these two years we can see that there is a decrease in the frequency of hurricanes yet there is no change in the mean intensity (46 m s^{-1}) nor is there a change in the median intensity (43 m s^{-1}). However, there is an increase in the quantile values of wind speed above the median. For instance, the 75th percentile increases from 49 to 52 m s^{-1} and the 90th percentile increases from 52 to 57 m s^{-1} over this period.

Others have argued that the percentage of strong hurricanes to total number of hurricanes is the important index for detecting change in hurricane activity (Webster et al. 2005). Consider another example, where in the earlier year there are only 3 hurricanes with maximum speeds of 33, 40 and 50 m s^{-1} and where the later year is the same as before. Then the ratio of major hurricanes ($\geq$ 50 m s^{-1}) remains the same yet the strongest hurricane is stronger. Thus we argue that the intensity of the strongest hurricanes as indicated by the change in the upper quantile values of maximum reported wind speed is the variable most relevant to the debate on hurricane intensity in a changing climate.

Moreover, the concern that if the total number of hurricanes is not changing and the number of strong hurricanes is increasing, then the number of weak hurricanes must decrease proportionally is misplaced. The rate of strong hurricanes is much smaller than the rate of weak hurricanes. As the ocean warms the stronger hurricanes can effectively "borrow" a few hurricanes from below a specified threshold intensity that may result in a significant increase in the rate of stronger hurricanes while not significantly reducing the rate of weaker hurricanes.

4 Increases in hurricane intensity with increasing SST accounting for ENSO

The value of a simple trend analysis (involving only one variable—usually time) is limited by the fact that other explanatory variables also might be trending. In the context of hurricane intensity, it is well known that the ENSO cycle can significantly alter the frequency and intensity of hurricane activity on the seasonal time scale. A trend over time in hurricane intensity could simply reflect a change in this cycle. Thus it is important to look at the trend after controlling for this important factor. Here we go beyond what was done in Elsner et al. (2008) and show the trend as a function of Atlantic SST after controlling for the ENSO cycle. Thus we answer the question of whether the data support the contention that the increasing trend in the intensity of the strongest hurricanes is related to an increase in ocean warmth conditional on ENSO.

Figure 1 shows the results of a quantile regression model using North Atlantic lifetime maximum intensity as the response variable and Atlantic SST and Pacific SOI as the explanatory variables. Other variables including the North Atlantic oscillation (NAO) and sunspots were found not to be statistically significant. The trend values are plotted for percentile values of wind speed between 5% and 95% in intervals of 5%.

Trend values for Atlantic SST range from near zero for the weaker hurricanes (lowest quantiles) to between 10 and 15 m s^{-1} per $^{\circ}$C. The trends are statistically significant for hurricanes above the 60th percentile (on average, above 52 m s^{-1}) as can be seen by the 90% confidence band sitting entirely above the zero trend line. The trend peaks at 16 m s^{-1} per $^{\circ}$C at the 75th percentile with a 90% confidence interval of between 7 and 20 m s^{-1} per $^{\circ}$C. The mean regression line indicates a trend of about 5 m s^{-1} per $^{\circ}$C which is statistically significant above the zero trend line as indicated by the dashed lines (90% confidence intervals).

Trend values for the SOI range from about 1 m s^{-1} per standard deviation for the weakest hurricanes to near 3 m s^{-1} per standard deviation for hurricanes above the median intensity (on average 49 m s^{-1}). The trends are mostly statistically significant and the mean regression line indicates a statistically significant trend of 2 m s^{-1} per standard deviation. The results clearly indicate that the rising trend of the most intense hurricanes as the ocean temperatures rise is significant after accounting for the ENSO cycle. Thus the ENSO cycle, although also significant as expected in modulating hurricane intensity, cannot explain the increasing intensity of the strongest Atlantic hurricanes as ocean temperature rises.

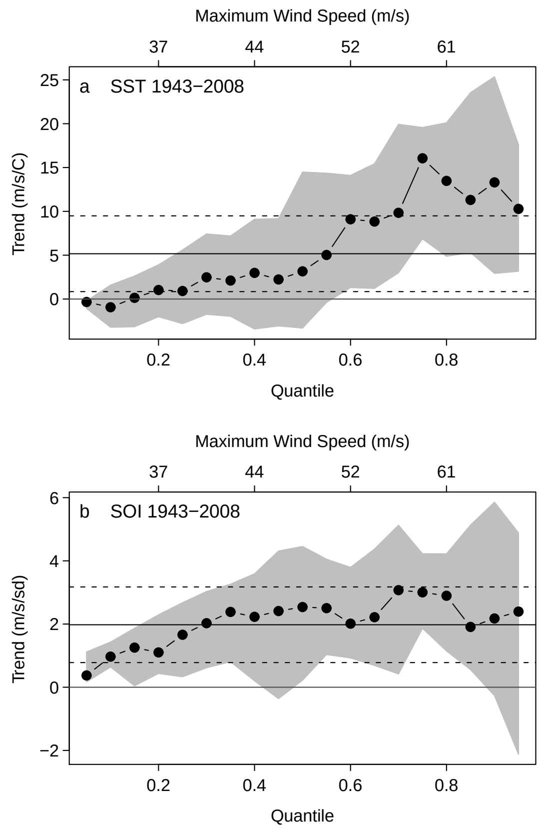


Fig. 1 Basin-wide trends in North Atlantic hurricane intensity. a. Quantile trends with respect to Atlantic SST controlling for ENSO. For an increase in SST there are increases in hurricane intensity with increases generally larger (above 10 m s^{-1} per $^{\circ}$C) at higher hurricane intensities. Statistically significant trends are noted for quantile values above the median hurricane intensity. The plot looks similar when using data starting with 1965 (satellite era). b. Quantile trends with respect to ENSO controlling for SST. For a 1 standard deviation increase in the SOI (toward La Niña conditions) there is an increase of around 2 m s^{-1} in hurricane intensity. The gray area defines the 90% confidence intervals about the trend estimates. The mean regression line is about 5 m s^{-1} per $^{\circ}$C for SST and about 2 m s^{-1} per s.d. for SOI and both are statistically significant above zero as shown by the dashed lines (90% confidence intervals).

5 Geographic distribution of lifetime maximum intensity

Even though the strongest hurricanes are getting stronger over the period 1943–2008, it does not necessarily imply that hurricanes approaching land or those over land are getting stronger. In fact it has been mentioned that or results might not be particularly relevant to decision makers if most hurricanes reach their maximum intensity far from land. Here we examine the geographic distribution of lifetime maximum intensity and find what might, at first, seem a bit surprising.

We do this by dividing the North Atlantic basin into nearly-equal area hexagon bins and counting the number of times the location of a hurricane's lifetime maximum intensity occurs within each bin. Hexagon bins are used instead of the more common rectangular bins because a hexagon represents the best compromise between overlap and spatial uniformity (Brettschneider 2008). As with the rectangles, hexagons provide a tiling of the two dimensional plane. That is they can be fit together with no gaps. Moreover since all interior angles are congruent and all sides are of equal length, the hexagon is the shape with the most angles that still tiles the plane and that best approximates the circle.

For each hurricane we determine where the hurricane *first* reached its lifetime maximum intensity. Figure 2 shows the results of this counting procedure along with the maximum value over all lifetime maximum intensities for hurricanes within each bin. The "bee hive" plot shows the geographic distribution of the frequency and intensity of the lifetime maximum intensity. Only locations with at least one lifetime maximum intensity value have a hexagon bin and the bin width is approximately 5° of longitude.

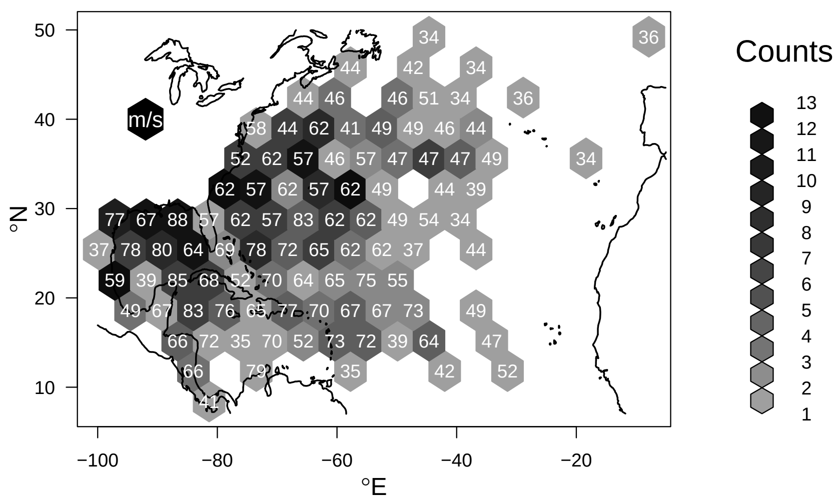


Fig. 2 Frequency and maximum intensity of Atlantic hurricanes at lifetime maximum intensity. The gray scale shows the number of times a hurricane reached its lifetime maximum intensity (first time only) within the hexagon bin using hurricanes over the period 1943–2008. The value inside the hexagon is the maximum intensity (m s^{-1}) of all lifetime maxima in the bin.

Perhaps somewhat surprising is that the U.S. coast (especially along the Gulf and southeast) are more threatened by hurricanes near their lifetime maximum compared with areas farther to the east and south over the open ocean. In fact, 69% of all 409 hurricanes over the period 1943–2008 have a lifetime maxima in a hexagon bin that is centered to the west of 60°W longitude.

Upon deeper reflection, near-coastal locations might be expected to have a greater number of hurricanes at lifetime maximum since an intensifying hurricane will decay after making landfall thereby capping intensity at or near the coast. Interestingly though, these regions tend also to be where the intensities of the lifetime maxima are large. This is not entirely surprising as these bins contain a larger collection of maxima. In fact the correlation between the number of times a hurricane reaches its lifetime maximum in the bin and the maximum intensity over all lifetime maxima is 0.5 [0.33, 0.63] (95% confidence interval) over the 98 bins.

Hurricanes typically originate over the waters of the wide expanse of the tropical oceans. They intensify over these warm waters then decay as they move over cooler waters or over land. Thus over the western part of the North Atlantic hurricane basin and especially near the Gulf coast the hexagon bins contain a mixture of hurricanes that are close to their theoretical maximum potential intensity as well as hurricanes that were intensifying prior to landfall, but still conceivably far from their theoretical maximum potential intensity. It is this mixture of hurricane intensities that might help explain why a climate change signal is not apparent in the set of hurricane intensities at landfall as it is for the larger set of hurricanes basin wide.

6 Geographic distribution of changes in maximum intensity

As noted previously, using only the lifetime maximum intensity limits the data set to 409 hurricanes over the period 1943–2008. Examining the geographic distribution of these lifetime maxima as was done in the previous section limits the number of cases to a median of about 3 hurricanes per bin. This is too few cases to examine the geographic distribution of changes in maximum intensity over time.

Therefore in this section we consider the intensity of hurricanes along their entire path at hourly intervals. The hourly intensities are based on a spline interpolation of the 6-hr estimates as mentioned in Sect. 2. The hourly hurricane intensities are binned using hexagons as before and the maximum intensity value for each bin is obtained. This maximum intensity reflects the strongest estimated wind speed over all hourly observations and over all hurricanes passing through the bin.

Figure 3 shows the geographic distribution of hurricane frequency and maximum intensities using hexagon bins. The regions of higher frequency corresponds to the preferred pathway of hurricanes across the basin. The most notable pathway being the parabolic sweep from the low latitudes of the central Atlantic northwestward to the Bahamas and then northward and northeastward towards higher latitudes. The main focal region for hurricane activity is the area near and just to the north of the Bahamas.

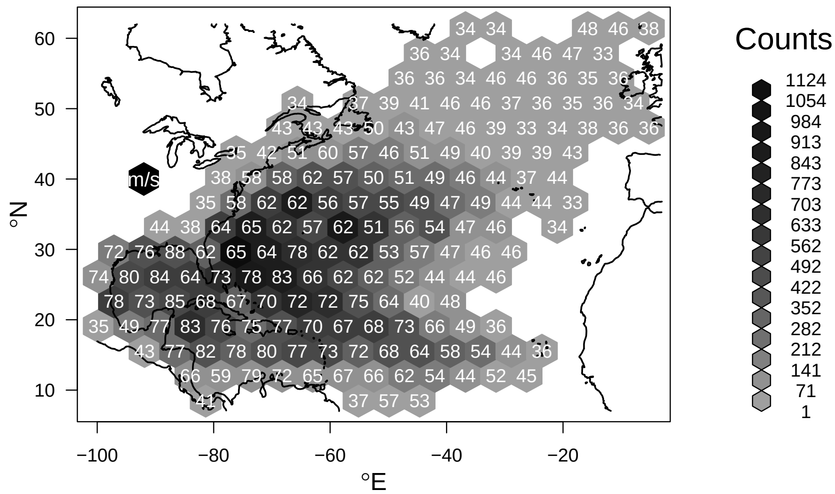


Fig. 3 Frequency and maximum intensity of hourly hurricane observations. The gray shade indicates the frequency of hourly observations in the hexagon bin and the number inside the bin is the maximum intensity over all hourly observations in the bin.

The correlation between the spatial density of hourly hurricane observations and maximum intensity is 0.73 indicating, as expected, a tight spatial relationship between factors that control hurricane frequency and factors that control intensity. However, the strongest of the strong hurricanes occur over the western Caribbean Sea and into the Gulf of Mexico. Next we consider the geographic variation in the change of maximum intensity over time. To do this we divide the 66-year record into two parts and create similar bee hives of hurricane intensity and frequency. We then plot the differences using the same bee hive plot. The division is based on separating the years into two equal groups.

The frequency and maximum intensity of hurricanes over two consecutive non-overlapping time periods are displayed in Figure 4. The top panels show the number of hourly observations and the bottom panels show the maximum intensity value over all the observations. The left panels show the data from the period 1943–1975 and the right panels show the data from the period 1976–2008.

Overall there are 9% fewer hourly observations over the later years compared with the earlier years. But over the Caribbean and Gulf of Mexico the difference is in favor of the earlier period. That is, there are 25% more hourly hurricane observations in the 20 hexagon bins comprising the Gulf of Mexico and the Caribbean during the 33-year period 1943–1975 as there are in the same 20 bins over the later 33-year

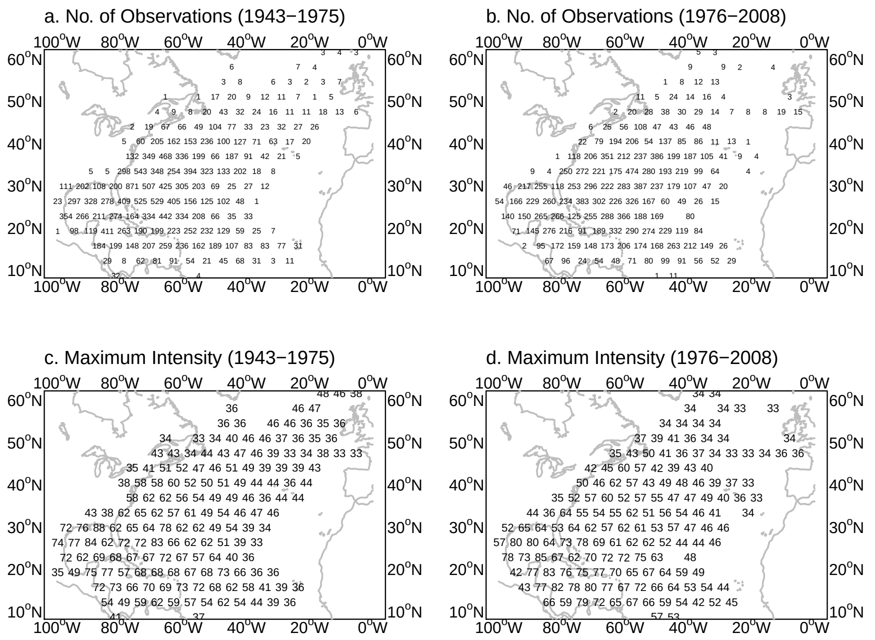


Fig. 4 Number of hurricane hourly values and maximum hurricane intensity by region and period. The regions are the hexagon bins used in Figure 3. The number of hourly values is based on a spline interpolation of the 6-hr HURDAT estimates. The maximum intensity in m s^{-1} is based on all hourly values in the bin. The two periods include the intervals before and after 1975.

period 1976–2008. There are also notably more hurricane observations during the earlier period over the Bahamas extending into the western North Atlantic.

One explanation for the fewer hourly hurricane observations is the faster forward speeds in the later period. Although the average forward speed of hurricanes over the entire basin during the earlier period is 6.5 m s^{-1}, which compares with 6.3 m s^{-1} over the later period. Over the region bounded by 100° and 60°W and 10° and 30°N, the average forward speed is 4.9 m s^{-1} over the earlier period compared with 5.2 m s^{-1} over the later period. Thus over the region including the Caribbean Sea, Gulf of Mexico, and the Bahamas, hurricanes moved on average about 6% faster during the most recent 33-year period compared with the earlier period. This difference in forward speed accounts for a 5.6% reduction in counts on average. With fewer hurricane observations we might expect the maximum intensities to be lower.

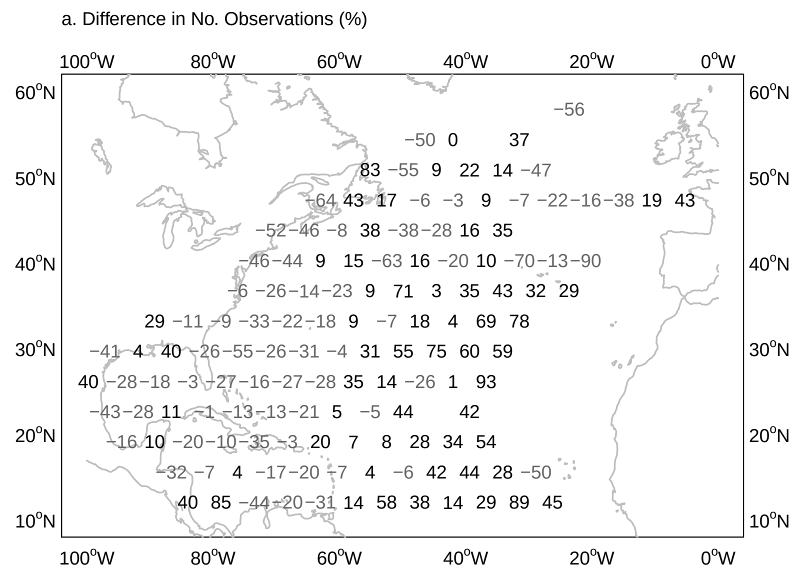
Indeed with fewer hurricanes more recently you would expect to see lower maximum intensities as is noted over the western North Atlantic. Interestingly, however, over the Gulf of Mexico and Caribbean Sea, where there are also fewer hurricane observations during the later half of the record, the maximum intensities tend to be larger. In fact the average maximum intensity over the 20 hexagon bins is 68 m s^{-1} during the early period compared with 74 m s^{-1} during the later period, an increase of about 10%. Thus over the Gulf of Mexico and Caribbean the strongest hurricanes are getting stronger. And this is also where hurricanes are generally strongest fueled by the largest ocean heat capacity of anywhere across the basin. In fact, 6 of the 20 hexagon bins over the Gulf and Caribbean have maximum intensities at 80 m s^{-1} or higher compared during the later period compared with only 1 during the earlier period.

The differences in the number of observations (expressed as a percentage) and the differences in maximum hurricane intensities between the two periods is illustrated in Figure 5. The positive (negative) percentages indicate more (fewer) hurricane observations over the later period. The positive (negative) values indicate higher (lower) maximum intensities over the later period. Increases as large as 10 to 19 m s^{-1} are noted over the Gulf of Mexico and the Caribbean Sea. Decreases are noted over the western North Atlantic to the northeast of the Bahamas. Decreases are also noted along most of the United States coastline. This is an interesting finding that is consistent with the hypothesis that continental aerosols can act to decrease hurricane intensity (Khain et al. 2009) and that might help explain why, despite the increasing intensity of basin-wide hurricanes, there is no upward tend in normalized insured losses (Jagger et al. 2008, Pielke et al. 2008). Because of the spatial correlation, the number of comparisons, and the arbitrary division of years, we make no attempt to estimate the statistical significance of these results, only noting that they are largely consistent with our admittedly limited theoretical understanding of hurricanes on a climate scale.

7 Summary and conclusions

Hurricanes are not well resolved in current climate models thus we must rely on the available historical data to get a glimpse of what might happen in the future. In a recent paper (Elsner et al. 2008) we showed that the strongest hurricanes have been getting stronger with a 26-year trend that is related to an increase in ocean temperature over the Atlantic and elsewhere. In this chapter evidence for this claim is examined in more detail. In particular, quantile trends with respect to SST are estimated after statistically controlling for ENSO. Moreover the geographic variability of lifetime maximum intensities and their changes over time are examined by dividing the North Atlantic hurricane basin into hexagon bins. Hexagon bins provide a tiling of the area of interest while best approximating the ideal shape of a circle.

It is found that the strongest Atlantic hurricanes are getting stronger and the increase is related to an increase in SST after controlling for changes in the ENSO. The trend peaks at 16 m s^{-1} per $^{\circ}$C at the 75th percentile with a 90% confidence interval of between 7 and 20 m s^{-1} per $^{\circ}$C. The problem of increasing intensity of the strongest hurricanes is not confined to the open ocean as nearly 70% of all hurricanes reach their lifetime maximum intensity west of 60°W longitude. The largest increase in the intensity of the strongest hurricanes is occurring over the Gulf of Mexico and the Caribbean Sea where ocean temperatures are warmest. Interest-



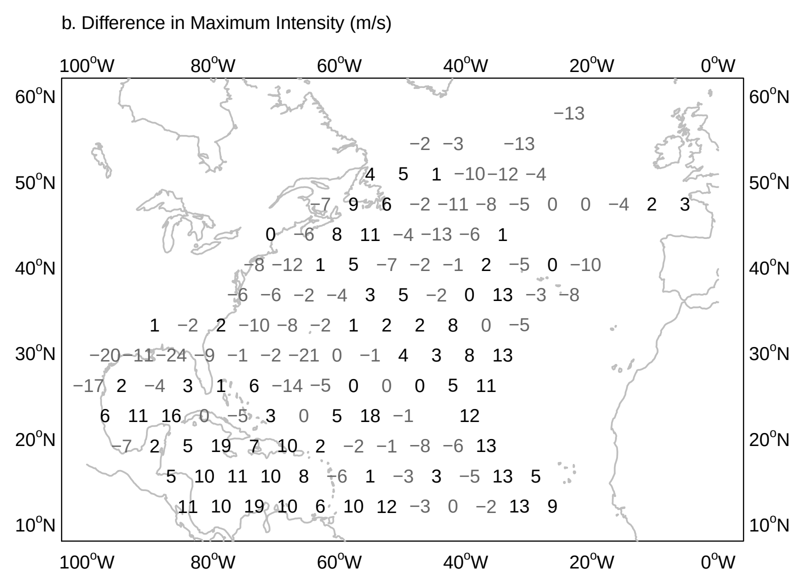


Fig. 5 Differences in the number of observations and maximum hurricane intensities. The differences are based on the periods 1943–1975 and 1976–2008, where the number of observations and maximum hurricane intensity in the bin during the earlier period are subtracted from the number of observations and maximum hurricane intensity in the bin during the later period. a. Positive (negative) values indicate more (fewer) hurricane observations over the later period. b. Positive (negative) values indicate an increase (a decrease) in the intensity of the strongest hurricanes. Note there are fewer but stronger hurricanes across much of the Gulf of Mexico and the Caribbean Sea during the more recent period.

ingly, these regions where the strongest hurricanes are getting stronger correspond to areas with fewer observations. We also note a tendency for decreases in maximum intensities for hurricanes along the U.S. coastline.

In summary, the heat-engine theory of tropical cyclone intensity (Emanuel 1991) is not about more intense hurricanes rather it is about a hurricane becoming more intense. There is an important difference. The first is about a collection of hurricanes so more intense hurricanes could result from simply having more hurricanes. But even under a scenario of constant (or decreasing) hurricane rate, the strongest hurricanes are getting stronger. If we consider near-coastal hurricanes as a subset of all hurricanes, then we do not necessarily expect to see the signal, since we are capturing hurricanes at a somewhat random part of their lifecycle. This mixing of intensity distributions might help explain why a climate change signal is not apparent in the set of landfall hurricane intensities. Moreover, increasing aerosol concentrations from the increasing built environments could be dampening the intensity of the strongest hurricanes as they approach the coast. More work on this interesting and important topic is needed.

8 Replies to comments on Elsner et al. (2008)

Our paper entitled: "The increasing intensity of the strongest tropical cyclones" published in the September 4th, 2008 issue of *Nature* garnered considerable attention in the scientific community. Here we present comments, listed as bullets, that were received on this work. The comments came from various sources including the *tropical storms mailing list* and we reproduce them here as is. Our replies to the comments follow in the gray boxes.

- Comment: Intuitively the number of tropical cyclones exceeding the mean rate plus 2 times the standard deviation as was shown in previous studies (e.g., Kossin et al. 2007) should be equivalent to number of tropical cyclones exceeding some upper quantile level as shown in Elsner et al. (2008).

> Reply: The number of cyclones exceeding plus 2 times the standard deviation is positively correlated to the rate of cyclones. A basin with a lower rate of tropical cyclones will have fewer cyclones exceeding plus 2 times the standard deviation compared with a basin with a higher rate, while the number of cyclones exceeding the 90th percentile is not necessarily dependent on the rate. Thus it is not appropriate to compare, in this way, the differences between Kossin et al. (2007) and Elsner et al. (2008).

- Comment: I've regressed the most intense tropical cyclones per season on year and my results do not match those presented in Elsner et al. (2008).

Reply: A regression of the most intense tropical cyclones per season is not the same as quantile regression on year as was done in Elsner et al. (2008) for the following two reasons. a) Quantile regression minimizes a linear absolute deviation statistic rather than a quadratic statistic, and b) quantile regression treats each intensity value equally; no wind speed contributes more to the model fit.

- Comment: Your results are only marginally significant and there are many factors contributing to hurricane intensification.

Reply: That is correct, but all else being equal, a warming of the tropical oceans where tropical cyclones form should increase their intensity. Since the strongest tropical cyclones are, on average, closest to their theoretical maximum potential intensity it stands to reason that if there is a warming signal it should be most apparent in the tendency of the strongest cyclones. Moreover, statistical inference is concerned with drawing conclusions based on data together with prior assumptions. Arguments that include the basic physics of the role ocean heat plays in tropical cyclone intensity have more weight before the data are examined.

- Comment: The authors claim that the increasing trend is consistent with theory, yet numerical modeling studies suggest a different sensitivity of tropical cyclone intensity to warming.

Reply: Numerical models are not theory. They are based on theory, but require ad hoc empirical arguments that place them into the realm of "scenario generators." The theory we have in mind is the 2nd law of thermodynamics. If the future is one with greater wind shear across the warming North Atlantic, then there may indeed be fewer hurricanes.

- Comment: I'm surprised that the relationship between intensity and sea-surface temperature is not stronger.

Reply: The physics of cyclone intensification works against the correlative relationship. An active year of tropical cyclones will effectively remove warmth from the ocean so that a seasonal average temperature will not correlate as strongly with tropical cyclone activity as one might expect even though the physical causality is strong.

- Comment: Yet when you look at scatter plots of these SST series versus number of intense TCs [tropical cyclones] there is no relationship in the warmer SST, more intense TCs direction.

Reply: We did not look at the number of TCs; we looked at the intensity. There is no theory for TC formation. However, given a TC, there is a nice theory for the efficiency of intensification. So, we focused on intensity rather than on frequency. Given a TC in a nearly optimal dynamic environment, we should expect to see it reach a higher intensity with warmer SST. If on average 10% of the storms get within 5% of their maximum potential intensity (MPI) and the MPI increases then we would see the strongest storms getting stronger, assuming all else stays the same.

- Comment: Here's a hypothetical, what if the predictor had been another quantity that also shows a significant trend over the period 1981-2006, I don't know…my weight, perhaps…would one be discussing what the physical meaning of a non-significant correlation between the two was?

Reply: This hypothetical has little to do with the relationship of hurricanes to warming seas since in the latter there is a theory linking the two, whereas with your weight and hurricanes there is none. In science this makes a big difference.

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