Potential Increased Hurricane Activity in a Greenhouse Warmed World

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The prospect of increased hurricane intensity in a greenhouse warmed world is arguably the greatest short term risk from greenhouse warming. This paper summarizes the key points in the scientific debate surrounding the detection of increased tropical cyclone activity and the attribution of this increase to greenhouse warming. Some speculations are given on future hurricane activity in the North Atlantic, including a discussion of the uncertainties in projections of future hurricane activity. Finally, a perspective is provided on proposed policy responses to risk associated with the prospect of increased hurricane activity.

Observations of increased hurricane activity

During the 2005 hurricane season, Emanuel (2005) and Webster et al. (2005) demonstrated an increase in hurricane intensity that was associated with an increase in tropical sea surface temperature. Webster et al. (2005) examined the global hurricane activity since 1970 (the advent of reliable satellite data). The most striking finding from this study is that while the total number of hurricanes has not increased globally, the number and percentage of category 4 + 5 hurricanes has nearly doubled since 1970 (Figure 1).

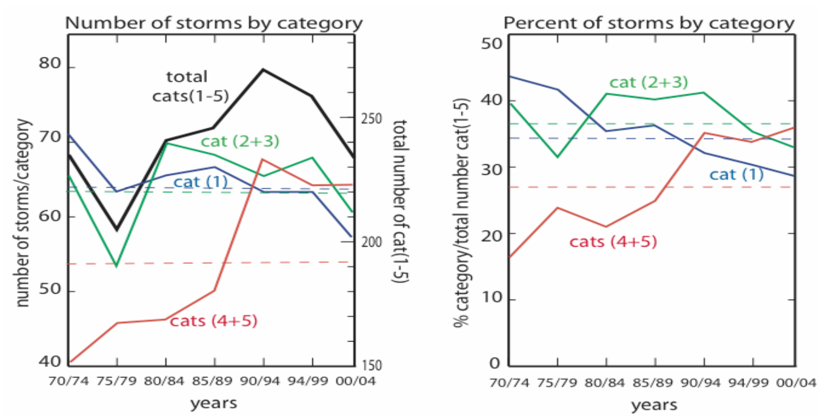

Figure 1: Intensity of global hurricanes according to the Saffir-Simpson scale (categories 1 to 5), in 5 year periods. (**A**) The total number of storms and (B) the percent of the total number of hurricanes in each category class. After Webster et al. (2006).

Scientists are debating the quality of the data upon which these analyses are based. The most reliable data on tropical cyclones is in the North Atlantic. The HURDAT data prepared by the National Hurricane Center goes back to 1851. Prior to 1944, only surface-based data were available (e.g. landfalling storms and ship observations). Since 1944, aircraft reconnaissance flights have been made in nearly all of the North Atlantic tropical cyclones. Since 1970, satellite observations have made observing and monitoring tropical cyclones more accurate.

Figure 2 shows the time series in the North Atlantic of the numbers of named storms (tropical cyclones), hurricanes, and category 4+5 hurricanes (NCAT45; NCAT45 is not shown prior to 1944 owing to concerns about data accuracy). To highlight the decadal and longer-term variability, the data has been smoothed (11 year running mean) to eliminate the year-to-year variability. A nominal 70-year cycle is evident from peaks ca. 1880 and 1950 and minima ca. 1915 and 1985. However, the most striking aspect of the time series is the overall increasing trend since 1970 and the high level of activity since 1995.

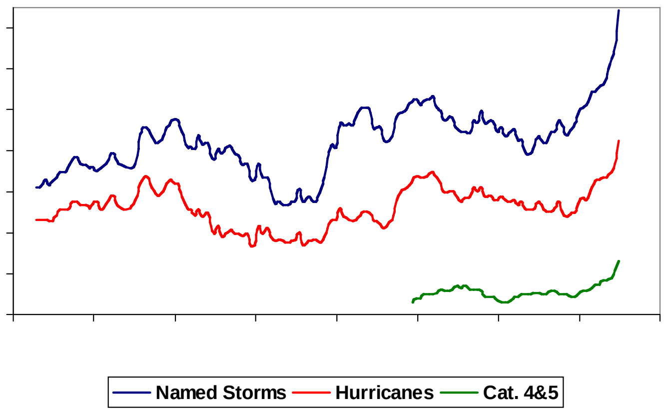

Figure 2: Number of total named storms, hurricanes and category 4-% storms since 1851, filtered by an 11-year running mean. Data are obtained from http://www.aoml.noaa.gov/hrd/hurdat/. Intensity of major hurricanes prior to 1970 is adjusted following Landsea. Figure courtesy of J. Belanger.

Linkage to increased tropical sea surface temperature

The increase in global hurricane intensity since 1970 has been associated directly with a global increase in tropical sea surface temperature (Emanuel 2005; Webster et al. 2005; Hoyos et al. 2006). Figure 3 shows the variation of tropical sea surface temperature (SST) in each of the ocean regions where tropical cyclone storms form. It is seen that in each of these regions that the sea surface temperature has increased by approximately 0.5^{o}C (or 1^{o}F) since 1970. The causal link between SST and hurricane intensity was established over 50 years ago, when it was observed that tropical cyclones do not form unless the underlying SST exceeds 26.5^{o}C and that warm sea surface temperatures are needed to supply the energy to support development of hurricane winds. The role of SST in determining hurricane intensity is generally understood and is supported by case studies of individual storms and by the theory of potential intensity.

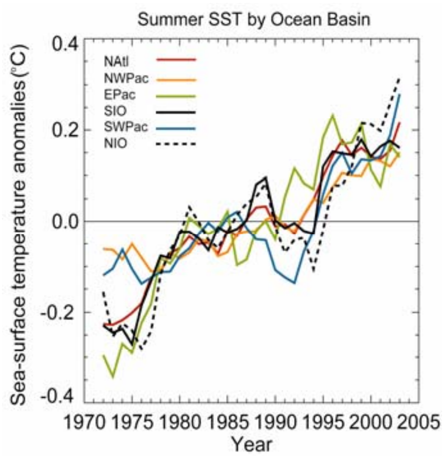

Figure 3. Evolution of the sea surface temperature anomalies relative to the 1970-2004 period for the North Atlantic, Western Pacific, East Pacific, South Indian Ocean, Southwest Pacific and North Indian Ocean Basins (Curry et al., 2006).

While globally the number of tropical cyclones has not increased (Figure 1), there has been an increase in the number of tropical cyclones in the North Atlantic. Figure 4 shows the time series of total named storms and the average sea surface temperature in the main development region of the North Atlantic. Comparison of the two time series shows coherent variations of the number of storms and the SST for periods greater than 20 years. In particular, the period 1910-1920 with low storm activity is associated with anomalously cool sea surface temperatures.

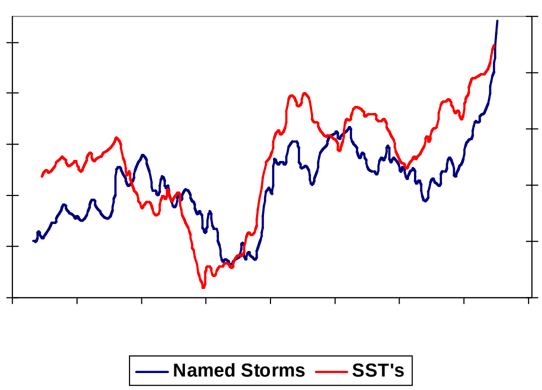

Figure 4: Number of total named storms in the North Atlantic and the average sea surface temperature in the main development region, filtered by an 11-year running mean. Data are obtained from http://www.aoml.noaa.gov/hrd/hurdat/. Figure courtesy of J. Belanger.

Attribution of the increased hurricane activity

The data show that the tropical SST increase is global in nature and occurs consistently in each of the ocean basins (Figure 3). The surface temperature trends over the last century has been extensively studied as summarized in the IPCC TAR (2001). The unanimous conclusion of climate model simulations is that the global surface temperature trend since 1970 (including the trend in tropical SSTs) cannot be reproduced in climate models without inclusion of anthropogenic greenhouse gases. The climate model simulations are the basis for attributing the increase in tropical sea surface temperatures to anthropogenic greenhouse warming.

A number of natural internal oscillations of the atmosphere/ocean system have a large impact on SST (e.g. El Nino, North Atlantic Oscillation), and some scientists have argued the increase in tropical cyclone intensity since 1970 can be explained by such natural variability. However, decadal-scale oscillations tend to be specific to each ocean basin and are often anti-correlated from one basin to another. In particular, there have been repeated assertions from the National Hurricane Center that the recent elevated hurricane activity is associated with natural variability, particularly the Atlantic Multidecadal Oscillation (AMO). Figures 2 and 4 suggest that natural modes of multidecadal variability, notably the AMO (~70 year cycle), do have an influence on North Atlantic hurricane activity. However, recent examination of the data by Mann and Emanuel (2006) suggest that the impact of the AMO on tropical sea surface temperature and hurricane activity has been overestimated owing to the convolution of the AMO with the global forcing (natural plus anthropogenic). Analyses that rely solely on SST to identify the AMO may have aliased the phase and amplitude of the AMO signal. The next peak of the AMO is anticipated ca. 2020. The strength of the tropical cyclone activity during the period 1995-2005 (50% greater than the previous peak period ca. 1950; see Figure 2), which is at least a decade away from the expected peak of the current AMO cycle, suggests that the AMO alone cannot explain the elevated tropical cyclone activity observed in the North Atlantic during the last decade.

What can we conclude from the above analysis regarding the global increase in hurricane intensity and the increase in the North Atlantic of the total number of tropical cyclones? The arguments for natural variability to explain the increase are refuted by: the known range of natural variability in the existing database; and the absence of a convincing mechanism for natural variability that can explain the global increase in both oceanic temperatures and the frequency of intense hurricanes. The best available evidence supports they hypothesis that greenhouse warming is contributing to an increase in hurricane activity, although the evidence is by no means conclusive at this point. The primary issue is whether the magnitude of the observed increase in hurricane intensity is as large as that observed by Webster et al. (2005) and Emanuel (2005), given concerns about the quality of the data. As previously stated, a reanalysis of the global hurricane data set is needed to create a robust and homogeneous climate data record. Current efforts to use very high resolution coupled climate models to examine the impact of global warming on hurricane characteristics will also shed new light on the subject once these models are capable of simulating realistic tropical cyclones.

Projections of future hurricane activity in the North Atlantic

While scientists that support the natural variability explanation versus those that support the global warming contribution all agree that hurricane activity in the North Atlantic will remain elevated for some years, the implications for future projections of hurricane activity are quite different. Based upon the hypothesis of natural variability being the cause of the high hurricane activity in the North Atlantic since 1995, there have been several predictions of a forthcoming downturn in hurricane activity: Goldenberg et al. (2001) imply a downturn in 10-40 years; and Gray (2006) anticipates a downturn in 3-8 years associated with a global cooling.

If our hypothesis is correct that greenhouse warming is causing an increase in hurricane intensity globally and also an increased number of storms in the North Atlantic, what does this imply for future hurricane activity as sea surface temperatures continue to rise as a result of greenhouse warming? The following analysis addresses specifically the projection of North Atlantic tropical cyclone activity. We consider a range of projections from two different approaches: climate model sensitivity to increasing greenhouse gases, and simplistic projections based upon the historical data record. A projection is made for average conditions in the year 2025 (such that high frequency fluctuations from short term oscillations such as El Nino are ignored), corresponding to an increase in tropical SST of 1^oF that is attributable to greenhouse warming.

The Webster et al. (2005) observations scale to a 6% increase in maximum wind speeds for a 1^oF SST increase. By contrast, high-resolution climate model simulations (Knutson and Tuleya 2004 and Oouchi et al. 2006) have found a 2% increase in intensity when scaled for a 1^oF SST increase, which is a factor of 3 times smaller than that determined from the observations. Oouchi et al. also found that the number of North Atlantic tropical cyclones increased by 30% for a 2.5^oC increase in SST, which scales to an increase of 1 tropical cyclone per 1^oF increase in SST. By contrast, based upon the historical data record in the North Atlantic (see Figure 4), an increase of 1^oF in tropical SST implies an additional 5 tropical storms per season, which is a factor of 5 greater than the number inferred from climate model simulations.

Projections of future hurricane variability must include both natural variability and greenhouse warming. Estimates of the magnitude of the impact of the Atlantic Multidecadal Oscillation (AMO) on the total number of tropical cyclones per year range from 0 (no effect) to 4-6 (the AMO explains the entire magnitude of the trough to peak variability in Fig. 1). Assuming that the AMO continues with a 70-year periodicity, the peak of the next cycle is expected in 2020 (70 years after the previous 1950 peak), so 2025 is very near the peak of the AMO cycle. Proponents of the natural variability explanation refer to active and quiet phases rather than actual cyclic behavior; their analysis states that we are currently in an active phase that will last 10-40 years, and there is no implicit assumption that the level of activity in 2025 will be higher than the activity of the past decade.

Based upon these assumptions, consider the following simple statistical model. The average number for the past decade of total North Atlantic tropical cyclones is 14.4. We assume that the effects of greenhouse warming and the AMO are separable and additive. Table 1 compares the simple statistical projections including both greenhouse warming (AGW) and AMO, AGW only, and AMO only. The range of projections given in Table 1 provides some broad constraints on the conceivable elevation of North Atlantic tropical cyclone activity in coming decades. The combination of AGW+AMO would result in the greatest elevation in the number of named storms, and an unprecedented level of tropical cyclone activity. The range of the different assumptions ranges from an increase of 0 to 6.5 named storms per year. In terms of the intensity of the storms, Figure 1 suggests that the distribution of the storm intensity is changing with warming, whereby the increase is in the number of tropical storms and in the number of category 4+5 storms (NCAT45), rather than in the weaker hurricanes. Once the AMO begins its descending mode ca. 2020, continued warming makes it doubtful that we will ever again see the low levels of hurricane activity of the 1980's and we can expect a leveling off rather than significant decrease in activity until the next ascending phase of the AMO.

Table 1. Projections for the average total number of North Atlantic tropical cyclones (named storms) for 2025. AGW refers to anthropogenic greenhouse warming; AMO refers to Atlantic Multidecadal Oscillation.

	AGW+ AMO	AGW only	AMO only
Average last decade:	14.4	14.4	14.4
Global warming increases SST 1°F:	+1 to +5	+1 to +5	0
Continued increase of AMO:	+1.5	0	0
Total	16.9-20.9	15.4 to 19.4	14.4

Impacts and policy responses

Hurricane-induced economic losses have increased steadily in the U.S. during the past 50 years, with estimated total losses averaging $35.8 billion per year during the last 5 years (e.g. Pielke et al., 2006). The 2005 season was exceptionally destructive, with damages from Hurricane Katrina exceeding $100B. During 2004 and 2005, nearly 2000 deaths were attributed to landfalling hurricanes in the U.S. 50% of the U.S. population lives within 50 miles of a coastline and the physical infrastructure along the Gulf and Atlantic coasts represents an investment of over $3 trillion; over the next several decades this investment is expected to double. The combination of coastal demographics with the increased hurricane activity will continue to escalate the socioeconomic impact of hurricanes.

The risk of elevated hurricane activity arguably represents the most devastating short-term impact of global warming, particularly for the U.S., Caribbean and Central American regions that are impacted by North Atlantic hurricanes. How should policy makers and other decision makers react to the risk of elevated hurricane activity associated with global warming in the face of the scientific uncertainties?

To address the short-term (decadal) impacts of elevated hurricane activity, decreasing our vulnerability to damage from hurricanes will require a comprehensive evaluation of coastal engineering, building construction practices, insurance, land use, emergency management, and disaster relief policies. Any conceivable policy for reducing CO_2 emissions or sequestering CO_2 is unlikely to have a noticeable impact on sea surface temperatures and hurricane characteristics over the next few decades; rather, any such mitigation strategies would only have the potential to impact the longer term effects of global warming. On the time scale of a century, sea level rise will compound the impact of increased hurricane activity owing to increased storm surge vulnerability. By 2100, a sea level rise of 1 to 2 feet is plausible. Hurricane prone regions in the U.S. at greatest risk from storm surge enhancement associated with greenhouse warming are New Orleans, South Florida, and portions of the mid-Atlantic coast.

Looking globally, Bangladesh is particularly vulnerable to the combination of increased hurricane intensity and sea level rise; several hundred million people live in the southern part of the country where the elevation is only a few feet above sea level, and three tropical cyclones during the 20th century each killed over 100,000 people. In Central America, there is substantial vulnerability associated with landslides that is exacerbated by deforestation; Hurricane Mitch in 1998 resulted in more than 75 inches of rain and catastrophic landslides that killed more than 11,000 people. The vulnerability of the developing world to increased hurricane activity and sea level rise raises not only the obvious humanitarian and economic issues, but potential regional instabilities associated with mass migrations raise serious international security issues.

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