Hurricanes and Typhoons - Will tropical cyclones become stronger and more frequent?

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The human and economic costs of Hurricane Katrina in 2005 or Tropical Cyclone Nargis in 2008, coupled with growing coastal populations, highlight the need to know how tropical cyclone activity will respond to human-induced climate warming. This is not easy given the complexity of the processes that go into the making of a cyclone and the fact that we have a relatively poor handle on long-term (century-scale) variations in tropical cyclone activity around the globe. In the Atlantic some recent efforts have been made to quantify the uncertainty in long-term records of tropical cyclone counts (e.g. Vecchi and Knutson 2011).

A recent review (Knutson et al. 2010) points to a growing consensus regarding how tropical cyclone activity – particularly the globally averaged frequency, intensity and rainfall rates associated with cyclones – will behave during the 21st century. Models suggest that when averaged globally, the frequency of tropical cyclones is likely to remain the same or decrease through the 21st century: the decreases in the most compelling modeling studies to date span -6 to -34%. Confidence in this projection is buttressed by the ability of several of the recent climate models or regional downscaling models to reproduce past tropical cyclone variability in several basins when forced with historical variations in boundary conditions (e.g. Emanuel et al. 2008; Zhao et al. 2009). Proposed mechanisms include a weakening of the time averaged tropical circulation (Sugi et al. 2002; Held and Zhao 2011) or changes in the time averaged vertical profile of moisture in the middle and lower troposphere (Emanuel et al. 2008). Projections for individual regions are far less certain than global averages because of the uncertainties in estimating the regional climate response (for example, the patterns of sea-surface temperature response). In the Atlantic basin, for example, 21st century hurricane activity projections depend, to first order, on the rate of warming of the tropical Atlantic compared to the rest of the tropical ocean, which is not well constrained by current climate models.

In contrast to tropical cyclone frequency, theoretical considerations and high-resolution models support the plausibility of an increase in globally averaged intensity of tropical cyclones through the 21st century, with a range of 2-11% among different studies (Knutson et al. 2010). Interestingly, recent high-resolution modeling studies suggest that the frequency of the strongest storms – for example Atlantic Category 4 and 5 hurricanes – will increase throughout the 21st century (e.g. Bender et al. 2010). In the model projections, there is a competition between the effect of fewer storms overall and an increase in the intensity of the storms that do occur. On balance, the latter effect dominates in this study for the case of very intense storms, but this very competition implies that we have less confidence in this projection. Existing studies unanimously project an increase in the rainfall rate associated with tropical cyclones during this century (Knutson et al. 2010), although the range is considerable (3 to 37%) and depends on such details as the averaging radius about the storm center that is used in constructing the storm precipitation measure.

In our view, more confident projections of 21st century tropical cyclone activity, including projections for individual basins, will require that climate modelers first reduce the uncertainty in projected sea-surface temperature patterns. This is challenging as it likely involves such difficult to model influences as cloud feedback and the climate response to changes in atmospheric aerosols (IPCC 2007). The potential importance of the latter is suggested by a recent study that concludes that aerosols have led to the recent increase in the intensity of Arabian Sea cyclones (Evan et al. 2011).

The attribution of tropical cyclone changes to anthropogenic forcing, which has not yet been convincingly demonstrated, requires long, homogeneous records of tropical cyclone activity and reliable estimates of the role of natural variability in observed tropical cyclone activity changes, among other things. Paleoclimate proxy records of tropical cyclone activity (e.g. Donnelly and Woodruff 2007; Nyberg et al. 2007) could help. For example, if a number of such reconstructions convincingly showed that the most recent 50-year period was highly unusual compared with the previous 1,000 years, this would be very suggestive of a detectable anthropogenic influence. However, such a clear signal remains to be demonstrated.

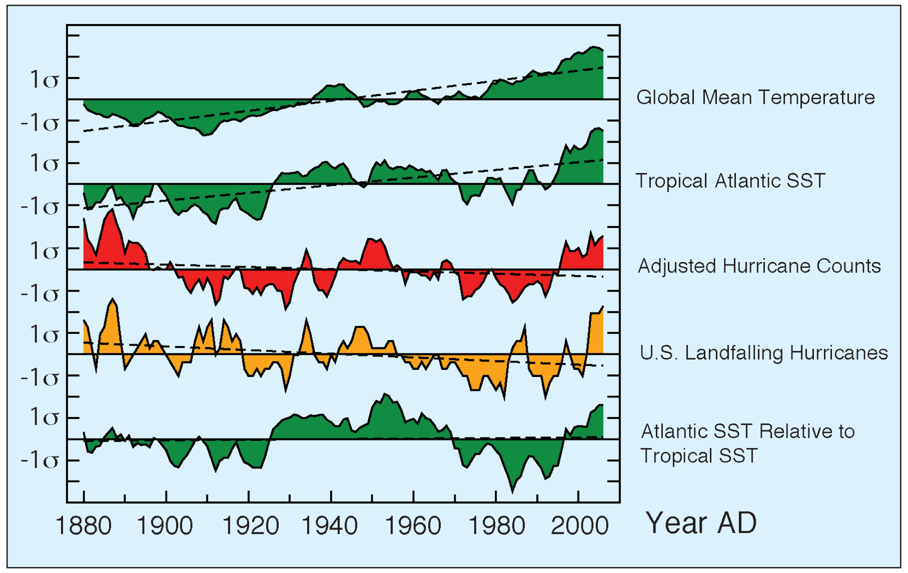

*Figure 1: Normalized anomalies relevant to Atlantic tropical cyclone activity changes: Global mean temperature (**green**, **top**); August-October sea surface temperature (SST) in the tropical Atlantic main development region (MDR; 10-20°N, 80-20°W; **green**, **second from top**); hurricane counts adjusted for missing hurricanes based on ship-track density (**red**); US landfalling hurricanes (no adjustments; **orange**), and MDR SST minus tropical mean SST (**green**, **bottom**). Vertical axis tick marks denote one standard deviation intervals. Curves are five-year running means; dashed lines are linear trends. Only the top three series have significant linear trends ($p<0.05$). Source: Vecchi and Knutson (2011).*

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Full reference list online under:
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Paleohurricane reconstructions extend storm records further into the past to improve our understanding of the relationship between tropical cyclones and climate. Though several types of tropical cyclone proxies are under development, sediment-based records, which can span millennia, have thus far provided the longest storm reconstructions and have revealed the coarse centennial to millennial-scale features of hurricane climate (e.g. Donnelly and Woodruff 2007). New, high-resolution sediment records developed from coastal ponds along the Northeastern Gulf of Mexico and in the Northeastern USA document statistically-significant changes in storm activity in response to the modest climate variations of the late Holocene (Fig. 1A). These records provide evidence both for intervals with significantly elevated and depressed storm activity relative to the historic, instrumental period. The largest variability in these paleohurricane records occurs on multi-centennial and millennial timescales, which suggests that Atlantic hurricane activity is poorly constrained by the relatively short instrumental record.

Late Holocene variations in storm activity have been dominated by changes in the frequency of intense hurricanes rather than the overall number of landfalling tropical cyclones (e.g. Lane et al. 2011). A comparison between a 4500-year storm surge record from the Florida Panhandle (Fig. 1A) and reconstructions of SSTs and Loop Current migration within the northeastern Gulf (Richey et al. 2007) suggests that intense storms were most frequent in the region not when Gulf SSTs were warmest but rather when the high ocean heat content of the Loop Current was closest to the study site. Future, intense hurricane activity may similarly respond more sensitively to upper ocean thermal structure rather than SST. Larger-scale factors also may have driven basin-scale variability in Atlantic hurricane intensities, with more (less) intense events occurring more often during periods of reduced (increased) ENSO variability (Conroy et al. 2008; Fig. 1B) and warmer (cooler) SSTs in the western North Atlantic (Keigwin 1996; Fig. 1C). This is consistent with the idea that the relative warmth of the tropical North Atlantic may be a good, aggregate indicator of Atlantic hurricane activity on greater than inter-annual timescales.

Given the stochastic nature of hurricane landfalls at a given location, any trend in basin-wide hurricane activity during the late 20th century would not be detectable in a single-site paleohurricane record. Further, given the possible disconnect between landfalling and basin-wide activity as well as high-frequency regional variability in the occurrence of landfalling storms, multi-site compilations of paleohurricane records may also fail to capture centennial or shorter scale trends or variability. However, on long timescales, North Atlantic paleohurricane records are fairly coherent revealing multi-centennial to millennial-scale intervals with either frequent or few intense hurricanes.

Though the Earth's climate state at the end of the 21st century may lack a Holocene analogue, hurricane proxies remain illustrative if not predictive. These records demonstrate that the climate system, on its own, can and has given rise to long-lived storm regimes much more active than anything experienced by vulnerable coastal cities and communities along the US Gulf and East Coasts. Paleo records of climate and hurricanes archive data from an experiment conducted in the laboratory of Earth's climate system, and reproducing the findings of that experiment would improve our understanding of the dynamical controls on hurricane activity. Forcing statistical and dynamical models of tropical cyclone climate with the boundary conditions of past millennia and comparing the results with paleohurricane records may provide a pathway to evaluate the predictive power of these emerging techniques and to identify the climatic causes of both the extremely active and very quiet storm regimes of the late Holocene.

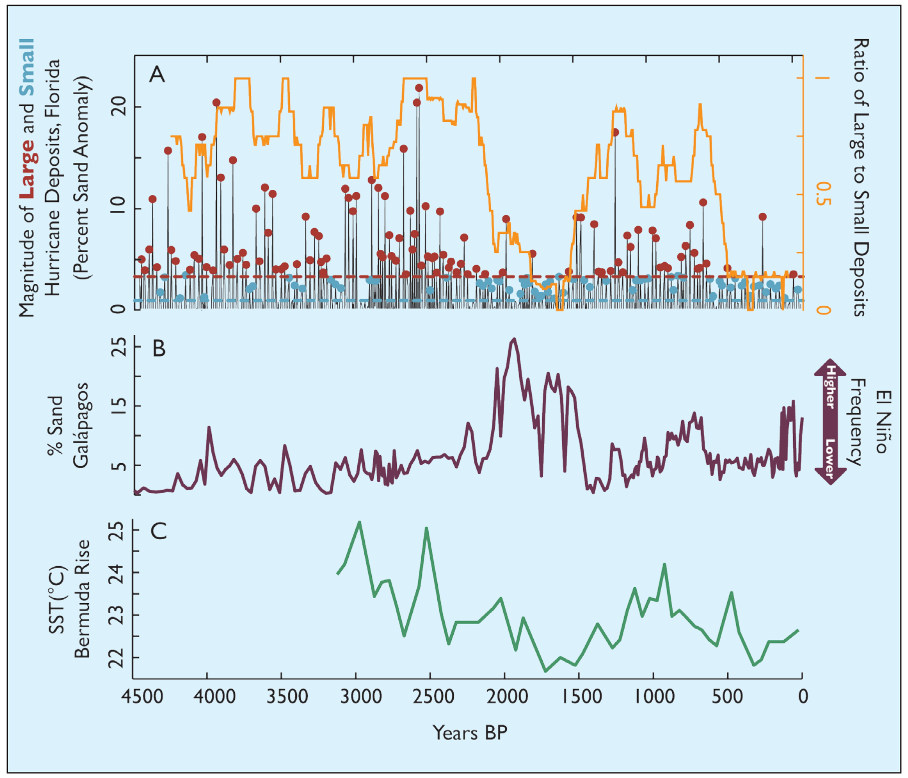

*Figure 1: **A**) shows a 4500-year record of hurricane storm surges at Mullet Pond, Florida. Blue and red dots represent chronologies of small and large storm deposits as defined by the dashed blue and red threshold lines, respectively. The orange curve is the ratio of intense to total activity found by applying a 157-year sliding window to the chronologies of discrete events. **B**) shows a proxy record of El Niño frequency based on lake level inferred from sand content in the crater lake El Junco in the Galapágos (Conroy et al. 2008). **C**) shows a time series of foraminiferal $\delta^{18}O$ (sea surface density) from the Bermuda Rise, inferred SST is shown on the y-axis, though a portion (estimated to be about one third) of the variability in $\delta^{18}O$ is thought to be related to changes in salinity also (Keigwin 1996).*

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