Predictability and Prediction of North Atlantic Hurricane Activity and Risk on Subseasonal to Decadal Timescales

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The risk of increased hurricane activity is arguably the greatest near term risk associated with global warming. The challenge to scientists is to assess this future risk in the face of incomplete data, imperfect models, and incomplete understanding. It has been hypothesized that as tropical sea surface temperature (SST) increases owing to global warming, tropical cyclone (TC) intensity, number, size, precipitation, season length, and tornadic activity could increase and tracks could be altered. Assessing these hypotheses and projecting future risk requires assessment of the available data, models, and physical understanding and integrating them into a statistically robust, plausible probabilistic projection of risk.

Predictability of TCs on weekly to monthly timescales has been demonstrated by high-resolution (50 km or less) global ensemble simulations and by "predicting the predictors" methodology. This predictability on subseasonal timescales provides confidence in the capability of high-resolution numerical models to capture TC genesis, intensification and tracking. TCs that originate from easterly waves show greater predictability than cyclones forming *in situ*. Additionally, TCs with small horizontal size that are currently not resolved well by models are also difficult to predict. Improved predictability may be achieved by reassessment and refinement of the traditional genesis factors.

Seasonal and interannual prediction using coupled climate models depends on the predictability of ENSO, which may vary with climate state. There is little predictability of seasonal Atlantic TC activity prior to late May owing to the springtime predictability barrier of ENSO. The increasing resolution and ensemble size of coupled climate models used in seasonal climate prediction, combined with predicting the predictors strategy, shows great promise for improved June 1 seasonal predictions of TC activity. Predictability on decadal timescales arises from the general predictability and persistence of multidecadal modes such as the Atlantic Multidecadal Oscillation (AMO) and the Interdecadal Pacific Oscillation, IPO (or Pacific Decadal Oscillation, PDO). Decadal scale projections of future TC activity must integrate in some way the climate model projections of externally forced century-scale climate change with what is known about natural modes of climate variability and their future changes.

Below is our assessment of the predictability and predictions of North Atlantic (NATL) TCs out to 2025, which integrates physical understanding, climate model projections, and analysis of the data record. During the next 10-20 years, the tropical SST is expected to increase by 1^{o}F owing to external forcing by greenhouse gases. The AMO is expected to remain in the warm phase, the IPO/PDO is expected to be in the negative phase (with greater frequency of La Nina), and the NAO is expected to be in a negative phase during the initial portion of this period before shifting to a more predominantly positive phase. A key element of the analyzed impact of these variations on NATL TC activity is consideration of the combined impact of AMO, NAO and ENSO on TC characteristics and landfall locations, in combination with global warming.

Hurricane intensity. Since wind damage is roughly proportional to the cube of wind speed and storm surge as well depends on wind speed, hurricane intensity is a critical metric for catastrophe modeling. Assessments of the average hurricane intensity increase for a 1^{o}F (0.5^{o}C) SST increase range from 6% (Webster et al. global observational analysis), 2% (high resolution climate models), and 2.7% (Emanuel) and 5.3% (Holland) from potential intensity theory. The observed value is almost certainly too high (owing to problems with the intensity data sets) and the climate model value is almost certainly too low, and hence we bound the expected average increase by 3-5%. This would suggest an increase between 9–15% in average wind damage. This increase in average intensity is associated with a change in the intensity distribution. This change in the intensity distribution was noted by Webster et al., but questions about the quality of the intensity data outside the NATL led us to examine changes in the intensity distribution. The intensity data during the periods 1970-1982 and 1983-1994 (cool phase of the AMO) are similar, lending credibility to the intensity data back to 1970. The intensity distribution in the current active phase (since 1995) compared with the early part of the data record shows a shift in the intensity distribution with substantially more category 4 hurricanes, consistent with the findings of Webster et al. Owing to uncertainties in the historical intensity data before 1970, the impact of natural variability on TC intensity cannot be convincingly established or separated from the global warming signal, although there is the perception of the warm phase of the AMO being associated with more major hurricanes. In summary, virtually all TC researchers expect an increase in TC intensity with increasing SST; the (often heated) debate is over the magnitude of the increase and whether it can be detected in the data record given the uncertainties.

Hurricane genesis and frequency. Total NATL TC frequency is an important indicator of our understanding of TC genesis and is also loosely associated with the number of landfalling TCs. Observations show a substantial increase (nominally 40-50%) in the number of TCs during the current active period since 1995, when compared with any other period in the historical data record. However, the dataset of NATL TC numbers (HURDAT) is plagued by inconsistencies in storm classification and by missed storms prior to 1970; current estimates of annual undercounting in the early part of the record range from 1-6, although these uncertainty estimates have not closely examined the issue of spurious inclusion of subtropical and extratropical storms in the database. This issue is the subject of intense debate within the TC community and the HURDAT data set is being reanalyzed. Arguments for believing that the HURDAT data set is generally credible (or at least useful) in terms of annual TC counts, is the decadal scale correlation with SST and the (relatively) consistent relationship of TC counts with ENSO. While the factors controlling TC genesis are generally understood, our understanding of what controls basin average TC counts and the TC counts in an individual year is poor. The NATL basin is the only basin globally that has shown an increase in TC count in recent decades. The two highest-resolution climate model simulations to date have shown an overall decrease in TC numbers outside the North Atlantic in a warmer world, while showing the NATL TC counts to remain approximately the same or increase by 30%. Analysis of the historical data record suggests an increase of about 4 TCs per 0.5^{o}C increase in SST. The key issue is to understand why the NATL TC counts would increase with global warming, while the TC counts in other basins decrease. Part of the reason is likely to be associated with the relatively cool temperatures of the North Atlantic MDR in comparison with the Pacific and Indian Oceans. During the early part of the 20th century, average tropical NATL SST was 26.5-27^{o}C, close to the climatological threshold for the onset of tropical cyclogenesis. Not only are average SSTs increasing, but the area of the NATL warm pool has extended significantly over the past century, with summertime temperatures above 28^{o}C now extending to the African coast. It is hypothesized here that owing to the relative coolness of the NATL tropical SSTs, the NATL has not yet saturated in terms of the number of TCs, whereas the other basins have and their numbers are declining with warming in concert with an increase in storm duration and intensity.

Season length. With the expansion of the North Atlantic warm pool both spatially and temporally, TCs can be expected to form outside the climatological Main Development Region (MDR) and during the early and later periods of the hurricane season and even outside of the traditional hurricane season. There is some indication from the data that average NATL TC season length has increased by about 50 days over the last 100 years. Successful analysis of season length data depends critically on filtering subtropical and extratropical storms from the HURDAT dataset, which is problematic particularly prior to 1950. The importance of season length as a metric arises from the perspective of seasonal TC projections, deployment of resources such as hurricane hunters, and also from macroeconomic considerations (e.g. tourism and its infrastructure).

Hurricane size. Storm surge and the geographic extent of hurricane damage have a substantial dependence on horizontal size of the storm. There has been very little research on hurricane size, and this is arguably a key metric for catastrophe modeling. Our analysis of TC size for U.S. landfalling TCs using ROCI (radius of closed isobar) and DOT (distance of tornadoes from TC center) since 1955 indicates a statistically significant increase (32% and 13% respectively ROCI and DOT) for Gulf landfalling TCs in the current active period (since 1995) when compared with period of previous elevated activity (1955-1964). The controls on hurricane size are not well understood, but our preliminary research indicates a link with mid tropospheric humidity, which is expected to increase with global warming.

U.S. landfall frequency; One of the most puzzling issues in analysis of the historical data record of NATL TCs is the lack of any trend in the number of U.S. landfalls, given the increase in total number of NATL TCs. During the recent active period, the proportion of U.S. landfalls (and also those striking the Caribbean and Central America) to total NATL TCs has been lower than historical values, and this has led to speculations that the total number of NATL TCs particularly prior to 1970 may have been significantly undercounted (Landsea). While this may be true, there are two alternative arguments that can be used to explain the lack of trend in U.S. landfalls and in particular the relative low proportion of U.S. landfalls. The frequency of U.S. landfalls shows low frequency variability that reflects the influence of the AMO, with more landfalls during the warm phase. The eastward extension of the North Atlantic Warm Pool has resulted in increased genesis in the eastern region of the tropical NATL, which has been associated with a greater number of TCs taking a track northward in the NATL and avoiding landfall. In the coming decades, with the projected predominance of the negative phase of the PDO and hence more frequent La Nina, and with at least some negative NAO years anticipated, it is expected that the number of U.S. landfalls could increase significantly in the next two decades.

U.S. landfall location: In exploring the predictability of landfall location, we tend to focus our attention on predictors with a seasonal scale influence on the steering behaviors in the NATL, including ENSO and NAO. In the last 80 years all portions of the US coast have become populated enough where it is believed we have captured all landfalling TCs. Combinations of seasonal drivers can also provide improved insights into landfall location probabilities. We are also just beginning to understand how these seasonal level influences behave in the presence of one or more multidecadal scale factors such as the AMO and PDO. The increased number of landfalls during the warm phase of the AMO is associated predominantly with an increase in Gulf landfalls. Coupled climate models used for seasonal forecasts have the potential to provide probabilistic projections of landfall locations if the model resolution is sufficient.

Hurricane induced tornadoes: Damage from hurricane-induced tornadoes has been estimated at 10% of total U.S. landfall damages. As hurricane intensity and size increases, the number of hurricane-induced tornadoes also increases. Tornado damage is greatest in the right front quadrant of the TC, and hence there are more tornadoes striking land in Gulf landfalls than in Atlantic landfalls. There is a credible dataset of U.S. tornadoes back to 1955. Prior to 1995 when the Doppler network was installed, undercounting has been estimated to range from a factor of 2-3. During the active period since 1995, there has been a very large increase (factor of 7) in the annual average number of hurricane induced tornadoes and average number of tornadoes per storm, largely driven by the 2004 and 2005 seasons. While a statistically significant trend cannot be determined for this data set, the probability of the very large tornadic activity caused by multiple TCs during the consecutive years 2004 and 2005 arising solely from natural variability is very low. With projected increases in both TC size and intensity, combined with increasing numbers of Gulf landfalls, the frequency of tornadoes induced by landfalling TCs, along with the associated damage, is expected to increase.

Research needs. It is proposed that new metrics (TC size and TC-induced tornadoes) be included in catatstrophe modeling (and possibly season length). Seasonal TC forecasts (starting in May or June) have substantial potential for improvement using high-resolution coupled atmosphere/ocean climate models in combination. The approach of integrating relationships derived from historical data, physical understanding, and climate model projections should be a focus of research activities to project the future risk of hurricane catastrophes in a warmer world.

Recent relevant publications, presentations and testimony from GT/CFAN:

Webster et al. (2005) Changes in Tropical Cyclone Frequency, Duration, and Intensity in a Warming Environment. *Science.* *http://www.sciencemag.org/cgi/content/full/309/5742/1844*

Hoyos et al. (2006) Deconvolution of the Factors Contributing to Increase in Global Hurricane Intensity. *Science.* *http://curry.eas.gatech.edu/currydoc/Hoyos_Science312.pdf*

Curry (2006) Congressional testimony on "Global Warming and Hurricanes" *http://www.cleartheair.org/documents/CurryCongressionalTestimony.pdf*

Curry et al. (2006) Mixing Politics and Science in Testing the Hypothesis that Greenhouse Warming is Causing a Global Increase in Hurricane Intensity. *Bull. Amer. Meteorol. Soc.* *http://curry.eas.gatech.edu/currydoc/Curry_BAMS87.pdf*

Curry and Webster (2007, in press) Potential Increased Hurricane Activity in a Greenhouse Warmed World. In *Sudden and Disruptive Climate Change*, M. MacCracken, ed., *http://www.eas.gatech.edu/static/pdf/Maccracken_chapter.pdf*

Curry (2007) Congressional testimony on "Dangerous Climate Change" *http://www.eas.gatech.edu/static/pdf/Curry_Energy.pdf*

Webster (2007) Interactions between climate and tropical cyclones. AGU Charney Lecture *http://webster.eas.gatech.edu/Presentations/Webster.2007.CharneyLecture.AGU.pdf*

Holland and Webster, (2007) Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend? *Phil. Trans. Roy. Soc. A* *http://webster.eas.gatech.edu/Papers/Webster2007a.pdf*

Belanger et al. (2007, in review) Recent Increase in Tornadoes Spawned by U.S. Landfalling Tropical Cyclones. *J. Appl. Meteorol. Climatol.* (manuscript available upon request)

Webster et al. (2007, to be submitted) Expanding tropical warm pools and their impact on global climate.