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Quantifying changes of wind speed distributions in the historical record of Atlantic tropical cyclone

This Issue

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Earth observation systems have over the past five decades detected numerous global warming signals, including an increase in global average temperature, a decrease of sea ice and snow cover extents, and a rise in global mean sea level. Global warming is now widely accepted as factual. That being the case, an important question for insurers - and society at large - is whether or not this warming is contributing in any significant way to increasing disaster losses. In particular, the degree to which this warming has affected tropical cyclone (TC, hurricane or typhoon) activity in the North Atlantic has been at the centre of a vigorous and at times acrimonious debate (Mooney, 2007).

Our recently published article (Chen et al., 2009) has some bearing on this concern. It sought to shed light on the three questions:

1. Can we really confidently use the long-term historical wind record to reveal evidence to support a positive linkage between a warming climate and hurricane activity?
2. If the early historical wind record is not reliable enough, what are the implications for tropical cyclone catastrophe loss modelling widely used by the insurance industry?
3. By focusing on the U.S. landfalling tracks, do windspeed statistics help detect and attribute increasing hurricane losses to the hazard or to the exposure/vulnerability components of risk?

The study re-examined the official Atlantic hurricane database HURDAT, concentrating on the spatial and temporal analyses of wind speed distributions of past hurricanes, an important issue that in our view has not been thoroughly investigated before. The results serve as a further warning to readers that any conclusions drawn from or applications based upon inherently low-quality wind speed data should be treated with caution.

1. North Atlantic tropical cyclones

Elevated hurricane activities in the North Atlantic basin since the mid 1990s have raised the question as to whether such a trend is part of a natural cycle and/or driven by anthropogenic global warming. The strength of the various claims hinges in part on the veracity and completeness of the HURDAT database. It is generally agreed that with the advent of aircraft reconnaissance in 1944, geostationary satellite imagery in 1966 and the development of the Dvorak intensity estimation technique since 1972, the recent TC record is more reliable than the earlier record. Early TC records were mainly derived from shipboard observations and/or measurements far less sophisticated than what is currently available and so it comes as no surprise that the merging of these with more recent measurements may not result in a homogeneous time series. While the limitations, inconsistencies and biases of wind speed estimates and their provenance in the early historical record are well known (e.g. Landsea, 2007), little has been reported about wind speed distributions at differing geographical and temporal scales. The issue is important since the wind speeds are used to calculate TC energy metrics such as the Power Dissipation Index (Emanuel, 2005) and moreover their distributions underpin TC catastrophe loss modeling as commonly used by the insurance industry to inform premium pricing, reinsurance rates and capital retentions.

2. Data and analysis

We analysed the most recent form of the official Atlantic basin tropical cyclone database HURDAT through the U.S. National Hurricane Center (http://www.nhc.noaa.gov/pastall.shtml, data file updated 14 May 2009). This version of HURDAT contains details of 1,410 events (including 560 tropical storms and 850 hurricanes) for the period 1851-2008, and covers the Atlantic Ocean, Gulf of Mexico and Caribbean Sea. Event details are recorded at six-hourly "best-track" segments and include Year, Month, Day, Hour, Name, latitude, longitude, storm movement speed and direction, wind speed and, where available, central pressure. The HURDAT has been used in many previous studies.

Windspeed estimates in the database refer to maximum sustained surface wind speeds at the conventional measurement height of 10 m. For analysis, we focus on track segments with wind speeds at least of tropical storm strength (≥34 knots). Wind speed descriptions follow the Saffir-Simpson Hurricane Scale: Category 1 (wind speed range 64-82 knots), Category 2 (83-95 knots), Category 3 (96-113 knots), Category 4 (114-135 knots) and Category 5 (≥136knots). Categories 3 to 5 events are referred to as major TCs and Category 4 and 5 as extreme.

We group the HURDAT record into two parts: the first comprises the early historical period (1851-1943) and the second, the most recent six decades (1947-2006), which we further sub-divide into three overlapping time series. We exclude the three years in between. We examine wind speed distributions at three geographical levels of study, each having varying numbers of samples (i.e. track segments with Category 1-5 wind speeds, 1851-2008): segments for all events in the entire Atlantic basin (14,003 segments, Fig. 1A), segments for all events that eventually crossed the United States' mainland (5,125 segments, Fig. 1C), and U.S. landfalling segments that crossed the coast from ocean to land including multiple landfalling segments of a single event (350 segments, Fig. 1E). This hierarchy of groupings is based on the presumption that as the region of study becomes more geographically constrained then the early historical wind estimates might have been better observed. In what follows, we first report wind speed distributions for the three levels of analysis.

3. Wind speed distributions at three geographical levels

Unlike previous studies that only reported aggregate statistics on the annual number of hurricanes or major hurricanes, we first stratify the annual number of tropical storms and hurricanes by Saffir-Simpson Hurricane categories (Fig. 2). Some patterns are evident: first, while the number of tropical storms appears to be increasing with time, no such trend is obvious for Categories 1, 2 and 3. Secondly and more particularly, no single Category 5 TC is listed prior to 1924, a result which clearly illustrates the limitations of the database: if the average frequency of Category 5 TCs during 1924-2008 were to be representative of the entire record, there should have been about 28 Category 5 TCs during the period 1851-1923. Lastly, and less dramatically than for Category 5 TCs, the number of Category 4 TCs during 1851-1943 (33 Category 4 TCs) is also clearly less than that recorded post-1944 (68 Category 4 TCs). We will return to these points in later discussion.

Instead of using discrete TC categories, Fig. 1B shows the same wind speed data (Category 1-5) plotted as the frequency for the four periods – 1851-1943, 1947-2006, 1967-2006 and 1987-2006. Wind speed distributions from the past two, four and six decades show little difference. Relative to the recent six decades, however, the period 1851-1943 exhibits an apparent overestimation in the frequency of wind speeds in the range 70-90 knots (largely corresponding to Category 1 and 2 TCs) and an underestimation in wind speeds beyond 110 knots (largely Category 4 and 5 TCs).

We now turn our attention to all track segments of the TCs that ultimately crossed the U.S. mainland. From Fig. 1D, it is even more apparent that while there is little variation in the wind speed distributions over the past two, four and six decades, the 1851-1943 record is again inconsistent with more recent observations. In the early historical record, there is a significant relative over-representation in the wind speed range 70-90 knots compared with the post-1947 data and a relative under-representation for wind speed of Category 4 and 5 TCs.

Let's now focus on the subset of U.S. landfalling segments, observations in which we might expect to have greatest confidence. From Fig. 1F, the distributions over the past two, four and six decades are again closely matched although the variability is understandably increased with the smaller sample size. The distribution of wind speeds for the 1851-1943 period remains distinctively different and is once again characterized by a relative over-representation for the wind speed range mainly corresponding to Category 1-2 TCs and under-representation for Category 4-5 TCs wind speeds. However, the margin of these differences is slightly smaller than for the complete tracks of these same storms as analyzed above. Other features, such as very low frequencies within the windspeed range of 60-70 knots and the change from relative over- to under-representation at windspeed range of 100-110 knots, are persistent at each geographical level of analysis.

4. Lack of reliability in the early historical record

For each of the three levels of analysis described above, the distribution of wind speeds during 1851-1943 is significantly different from those of the last six decades ($p < 0.001$, for all pairs of Pearson's Chi-square goodness-of-fit tests). Sensitivity analyses undertaken by randomly moderating all wind speeds by ± 5 or zero knots confirm that the observed differences cannot be attributed to an artifact of binning windspeeds into 10 knot categories. Even for the supposedly best quality subset (the landfalling segments), the average annual number of landfalling segments at extreme TC wind speeds jumps from 0.140, for the 93-year period spanning 1851 to 1943, to 0.308 over the 1944-2008 period. The apparent incompleteness of the HURDAT database in respect to the relative paucity of Category 4 and 5 TCs in the early historical record does not seem to have been widely noted.

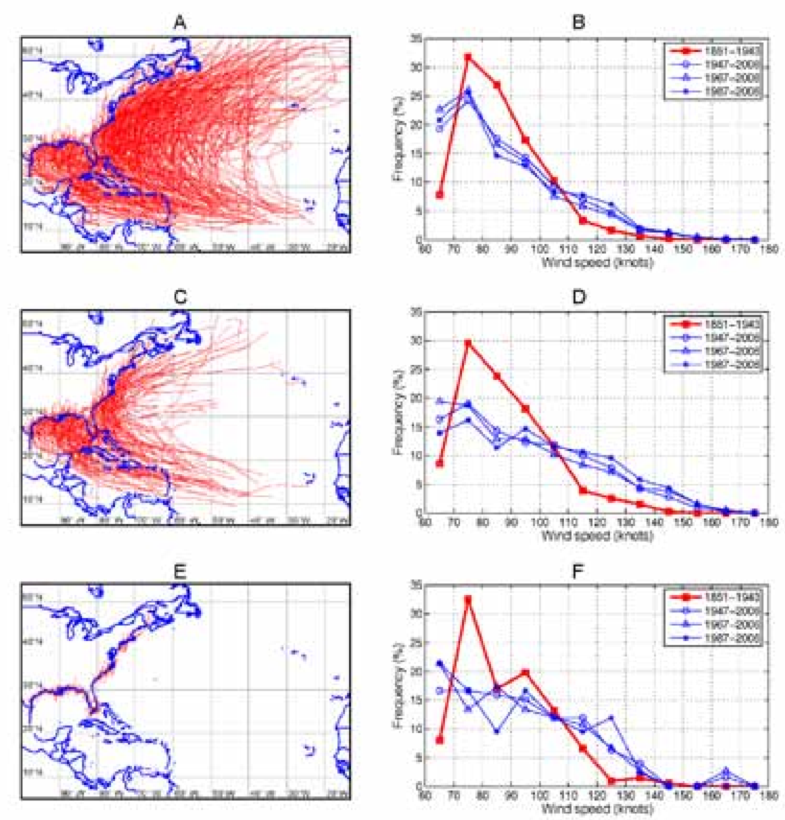

Fig. 1. Atlantic TC track segments (Category 1-5 wind speeds, 1851-2008) at three geographical scales and associated wind speed distributions for four historical periods selected: 1851-1943, 1947-2006, 1967-2006 and 1987-2006. (A) All segments of all Atlantic basin TCs. (B) Wind speed distributions for A. (C) All segments of all TCs that crossed the U.S. mainland. (D) Wind speed distributions for C. (E) U.S. landfalling segments. (F) Wind speed distributions for E.

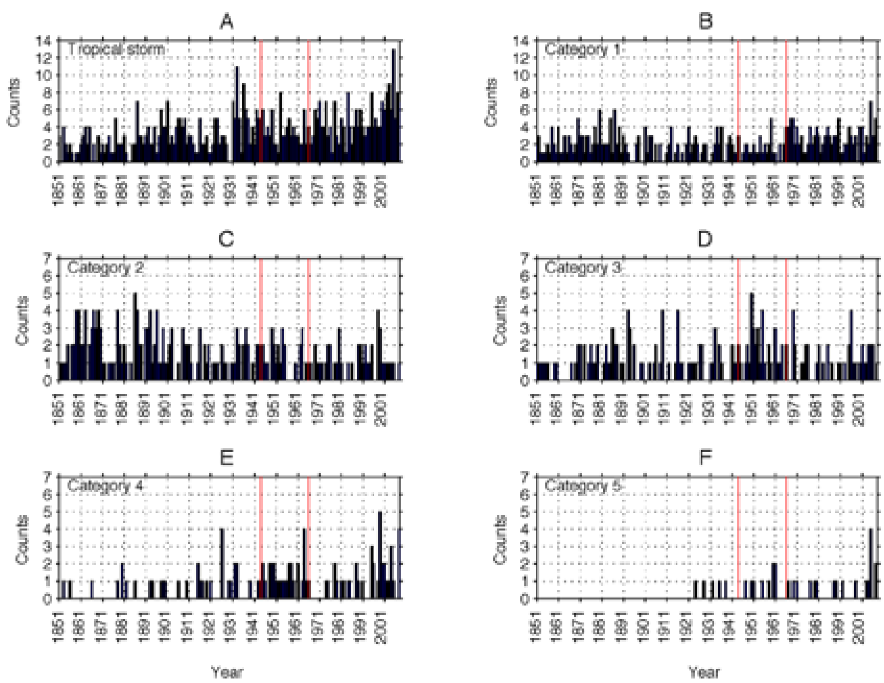

Fig. 2. Annual number of Atlantic tropical storms and hurricanes (1851-2008) by Saffir-Simpson Hurricane categories. (A) Tropical storms. (B) Category 1. (C) Category 2. (D) Category 3. (E) Category 4. (F) Category 5. Two vertical lines indicate the starting years of aircraft reconnaissance (1944) and satellite observation (1966), and this is the same for Figure 4.

On the other hand, wind speed distributions over the recent two, four and six decades display little structural change across three geographical scales (Fig. 1B,D,F). These results suggest that the differences between the earlier and post-1944 portions of the data record that are persistent across the different geographical levels investigated here are likely the consequence of instrumental and observational deficiencies that have already been well documented (e.g. Landsea, 2007). As discussed elsewhere, the accuracy and reliability of earlier wind record has serious implications for long-term trend analysis and for examination of the possible role of Global Climate Change in influencing the frequency and intensity of tropical cyclones.

In this juncture, we believe the highest-quality historical wind record since 1970s for Atlantic basin should be further exploited especially when probing the relationship between a warming climate and extreme TCs, a very critical aspect that cannot be sufficiently explored at present by using dynamical climate models and simulations. Of special note here is that the suitability of regression-based, “globally consistent” windspeed data (UW/NCDC data) for the relatively short period 1981-2006 (Kossin et al. 2007) is questionable due to the fact that it was specifically designed to retain relative annual means rather than capture absolute intra-storm or even inter-storm variability. The regression-based UW/NCDC windspeed data show very wide scattering with respective to the best track data (Fig. 3A), and significantly underestimates frequencies of wind speeds at 90 knots and beyond; i.e., the windspeed range of major hurricanes (Fig. 3B).

5. Implication for hurricane loss modeling

The shortcomings revealed in the early record also have implications for hurricane loss modeling, where emulation of the spatial-temporal attributes of wind speeds in the historical period is routinely exercised. To the best of our knowledge, proprietary and public hurricane loss models all rely on hurricane attributes drawn from the historical wind record most commonly choosing 1851 or 1900 as starting dates. As shown here, naive use of the longest historical record would seriously underestimate the frequency of Category 4-5 TCs; in other words, using the longest historical record does not necessarily impart the most reliable representation of the wind speed distribution. Therefore, for insurance or economic loss modeling applications, the period chosen to establish distributions of wind speeds should be critically evaluated.

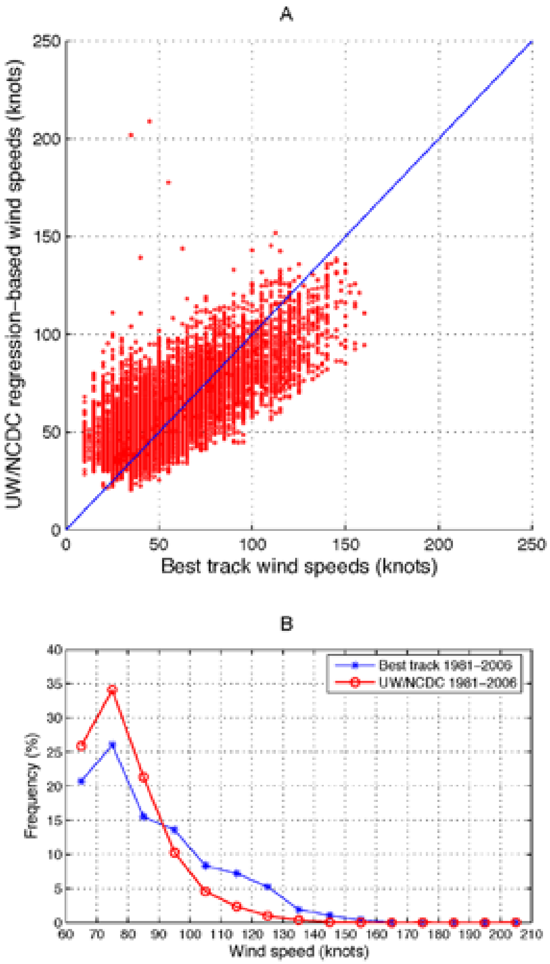

Fig. 3. Differences between best-track wind speeds (HURDAT) and UW/NCDC regression-based wind speeds of the North Atlantic basin during 1981-2006. (A) Scatter plot of track wind speeds from the two sources. (B) Wind speed distributions for all track segments with wind speeds at least of Category 1 TC strength. (Data Source: J. P. Kossin, 10 July 2008.)

The evidence reported here suggests that the hurricane record of the last six decades or so can be sensibly used to determine the relative distribution of wind speeds.

6. Hurricane loss attribution

Finally, we turn our discussion from the hazard to impacts in terms of insured or economic losses. It can be argued that wind speeds at landfall are most directly associated with damage to property and other assets at risk, but damage outcomes from TCs are also highly influenced by the spatial variability of wind speed and other physical attributes of the system, as well as associated hazards such as storm surge and flooding. Even more important are variables such as the density of population and housing with respect to TC tracks and the quality of construction. Focusing on the past six decades, we observe no sustained upward trends in wind speed distributions (Fig. 1), the mean wind speed at landfall or the annual frequency of occurrence of landfalling segments (Fig. 4). This being the case, the dramatic increases in total economic and insured losses from TCs, which have been manifest over the past many decades, indicates that the increasing losses must be attributed to the factors other than wind speed alone. This is in accord with recent studies (Pielke et al., 2008), which demonstrate the importance of demographic changes in driving the increasing economic cost of hurricane losses.

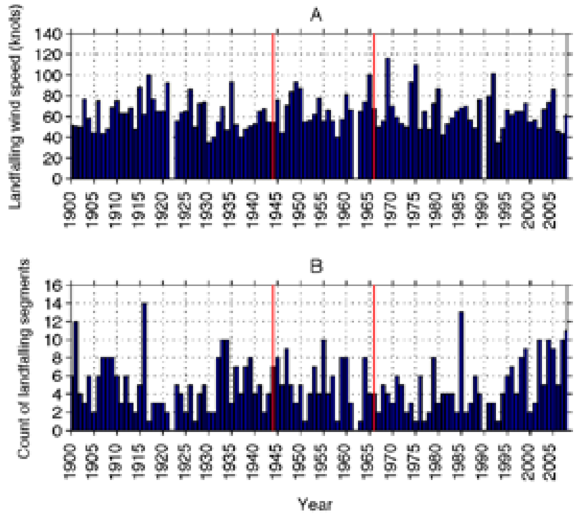

Fig. 4. Average annual statistics for U.S. landfalling segments of tropical storms and hurricanes since 1900. (A) Landfalling wind speed. (B) Number of landfalling segments. Note that TC landfalls occurred in 1922, 1962 and 1990 but the landfalling segments had wind speeds less than the tropical storm strength.

7. Conclusions

The quality of observational data is central to the ongoing debate between a warming climate and consequences for TC frequency and intensities. Our analyses show clear, anomalous differences in the wind speed distributions between the early historical period and the most recent six decades. While these differences cannot unequivocally exclude a possible Global Climate Change cause, we suggest that data quality issues are more plausible.

An enormous challenge lies ahead for recovering reliable wind estimates in the early historical record, especially for highly dynamic and short-lived extreme TCs. The counting of events by Saffir-Simpson Hurricane categories is determined by threshold wind speeds, and if the wind estimates are themselves unreliable, how can derivative statistics be trusted sufficiently for long-term trend analysis? It is timely to recognise that using the early historical record will inevitably involve some irreducible uncertainties and "fixing" these may not be possible and that more physically-based models are needed to help resolve the data impasse. Conclusions drawn from scientific and insurance applications using the inherently lower-quality components of the record should be treated with caution.

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