

# Homogeneous record of Atlantic hurricane surge threat since 1923

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**Detection and attribution of past changes in cyclone activity are hampered by biased cyclone records due to changes in observational capabilities. Here we construct an independent record of Atlantic tropical cyclone activity on the basis of storm surge statistics from tide gauges. We demonstrate that the major events in our surge index record can be attributed to landfalling tropical cyclones; these events also correspond with the most economically damaging Atlantic cyclones. We find that warm years in general were more active in all cyclone size ranges than cold years. The largest cyclones are most affected by warmer conditions and we detect a statistically significant trend in the frequency of large surge events (roughly corresponding to tropical storm size) since 1923. In particular, we estimate that Katrina-magnitude events have been twice as frequent in warm years compared with cold years ( $P < 0.02$ ).**

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The relationship between global warming and Atlantic hurricane activity is a controversial topic (1–3). Some have linked cyclone activity to sea surface temperatures in the cyclogenesis region (2, 4). Other competing hypotheses include teleconnections with El Niño–Southern Oscillation (5), North Atlantic Oscillation (6–8), Atlantic Multidecadal Oscillation (6), tropical temperatures (3, 9), and Sahel drought (10). Whereas others note that bias in the observational record casts doubt on any statistical power from the relationship (11). Estimating and correcting the historical bias hamper assessment of the links between tropical cyclone activity and climate change (1, 2, 11, 12). Hence, any discussion of observational links or causality between global mean temperatures and hurricane impacts relies on an unbiased estimate of hurricanes as a function of time. There is a rising trend over the 20th century in the observed numbers of Atlantic tropical cyclones (1, 12). However, observational methods have improved over time, especially since the satellite era, but also after airborne observations became commonplace; therefore some cyclones were missed in the past.

Most efforts have focused on estimating total Atlantic cyclone activity rather than the number of land-falling storms. This is because relatively few storms make land, and small changes in storm tracks can make a difference between a landfall and a near miss. However, from the economic damage perspective the hurricanes that remain far away from shore in the Atlantic are much less important than those closer to land. Hence in constructing an unbiased record of storms we need to ask what we want to measure. The strong winds and intense low pressure associated with tropical cyclones generate storm surges. These storm surges are the most harmful aspect of tropical cyclones in the current climate (1, 12), and wherever tropical cyclones prevail they are the primary cause of storm surges. A measure of storm surge intensity would therefore be a good candidate measure of cyclone potential impact.

In this paper we construct such a record, using long-term tide-gauge records from stations that have been operational for much longer than the satellite era. These provide a consistent dataset for examining hurricanes affecting the southeastern United States. We also show that the index is actually dominated by land-falling hurricanes rather than winter storms and that the

index reflects economic damage. Rather than a simple number count of cyclones, we produce a yearly probability distribution of storm surge intensity. We then apply a robust method of estimating confidence intervals to the frequency of extreme events. Finally we show that there is a difference in frequency of cyclones between cold and warm years and that the effect is strongest for the larger cyclones and hurricanes.

## Results

We wish to produce a long-term, homogeneous record of storm surge activity. Tide gauges are very suitable as they are simple devices that have been used for hundreds of years to measure sea level. We define the region of interest to be the western Atlantic between 10°N and 40°N. This leaves us with the six tide gauges from the region of interest (Fig. 1, *Inset* and Fig. S1) with the main criteria that we wanted to construct a homogeneous record that covered the great 1926 storm surge (13) and the general high cyclone activity of the 1930s. Here, we use data from the Research Quality Data Set (RQDS) (14). The RQDS records are extended to the present using fast delivery data from the global sea level observing system (14) and in a single instance (Mayport, FL) using preliminary water-level data from the National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (15). We manually screen the data quality of the Mayport preliminary water-level data before down-sampling. We then proceed to filter these records to enhance the storm signal while reducing the signals due to instrument changes, harbor development, and erroneous time shifts in the records.

Tropical cyclones are highly localized. However, over time the sea-level disturbance will dissipate. Daily averages increase the storm footprint to hundreds of kilometers, which means that relatively few tide-gauge stations provide adequate coverage. Large storms can also produce extreme sea levels that can be seen in tide-gauge records for several days. The potential energy stored in a sea-level perturbation is related to the square of the vertical displacement of the sea surface (16); hence we use squared day-to-day difference in local sea level. Daily data are insensitive to harbor development and changes in measurement methods, which can strongly affect high-frequency variability such as significant wave height. Day-to-day differencing further minimizes tidal influence and slowly varying trends from, e.g., rising global sea levels (17).

We observe that summer sea level is relatively calm except for the sporadic and obvious influence from cyclones, whereas winters have a higher degree of background variability. We therefore

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**Table 1. Correlations between July–November surge index and other measures of cyclone activity**

Series	Period of overlap	Correlation full period	Correlation 1950–2005	High-frequency correlation	Low-frequency correlation
Cat 0–5	1923–2008	0.56	0.65	0.51	0.64
Cat 1–5	1923–2008	0.55	0.57	0.54	0.56
Cat 2–5	1923–2008	0.50	0.42	0.51	0.50
Cat 3–5	1923–2008	0.51	0.47	0.42	0.58
Cat 4–5	1923–2008	0.53	0.50	0.46	0.62
Cat 5	1923–2008	0.38	0.61	0.41	0.48
US cat 0–5	1923–2008	0.54	0.55	0.55	0.56
US cat 1–5	1923–2008	0.57	0.57	0.55	0.67
US cat 2–5	1923–2008	0.55	0.56	0.51	0.66
US cat 3–5	1923–2008	0.57	0.60	0.55	0.67
US cat 4–5	1923–2008	0.61	0.70	0.57	0.74
US cat 5	1923–2008	0.38	0.62	0.38	0.46
ACE	1923–2008	0.61	0.58	0.54	0.72
US ACE	1923–2008	0.58	0.58	0.51	0.77
NTC	1923–2006	0.58	0.55	0.48	0.54
PDI	1923–2008	0.60	0.58	0.53	0.73
US PDI	1923–2008	0.58	0.61	0.52	0.75
NHD	1923–2005	0.65	0.66	0.59	0.38

Low-frequency correlation is the correlation of the two series after a 5-y moving average. High-frequency correlation is the correlation of the residuals after subtracting this moving average. A US prefix indicates that the metric has been restricted to US-landfalling storms only. Cat, category.

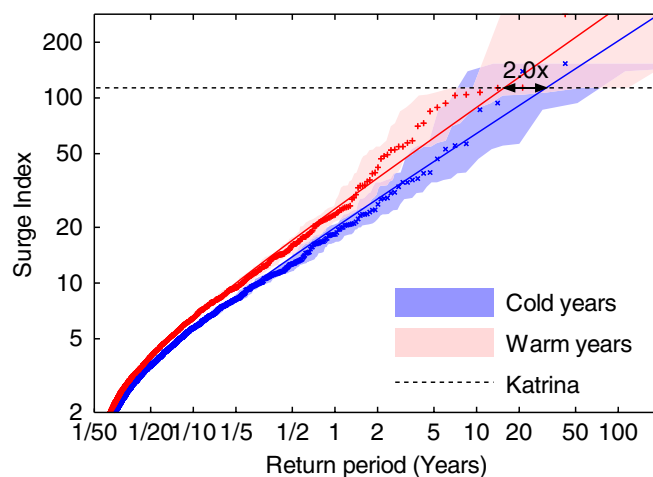
events, however, show up in other records of extreme weather; e.g., the large March 13, 1993 event is commonly known as the 1993 superstorm (22).

The surge index can be interpreted as a potential threat to infrastructure. A large surge does not necessarily mean that the associated storm caused a lot of damage. It depends on the detailed conditions of when and where the storm hit the coast. We argue that the surge index is a more direct measure of threat than most of the HURDAT-derived measures. Large surge index values are a manifestation of what the storm is able to do exactly at the time of landfall. Other measures, such as integrated kinetic energy (IKE) (24), have been proposed as proxies for the destructive potential. It is beyond the scope of this study to make a detailed comparison with IKE, which relies on high-quality wind data that are not available for all storms. However, the surge index can be used as a method of testing how IKE-type measures reflect actual surge data. For such a comparison it would be possible to include many more additional tide-gauge records as the time frames for high-quality wind data are relatively short.

To estimate the trend in landfalling storm counts, we count the number of large surge events greater than 10 units in 1 y, which is roughly equivalent to hurricane categories 0–5. This threshold was chosen as a compromise between looking at large events and having sufficiently many events to obtain robust statistics. Since 1923 the average number of events crossing this threshold has been 5.4/y, which would increase to 9.5 events/y by 2100 were the best-fitting trend to continue (Fig. 1B). This trend is statistically significant against a null hypothesis with the same power spectrum as the input series ( $P < 0.02$ ). We do not find a statistically significant trend in the seasonal average surge index (Fig. 1A), which by construction emphasizes the very largest events. This is because the strongest events are rare, and hence a longer time series is needed before a robust trend emerges. The same issues make it more difficult to detect trends in counts of major landfalling hurricanes (or PDI or ACE), compared with counts of all tropical storms.

As we are primarily interested in extreme events, it is constructive to examine the changes to the entire surge index probability density function (pdf). We split the surge index into cold and warm years (Fig. 1D) and compare the derived return periods (Methods) for the two subsets (Fig. 3). It is clear that events with annual return periods (reciprocal frequency) are significantly more intense in warm years than in cold years. We can therefore

conclude that the surge index distribution is not stationary. For rarer events (with return periods greater than 1 y) the confidence intervals from the warm and cold years overlap, which makes it difficult to visually assess whether the difference is significant. We address this by fitting generalized extreme value (GEV) distributions (Methods) to the cold and warm year data separately in Fig. 3. It is evident that the GEV distribution fits the surge index data, but that there are significant differences between the GEV parameters describing the warm and cold years. Both GEV fits give return periods that are consistent with the 9- to 30-y period for US coastal Katrina-magnitude events estimated from HURDAT (25). We observe that warm years are more active than cold years and that the relative difference in frequency is greatest for the most extreme events. The separate GEV fits suggest that events of Katrina magnitude are approximately two times more frequent in the warm years than in cooler



**Fig. 3.** Return period plot of surge index distribution for cold (blue) and warm (red) years separately (Fig. 1D). The crosses and shaded bands show return periods and confidence intervals estimated from the empirical cdf (Methods). Solid lines show best-fitting GEV distributions (SI Methods, section S3). The maximal surge index during hurricane Katrina in 2005 is shown as a dotted line.



