Assessment of strategies used to project U.S. landfalling hurricanes

Climate Forecast Applications Network

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OBJECTIVES

To assess the future U.S. risk from Atlantic landfalling hurricanes in the coming years, we must assess the impact of global warming and natural variability on the number, intensity and tracks of hurricanes. Local risks must then be assessed from storm surges, extreme winds, flash floods, and landslides and interpreted in the context of the local socioeconomic vulnerability associated with emergency management plan, building codes, and societal infrastructures.

Here we analyze the historical North Atlantic hurricane data since 1900 in the context of climate dynamics. We assess the impact of uncertainties and discrepancies in the HURDAT, and assess the impact of global warming on the statistics of U.S. landfalling hurricanes. We make projections of landfalling tropical cyclones for the 5-year period 2011-2016. Specific projections of the range of likely landfalling tropical cyclone characteristics are made for the following individual regions: Northeast, Mid-Atlantic, Southeast, Florida, Gulf, and Texas.

HISTORICAL U.S. LANDFALL OCCURRENCE

The basis of the climate dynamics analysis is the historical database of landfalling hurricanes. The HURDAT dataset provides information for all recorded tropical cyclones since 1851 about the latitude, longitude, minimum pressure and maximum wind speed at the center of circulation at the six-hourly scale. The homogeneity of this record has been the subject of a substantial amount of research, particularly with regards to the total number of tropical cyclones and also intensity. It is conditionally assumed that the record of landfalling hurricane counts is complete since 1900. Statements about the presence of increasing linear trends in total tropical cyclone frequency and intensity are unavoidably affected by the large uncertainties in the record. In any analysis of total the HURDAT data set, there is an unavoidable trade-off between the availability of the longest possible record and having results that are affected by significant uncertainties.

Below are two versions of the table for annual averages of historical U.S. landfalls for named tropical cylcones (tropical storm and greater). The first is based on the most recent HURDAT landfall data. The second is based on CFAN's revised/corrected version of HURDAT. The tables provide only one entry per storm per region, even if it may have hit part of a region as Cat 3-5and part as a Cat 1-2. This means one entry per storm at max landfall category. It also includes those where an impact was designated even if a direct landfall did not occur.

HURDAT	Northeast	Mid-Atlantic	Southeast	Florida	Gulf	Texas	US
All	0.11	0.05	0.43	0.66	0.46	0.40	1.70
CAT1-2	0.05	0.05	0.32	0.40	0.29	0.25	1.07
CAT3-5	0.05	0.01	0.11	0.26	0.17	0.14	0.63

CFAN	Northeast	Mid-Atlantic	Southeast	Florida	Gulf	Texas	US
All	0.10	0.05	0.44	0.66	0.47	0.39	1.70
CAT1-2	0.09	0.05	0.39	0.39	0.32	0.24	1.14
CAT3-5	0.01	0.00	0.05	0.27	0.15	0.14	0.57

Table 1: Annual counts of landfalling tropical cyclones for the period 1900-2010. The top table labeled "HURDAT" is data from the most recent version of the HURDAT landfall database. The lower table labeled "CFAN" is our revised/corrected version of HURDAT (see text).

For the two tables above, the first is based only on values directly found in HURDAT landfall data set. The CFAN table incorporates corrections based on track data available for each storm. The datasets are now identical between 1900 and 1930. The majority of the discrepancies are in the non-satellite years (before 1970), but there are discrepancies up to 1999. The reasons for the differences between the data sets is that quite often, the official track data supports different designations based on track positions very different from landfall designations or transitions to a non-tropical structure well before a storm made landfall. This second case happens frequently along the Atlantic seaboard. In general, the HURDAT revisions to reconcile the discrepancy usually settle in the middle somewhere. For cases where they decide to keep the original landfall designations, most often the track values are changed to reflect land based measurements and map data, versus when they decide the track position/intensity/tropical nature components are valid they will drop the landfall designations.

The NOAA group responsible for the HURDAT dataset has been proceeding slowly in resolving these discrepancies. CFAN co-author Mark Jelinek has been very active in identifying discrepancies and submitting recommended changes to the HURDAT group (http://www.aoml.noaa.gov/hrd/hurdat/metadata_jan11.html). We note that a number of new changes to the HURDAT database have been submitted to the HURDAT committee by Hagen and Landsea (2011). Of particular relevance is a reanalysis of hurricanes during the period 1944-1953, where the intensity and landfall location of 27 tropical cyclones are recommended to change. In particular, the reanalysis includes a slight increase in the total number of North Atlantic hurricanes and a significant decrease in the number of major hurricanes.

In addition to the uncertainties and discrepancies mentioned above, there is a wide array of additional causes of variance within the data used for analysis. Different catastrophe modeling groups may have also chosen to adjust the HURDAT data in different ways and for different reasons. It is important to note that HURDAT was originally compiled on 80 column punch card formats for FORTRAN analysis. The official data file is still in this same format. Even within that format, the structure is a bit confusing and can lead to errors in calculations. So many people try to use the alternate formats provided or even source from non-NOAA sources. Our original analysis found even the different 'easy to use' NOAA formats were riddled with errors. It is also important to keep in mind that there have been numerous, significant revisions to the data set since 2006. Often, secondary data stores do not frequently revise their versions of the data set when updates become available. Further, the tables from different sources could differ in terms of how landfalls are actually counted. Many tropical cyclones make multiple landfalls, within a region or in multiple regions, and exactly how these multiple landfalls are handled can result in different total.

IMPACT OF MODES OF NATURAL CLIMATE VARIABILITY ON U.S. LANDFALL OCCURRENCE

Interannual and multidecadal modes of climate variability have long been known to have an influence Atlantic hurricane activity. Several studies have explored the impact of different climate indices on Atlantic hurricane activity, including Atlantic and tropical sea surface temperatures, El Nino-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), West African monsoon, Atlantic Multidecadal Oscillation (AMO), Atlantic Meridional Mode (AMM), Madden-Julian Oscillation (MJO), Quasi- Biennal Oscillation, and the solar cycle. In the analysis provided here, we focus on the ENSO, AMO and PDO because of their potential for longer-range predictability.

ENSO

The El Nino Southern Oscillation (ENSO) dominates the interannual variability of North Atlantic hurricanes. Recent research by Kim, Webster, Curry (2009) highlighted the impact of the increasingly frequent Modoki El Nino on Atlantic hurricane activity. The Modoki is associated with central Pacific warming, rather than with eastern Pacific warming that characterizes the canonical El Nino.

Kim, Webster and Curry (2009) demonstrated that the two distinctly different forms of tropical Pacific Ocean warming are shown to have substantially different impacts on the frequency and tracks of North Atlantic tropical cyclones. Climatologically, the greatest number of cyclones occurs during August to October. There is a clear difference between the number of cyclones forming during EPW (El Nino) and EPC (La Nina) events, but there is almost as large a difference between the EPW (El Nino) and CPW (Modoki) events.

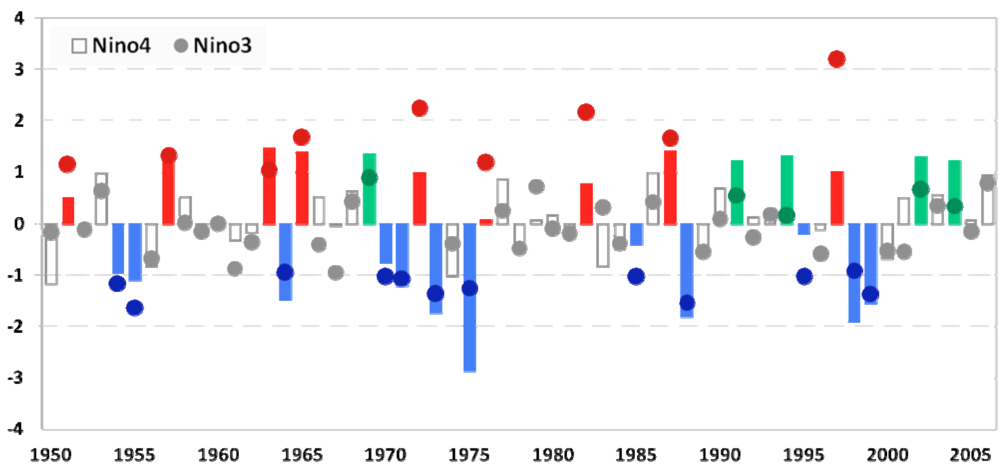


Figure 1: Time series of normalized Niño 3 (East Pacific; circle) and Niño 4 (Central Pacific; bar) index based on the SST anomaly from the 1950 to 2006 average in the three-month period August- October. A total of 9 EPW (El Nino) years (red; 1951, 1957, 1963, 1965, 1972, 1976, 1982, 1987, and 1997), 5 CPW (Modoki) years (green; 1969, 1991, 1994, 2002, and 2004), and 12 EPC (La Nina) years (blue; 1954, 1955, 1964, 1970, 1971, 1973, 1975, 1985, 1988, 1995, 1998 and 1999) were identified.

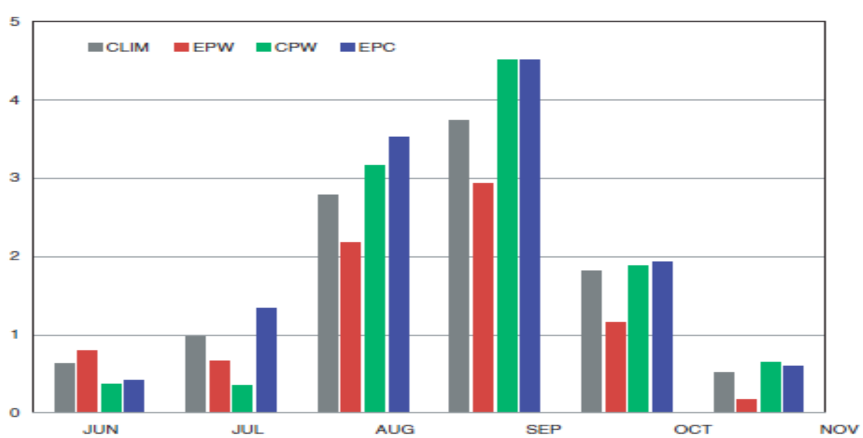


Figure 2: The average number of North Atlantic tropical cyclones per month for climatology (gray bar), El Nino (EPW; red bar), La Nina (EPC; blue bar) and El Nino Modoki (CPW; green bar).

The location of the tropical Pacific warming (central or eastern) also affects the location of cyclogenesis and the tracks of tropical cyclones. Figure 2 shows the composite of mean track density anomalies relative to the 57-year climatology. During an EPW (El Nino) (Fig. 3A), track density is reduced over most of the North Atlantic, with a concentration in the western and Caribbean regions. The tracks during a CPW (Modoki) event (Fig. 3B) differ markedly from those occurring during an EPW event: Compared to climatology, track density for CPW increases across the Caribbean, the Gulf of Mexico, and the U.S. east coast, but it decreases in the central and western North Atlantic. During an EPC (La Nina) event (Fig. 3C), large increases in track density occur across the entire North Atlantic.

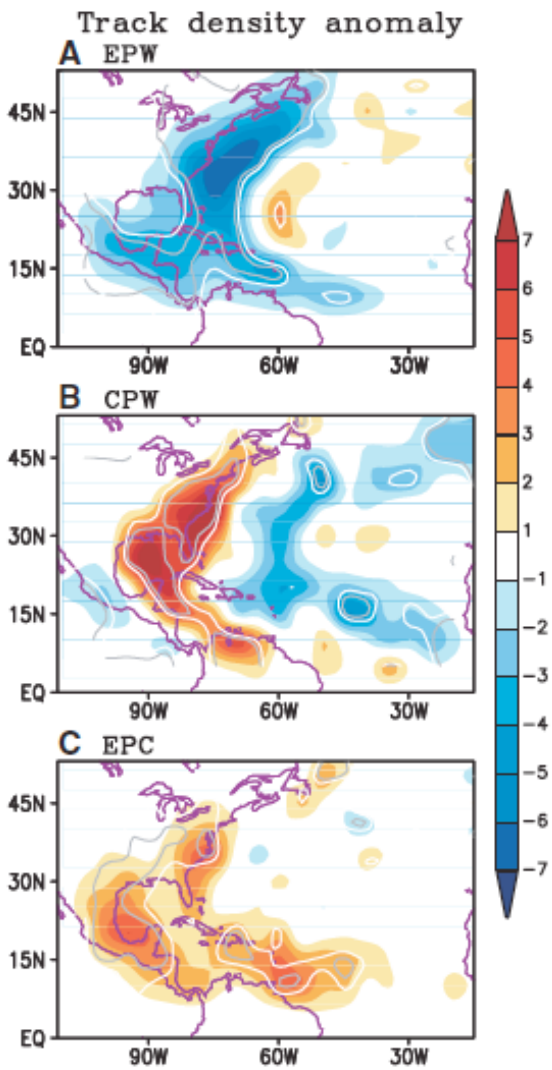


Figure 3: Composites of track density anomaly (multiplied by 10) during the August to October period for A EPW (El Nino), B CPW (El Nino Modoki), C EPC (La Nina).

The year 2004 was a CPW year. Seasonal cyclone forecasts predicted lower-than-average activity based on predictions of El Niño. However, the cyclone activity was unusually high, contrary to normal expectations for an El Niño year. A total of 15 tropical cyclones developed in the North Atlantic, of which 12 were named storms. In 2004, tropical cyclones caused a total of $40B in damage and led to the loss of 3000 lives. There was a concentration of cyclones in the Caribbean and the Gulf of Mexico. Also, 2002 was a CPW year, with a higher than expected number of landfalling cyclones.

North Atlantic Oscillation

Several studies have identified the NAO as providing an important control on the tracks (and hence landfall locations) of North Atlantic hurricanes. The NAO influences landfall probability for Atlantic hurricanes through changes in the subtropical high-pressure cell over the Atlantic Ocean (Azores high). A positive NAO index is correlated with elevated pressures in the subtropical high over the North Atlantic Ocean and more frequent re-curvature of Atlantic hurricanes (higher landfall probabilities along the East Coast or non-landfall systems). A negative NAO index is correlated with lower pressures in the subtropical high and a more zonal atmospheric flow that tends to maintain an east-to-west hurricane track (higher landfall probabilities along the Gulf Coast). We mention that NAO, given it is the best indicator of the steering during the course of the North Atlantic season. However, it has yet to be predicted with meaningful skill in advance of the season.

Multidecadal Oscillations

Multidecadal oscillations in both the Pacific and Atlantic influence Atlantic hurricane activity on the time scales of relevance to this analysis. In the Atlantic, the AMO is the relevant Atlantic index on the 1-5 year timescale. We note that the change points used in the RMS analysis are consistent with phase changes in the AMO and PDO

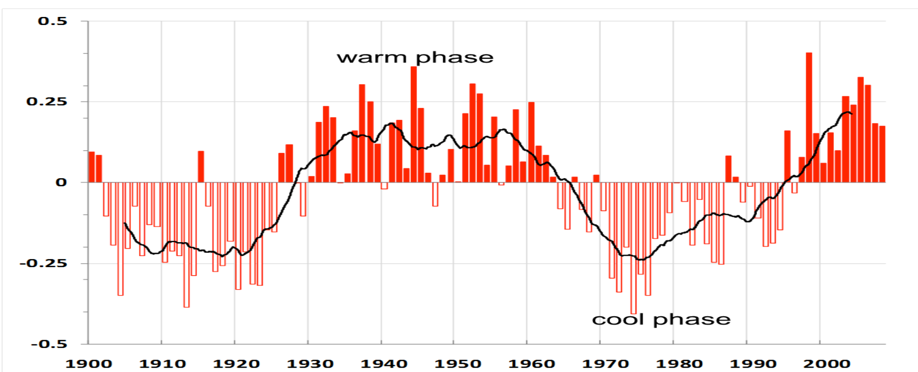


Figure 4. Atlantic Multidecadal Oscillation Index.

The Pacific Decadal Oscillation (PDO) modulates the frequencies of El Nino/La Nina.

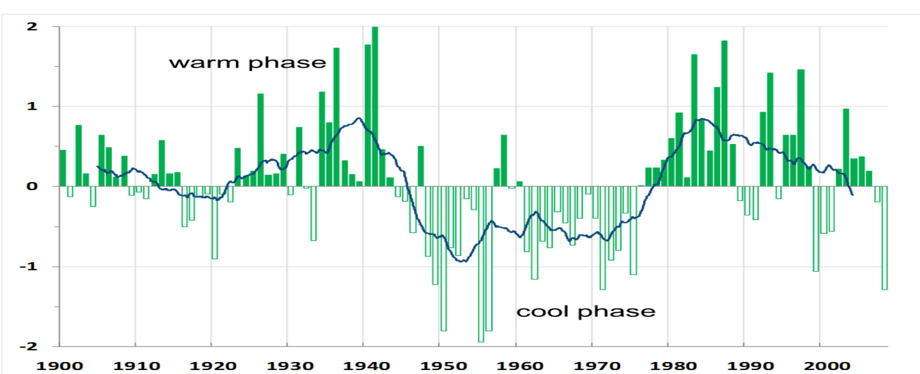


Figure 5. Pacific Decadal Oscillation Index.

Impact of AMO/PDO on U.S. landfalling hurricanes

We are currently in the warm phase of the AMO and the cool phase of the PDO. The impacts of the PDO and AMO on Atlantic hurricanes are shown in the following Figures, using BestTracks data from 1920-2008. On the figures below, the warm AMO is indicated by yellow shading, and the cool PDO is indicated by blue shading; the overlapping periods of warm AMO and cool PDO are shaded in green. Relative to the AMO and PDO values shown in Figures 4 and 5, the shading reflects a low pass filter on the index to reflect the longer (ca 30 year) warm/cool periods. This low pass filter provides a simple illustration of the hurricane activity in the different regimes, although the fluctuating PDO between 1999 and 2007 result in an ambiguous assignment of individual years (including 2004 and 2005) to the warm or cool phase of the PDO.

Figure 7 indicates that the total number of Atlantic hurricanes has strong interannual and interdecadal variability, but the highest numbers are in the green region, characterized by warm AMO and cool PDO.

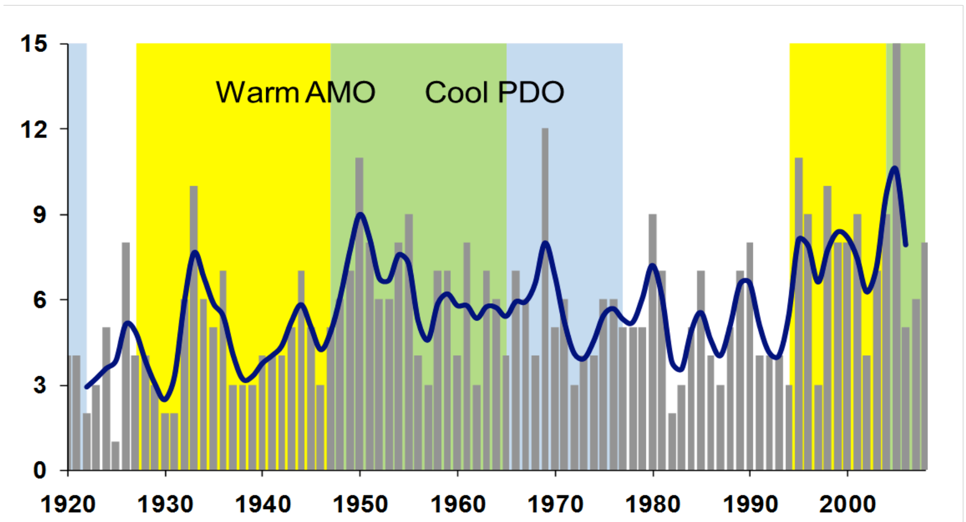


Figure 7: Frequency of total Atlantic hurricanes.

Figure 8 shows the frequency of major Atlantic hurricanes. The greatest frequency of major hurricanes occurs in the green region, characterized by warm AMO and cool PDO. It is noted here that there is significant uncertainty in the determination of hurricane intensity prior to 1970.

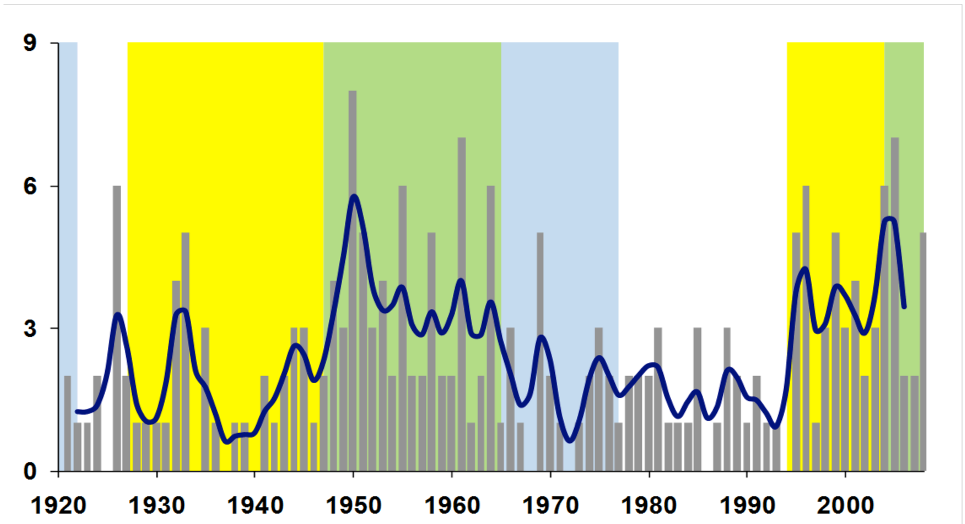


Figure 8: Frequency of major hurricanes in the Atlantic.

Figure 9 shows the total U.S landfalling hurricanes. The dominant signal for total landfalling hurricanes is the AMO, with the greatest number of landfalls occurring during the warm phase of the AMO.

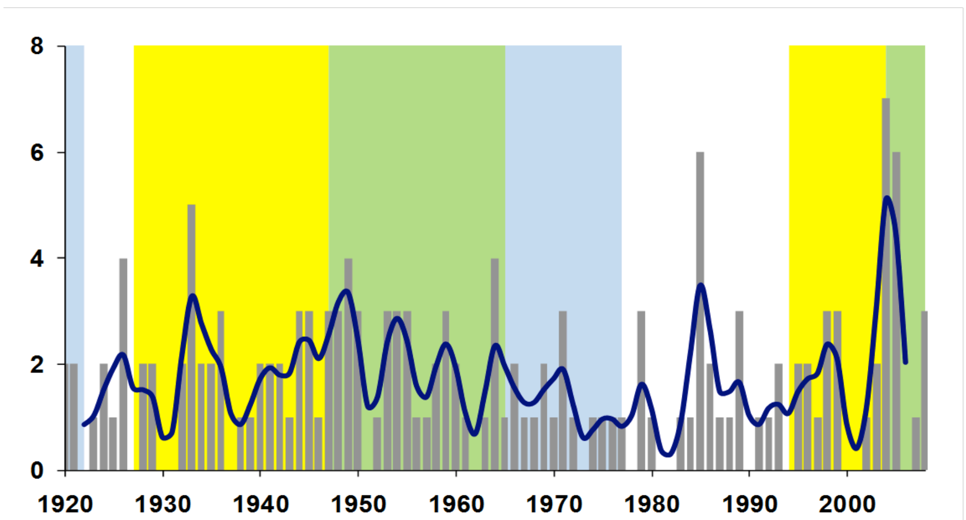


Figure 9: Total number of U.S. landfalling hurricanes.

Figure 10 shows the number of major hurricanes that have struck the U.S. The dominant signal appears to be associated with the AMO, with a secondary impact of the PDO.

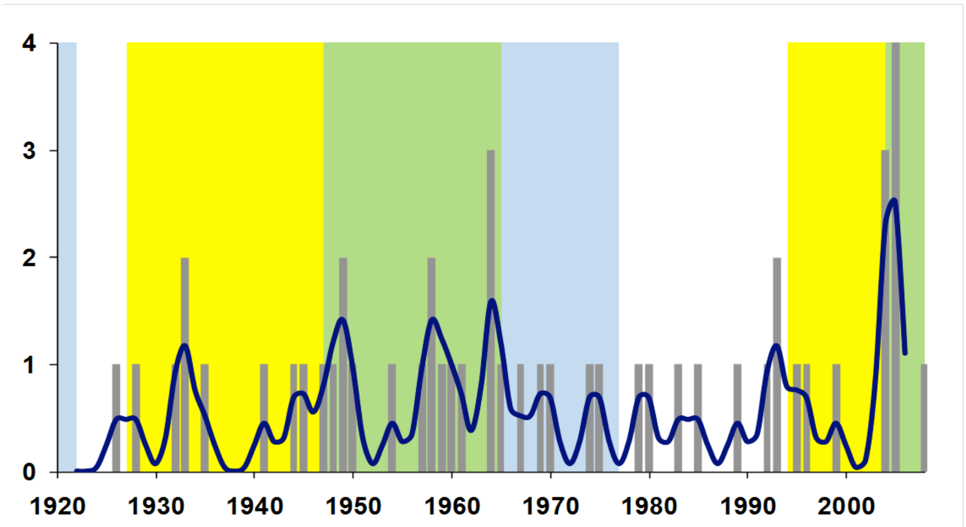


Figure 10: Major hurricanes that have struck the U.S.

The AMO and PDO also provide a signal regarding the location of the landfalls:

- Atlantic coast: more frequent landfalls during warm AMO, and cool PDO
- Florida coast: more frequent landfalls during warm AMO
- Gulf coast: no strong multidecadal signal

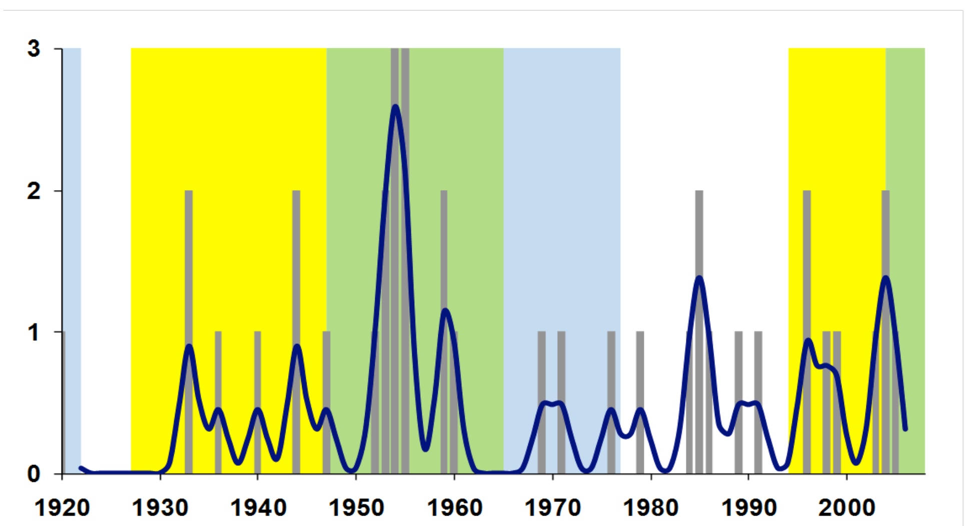


Figure 11: Atlantic coast landfalling hurricanes

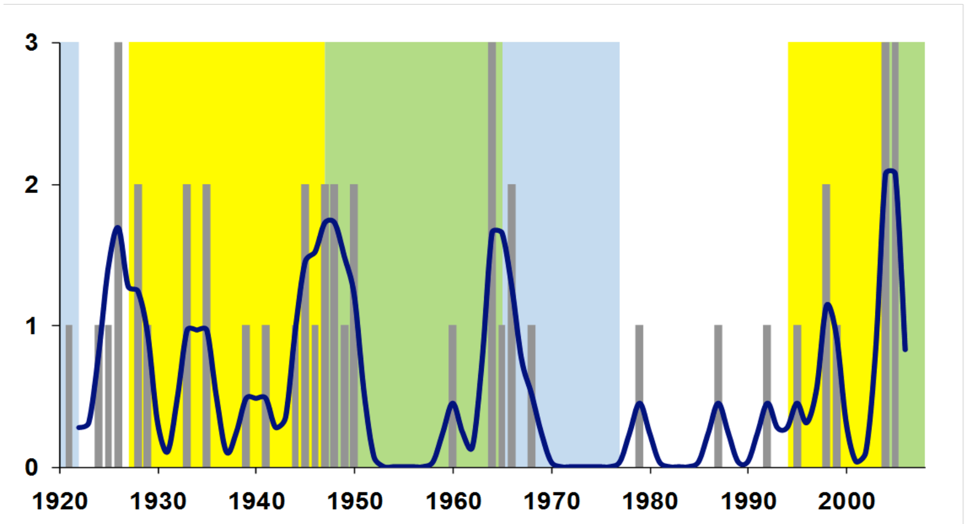


Figure 12: Florida coast landfalling hurricanes

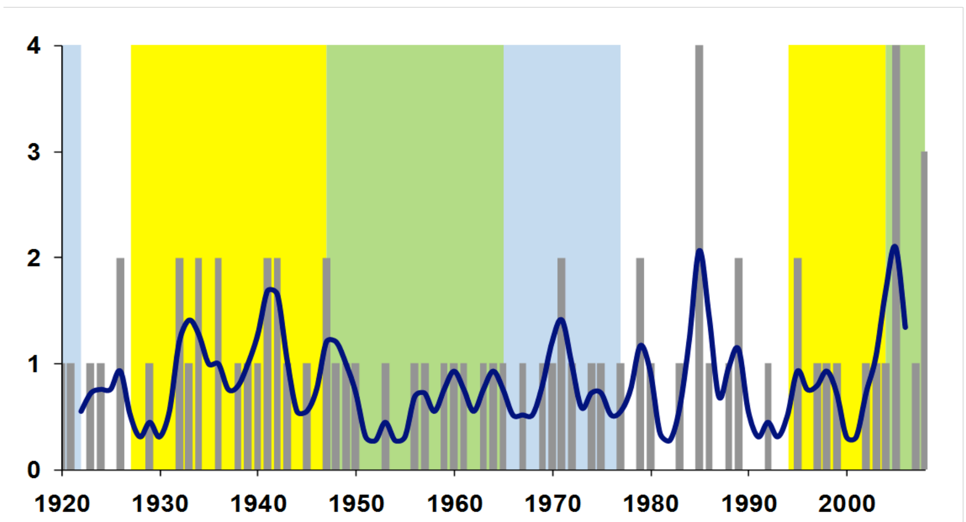


Figure 13: Gulf coast landfalling hurricanes

Summary figures are provided below that clarify the impact of the AMO and PDO on total Atlantic hurricanes and U.S. landfalls. There are 30% more hurricanes and 50% more landfalls during the warm phase of the AMO.

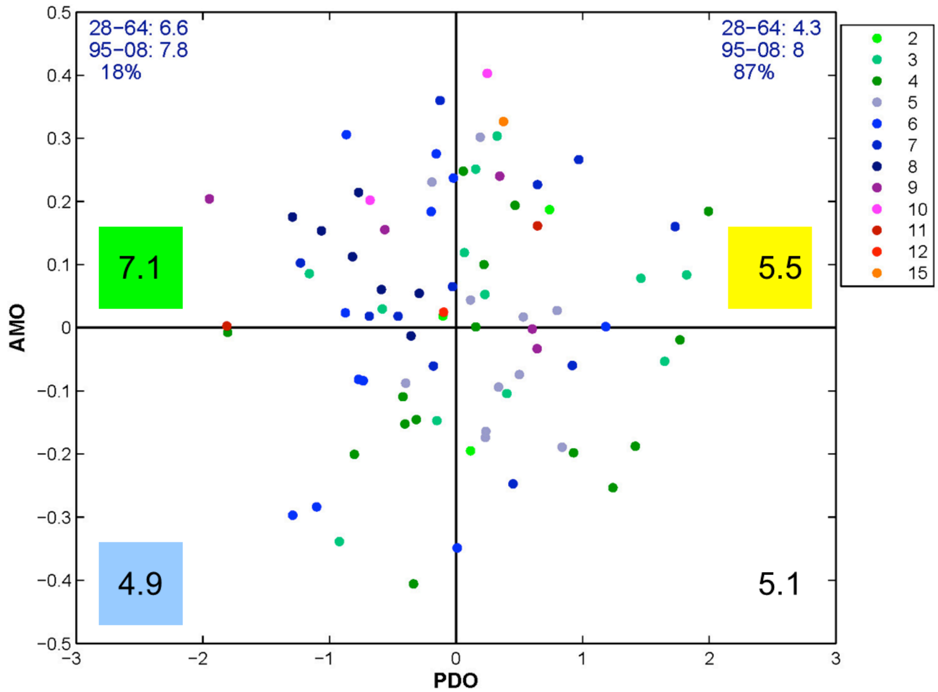


Figure 14: Total Atlantic hurricanes, sorted by PDO and AMO indices (annual values; 1920-2009).

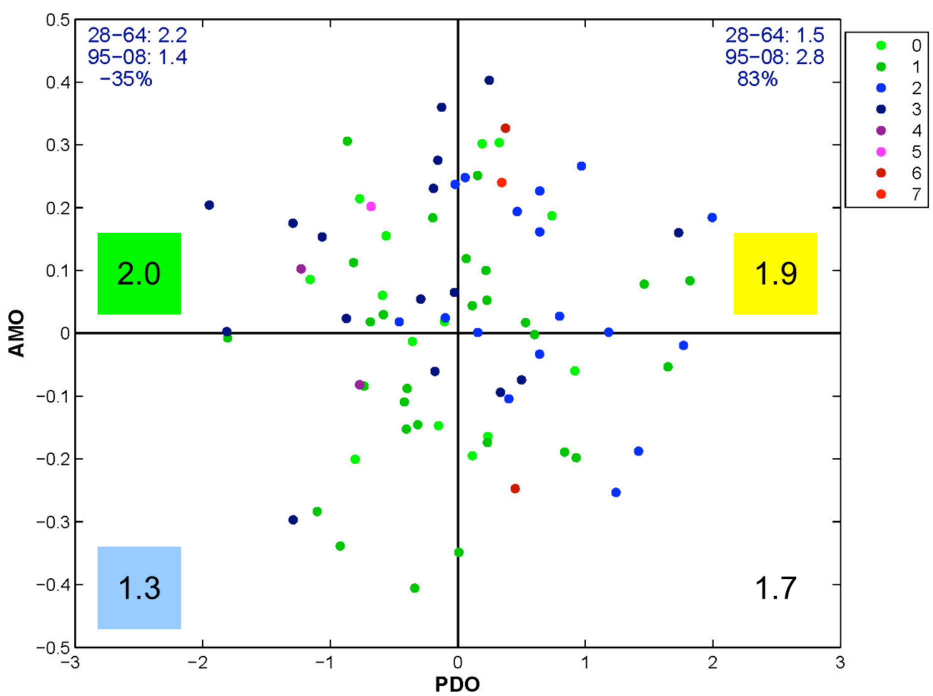


Figure 15: U.S. landfalling hurricanes, sorted by PDO and AMO indices (annual values; 1920-2009).

IMPACT OF GLOBAL WARMING

The impact of global warming on hurricane activity is being hotly debated; for an overview of the debate, see Curry et al. (2006). A critical issue for future projections of Atlantic hurricane activity based upon the historical HURDAT record is the extent to which global warming has influenced the frequency, intensity and landfall locations in recent decades. This discussion provides a summary of recent assessments of the impact of global warming on Atlantic hurricanes, and update on the Webster et al. (2005) study on global hurricane intensity, inferences from global climate models, and our assessment.

Assessments of the impact of global warming on Atlantic hurricanes

Since 2005, assessments of climate change detection and attribution research with regard to tropical cyclones have been undertaken by two international groups (the IPCC and the WMO) plus the U.S. Climate Change Science Program. Below, we highlight the major conclusions from each of the three assessment reports. All likelihood statements follow the conventions of the IPCC (2007).

The IPCC AR4 WG1 Summary for Policy Makers (published in 2007) concluded the following:

- *Detection and attribution: "There is observational evidence for an increase in intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures. There are also suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater. Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity. There is no clear trend in the annual numbers of tropical cyclones."*
- *Projections: "Based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures. There is less confidence in projections of a global decrease in numbers of tropical cyclones. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period."*

The CCSP Synthesis and Assessment Report on Weather and Climate Extremes in a Changing Climate (2008) focused on tropical cyclones in the North Atlantic and North Pacific:

- *Detection and attribution: "[I]t is likely that the annual numbers of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased. . . This evidence suggests a substantial human contribution to recent hurricane activity."*
- *Projections: "For North Atlantic and North Pacific hurricanes, it is likely that hurricane rainfall and wind speeds will increase in response to human-caused warming. Analyses of model simulations suggest that for each 1C (1.8F) increase in tropical sea surface temperatures, core rainfall rates will increase by 6-18% and the surface wind speeds of the strongest hurricanes will increase by about 1-8%. It is presently unknown how late 21st century tropical cyclone frequency in the Atlantic and North Pacific basins will change compared to the historical period."*

A review article published in 2010 by the World Meteorological Organization Expert Team on Climate Change Impacts on Tropical Cyclones (Knutson et al. 2010) concluded the following:

- *Detection and attribution: "It remains uncertain whether past changes in any tropical cyclone* *activity (frequency, intensity, rainfall, and so on) exceed the variability expected through natural causes, after accounting for changes over time in observing capabilities."*

- *Projections: "It is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged owing to greenhouse warming. . . Current models project changes ranging from −6 to −34% globally, and up to ±50% or more in individual basins by the late twenty-first century. Some increase in the mean maximum wind speed of tropical cyclones is likely (+2 to +11% globally) with projected 21st century warming."*

Differences among these assessments are described by Knutson et al. in the supplementary material. Relative to the CCSP report:

"[Knutson et al.] do not assign a likely confidence level to the reported increases in annual numbers of tropical storms, hurricanes and major hurricanes counts over the past 100 years in the North Atlantic basin. . . Specifically [Knutson et al.] do not conclude that there has been a detectable change in tropical cyclone metrics relative to expected variability from natural causes, particularly owing to concerns about limitations of available observations and limited understanding of the possible role of natural climate variability in producing low frequency changes in the tropical cyclone metrics examined."

Relative to the IPCC AR4:

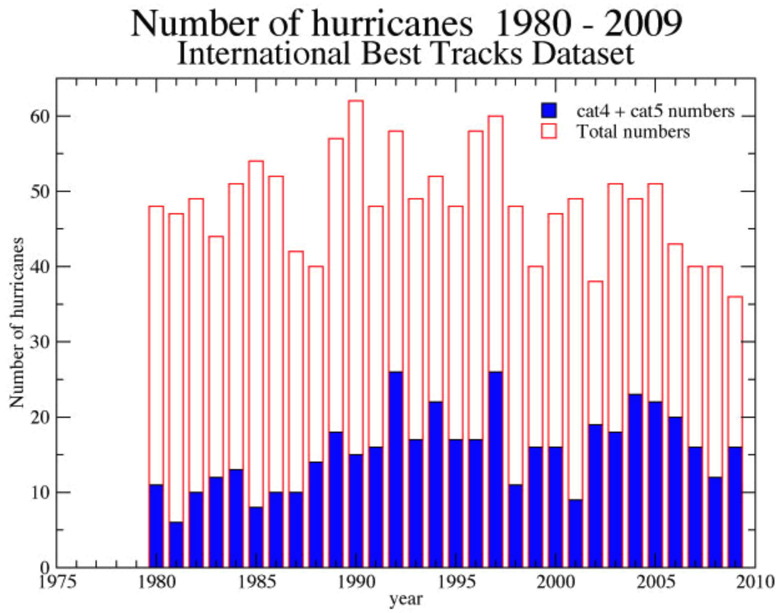
"[Knutson et al.'s] conclusions–that it is more likely than not that global tropical storm frequency will decrease and more likely than not that the frequency of the more intense storms will increase in some basins–are more specific than IPCC AR4, which concluded that there was "…less confidence [than likely] in these projections [of a decrease in the overall number of tropical storms] and in the projected decrease of relatively weak storms in most basins, with an increase in the numbers of the most intense tropical cyclones."

How should we interpret these differences in conclusions and confidence levels of the three different assessments? One issue is the time derivative factor of comparing assessments published in 2007, 2008, and 2010. The differences in confidence levels of the three different assessments reflect different groups of experts (with some overlap). Given the explicit reliance on the consensus among experts in the confidence assessment, it is not difficult to see how different groups of experts can assess the same information in different ways.

Detection of an increase in hurricane intensity?

Since the Webster, Holland, Curry, Chang (2005) paper was published, two major developments have occurred that have improved the global hurricane database. The first is development of the International Best Tracks (IBTrACS) dataset, which reflects a consolidation of the data relative to what was used by Webster et al. The second advance is the development of a new homogeneous satellite-based intensity analysis (developed by Kossin et al. 2007).

Data from 1980-2009 from the IBTrACS are used to recreate the Webster et al. analysis in Figure 16. Note, data from the 1970's are not used in this new analysis owing to the substantial uncertainty of data in the southern hemisphere.



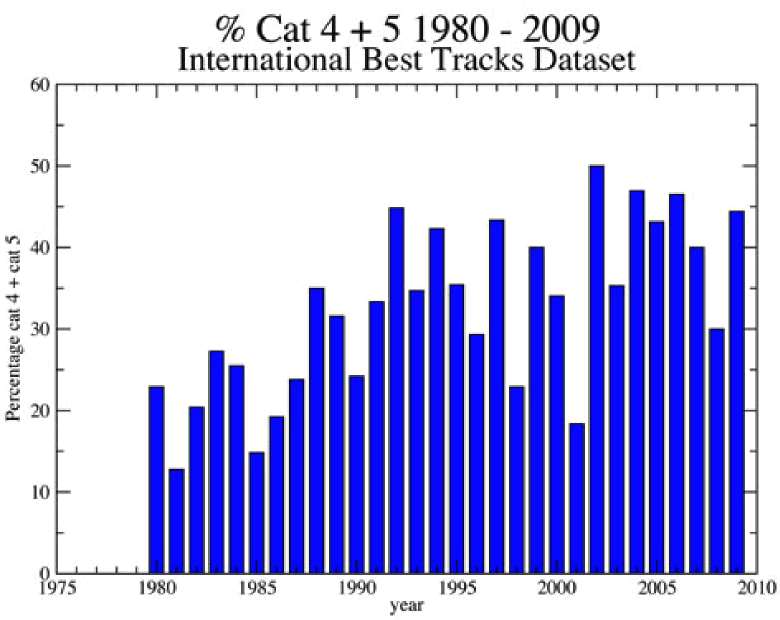


Figure 16: Frequency of global hurricanes and category 4 and 5 hurricanes since 1980; and percent of category 4 and 5 hurricanes relative to the total number of hurricanes.

The total number of global hurricanes shows no overall trend, with 2007, 2008, and 2009 ranking among the 4 lowest totals in the record. The numbers of category 4 and 5 hurricanes during 2007 2008, and 2009 are also correspondingly low. However, consideration of the % of category 4 and 5 hurricanes shows a continued overall increase, with 2002, 2004 and 2006 ranking as the highest years in the record, and all years since 2004 are above average except for 2008. Further support for an increase in the proportion of the most intense hurricanes is provided by Elsner et al. (2008) (using the Kossin et al. satellite dataset). Although not directly comparable with the Webster et al. analysis, Elsner et al. shows that the global increase in the % of most intense hurricanes is dominated by increases in the North Atlantic and also the North and South Indian Oceans.

Hence, the available information that we have on global hurricane intensity supports the original findings of Webster et al. (2005) of a global increase in the % of category 4 and 5 hurricanes, although the trend is somewhat smaller than that found by Webster et al. The increase in the % of category 4 and 5 hurricanes reflects a shift in the distribution of hurricane intensities, i.e. a fattening of the tail of the intensity distribution.

However, given the short period (since 1980) for which we have reliable intensity data, we cannot unambiguously attribute this increase to global warming. Linking the increase in % of category 4 and 5 hurricanes to increasing sea surface temperatures in the main TC formation regions does not provide a complete explanation for the increase in the % of category 4 and 5 hurricanes, nor can we unambiguously attribute all of the increase in tropical sea surface temperatures to global warming (as opposed to natural modes of variability such as AMO and PDO).

Detection of an increase in frequency of Atlantic hurricanes?

The global warming signal in the North Atlantic tropical cyclone count is difficult to discern owing to the convolution of the decadal climate signals with the global warming and the issue of undercounting in the earlier part of the data record. While there is an apparent increase in the frequency of Atlantic hurricanes over the past 100 years (Figure 7), Landsea et al. (2010) attribute this apparent increase to undercounting of short-lived tropical cyclones in the early part of the record.

With regards to the frequency of major hurricanes, there is substantial uncertainty in the classification of hurricanes during the period 1943-1970 as "major" (category 3-5). While there is general agreement that there are too many major hurricanes during this period, several attempts to make corrections to the intensity of major hurricanes during this period have not achieved a resolution to this problem. It is hoped that the recent analysis of Hagen and Landsea (2011) will provide a definitive solution to this issue.

Possible change of track location of Atlantic hurricanes?

There have been a few hypotheses in the scientific literature about possible changes in track location of Atlantic hurricanes with global warming. Greg Holland has a found a trend in the recent decade of more tracks into the Gulf of Mexico, but that could be associated with short term natural variability. A new paper submitted by Hoyos and Webster finds an eastward expansion of the North Atlantic warm pool and the main development region, with an associated eastward shift in the pattern of tropical cyclogenesis. The implication of more TC's forming from African Easterly Waves in the eastern part of the basin suggests that major hurricanes are more likely to recurve in the Atlantic rather than track into the Gulf. However, these ideas are speculative, and it remains very difficult to separate the impacts of natural variability from global warming.

Inferences of future hurricane activity from climate model simulations

Because of the coarse resolution of climate models, inferences about hurricane activity require either statistical relations between the model's predicted fields and hurricane activity, or some sort of downscaling with a seeding mechanism. The seeding is required because even at much higher resolutions, models do not always do a good job of predicting genesis (formation) of tropical cyclones. Prediction of hurricane intensity is very challenging, even in an operational forecasting environment using high-resolution models for a hurricane that has already formed. Given these issues with understanding and modeling tropical cyclogenesis and intensification, what kind of confidence should we have in inferences of hurricane statistics from climate model simulations? While such inferences are becoming increasingly sophisticated (e.g. Bender et al. 2010, Emanuel et al. 2008), we find it difficult to take them with more than a grain of salt: the seeding is artificial and intensification mechanisms are uncertain. Further, issues of climate model structural deficiencies of relevance to hurricane development have been raised with regards to the substantial disagreement between modeled and observed values of upper topospheric temperature and humidity.

Conclusions

Here is what we think can be stated with some sort of confidence:

- Hurricane frequency and intensity in the North Atlantic has likely [>66%] increased since 1970. The transition from the cold to warm phase of the AMO is a plausible explanation for this increase. Attribution of a portion of the increase in hurricane intensity to AGW would require (at minimum) resolution of the problems with the intensities during the period of 1945-1970 (encompassing the previous warm period of the AMO).
- It is likely [>66%] that the % of category 4 and 5 hurricanes has increased globally since 1980. Increased confidence requires continued efforts to reprocess the data. Attribution of any portion of this increase to anthropogenic global warming would require careful examination of the data and modes of natural variability in each of the regions where hurricanes occur.
- It is more likely than not [>50%] that the maximum intensity of the strongest hurricanes would increase in a warmer climate. While there is an absence of evidence against this hypothesis, there are also substantial uncertainties in the observations and theory.
- We do not currently place any confidence in climate model projections of future hurricane activity. At the same time, we recognize the substantial advances have been made on this front in recent years, particularly by the GFDL group and ongoing efforts by several other groups.

PROJECTIONS OF LANDFALL ACTIVITY 2011-2016

The challenges for the insurance and reinsurance industry to project future hurricane activity:

- autumn forecast of the following year's hurricane activity
- spring (Feb/Mar) forecast of the coming hurricane season
- provide some level of consistency from year-to-year

Predictability

No agreement exists in the academic literature regarding which predictor variables should be included in a model describing North Atlantic and US landfalling hurricane frequencies. Bove et al. (1998) found that the probability of two or more US hurricane strikes increased from 28% during an El Nino year to 66% during a La Niña year. Jagger and Elsner et al. examined the relation between US landfalling hurricane data and ENSO and NAO. Parisi and Lund (2008) found that NAO and the ENSO index can be used to model the US landfalling hurricane strike count. Dailey et al. (2009) examined the relation between Atlantic SST and US landfalling hurricanes. Kossin et al. (2010) investigated total frequency in terms of ENSO, AMM, NAO, and MJO. Villarini et al. (2011) model total and landfall frequency in terms of Atlantic SST, global tropical SST, ENSO, and NAO.

Based upon our analysis, we view the following variables as the most useful predictors for Atlantic hurricanes: AMO, NAO, ENSO (Modoki), PDO. Note: we do not use SST or the SST anomaly relative to global tropical SSTs since the covariance of these variables with hurricane activity is captured by the AMO and PDO. Further, use of SST as a predictor confounds the impacts of natural multi-decadal variability with global warming, in ways that can be misleading.

Predicting the U.S. hurricane landfalls 6-12 months in advance is associated with considerable challenges, since most of the predictors in the above-mentioned studies are not known 6-12 months in advance. For ENSO, there is the well-known spring predictability barrier; hence there is little predictability of ENSO for the coming hurricane season prior to May or June. While Jagger and Elsner claim that the Oct-Jan NAO index is a useful predictor for the following years landfall activity, the mechanism for this relationship is unclear.

The major portion of the predictability on these time scales lies in the assumption that a credible argument can be made that for the next five years, the AMO will remain in the warm phase, and the PDO in the cool phase. While the PDO is not widely used in predicting Atlantic hurricane activity, we find it to be useful on these time scales since the cool phase of the PDO is associated with a greater probability of La Nina events.

Prediction

The following landfall statistics are provided for the warm phase of the AMO:

HURDAT	Northeast	Mid-Atlantic	Southeast	Florida	Gulf	Texas	US
All	0.13	0.09	0.47	0.70	0.45	0.42	1.83
CAT1-2	0.04	0.08	0.32	0.42	0.30	0.25	1.09
CAT3-5	0.09	0.02	0.15	0.28	0.15	0.17	0.74

CFAN	Northeast	Mid-Atlantic	Southeast	Florida	Gulf	Texas	US
All	0.13	0.08	0.49	0.70	0.47	0.40	1.83
CAT1-2	0.11	0.08	0.43	0.42	0.32	0.23	1.21
CAT3-5	0.02	0.00	0.06	0.28	0.15	0.17	0.62

Table 2: Following Table 1, except for the warm phase of the AMO (using annual AMO indices).

Differences among these Tables and those provided by others may arise from differences in the base database (as described for Table 1), or in terms of exactly which years are included in the warm phase. We have elected to assign each individual year to the warm phase of the AMO based upon the annual average of the AMO index. Others may use a smoothed index so that year-to-year fluctuations in the sign of the index are eliminated.

Comparing Table 2 with Table 1, it is seen that the overall landfall frequency in the warm phase of the AMO is 8% higher than for the total period since 1900, and the frequency of major hurricanes is 10% higher. The warm phase of the AMO does not have a strong influence on location of the landfalls relative to the overall statistics since 1900.

Table 3 shows the landfall frequencies for the warm phase of the AMO combined with the cool phase of the PDO. The addition of the cool phase of the PDO results in a slightly greater number of total landfalls and lower number of major hurricane landfalls. The most significant difference relative to the warm AMO only (Table 2) is the distribution of the landfall locations: relative to the overall statistics since 1900 and the warm phase of the AMO, the warm AMO/cool PDO is associated with a greater number of landfalls on the Atlantic coast and fewer on the Florida and the Gulf coasts.

HURDAT	Northeast	Mid-Atlantic	Southeast	Florida	Gulf	Texas	US
All	0.19	0.15	0.62	0.50	0.27	0.46	1.85
CAT1-2	0.08	0.12	0.38	0.31	0.23	0.31	1.15
CAT3-5	0.12	0.04	0.23	0.19	0.04	0.15	0.69

CFAN	Northeast	Mid-Atlantic	Southeast	Florida	Gulf	Texas	US
All	0.19	0.12	0.65	0.50	0.27	0.42	1.85
CAT1-2	0.19	0.12	0.58	0.31	0.23	0.23	1.35
CAT3-5	0.00	0.00	0.08	0.19	0.04	0.19	0.50

Table 2: Following Table 1, except for the warm phase of the AMO and cool phase of the PDO (using annual AMO and PDO indices).

The analogue for the present period in terms of AMO/PDO is the period 1946-1964, with only a few years during the current period. In interpreting the numbers in these tables, it is important to understand that in any given year, a large variation from these numbers could arise; it is only over a number of years that the statistics from such projections are useful. For the range of year-to-year variations, it is instructive to consider Figure 15, which shows a range of 0-5 U.S. landfalls for individual years characterized by warm AMO/cool PDO. Hence these tables are most useful in the context of say 5-year predictions for periods during which a change point to a new regime is not expected.

With regards to the effects of global warming, it is very difficult to deconvolute any global warming effects from those associated with the AMO, PDO and ENSO. Relative to using data from the period 1946 to 1964 as analogues, the frequency of major hurricanes is known to be too large, so this period with its errors in the frequency of major hurricanes may actually be a fairly good analogue for the current period and the next 5 years.

Finally, how can we interpret 2004 and 2005 and their catastrophic impacts? Is there any way to have predicted these impacts 6-12 months in advance? 2004 was a Modoki El Nino year, which is not predictable until possibly May. 2005 was a year with a very high AMO index value, the third highest in the record. Predicting an anomalous year such as 2004 or 2005 up to 6-12 months in advance is beyond our current understanding and capabilities.

Forecast summary

Based upon the above analysis, we provide the following broad framework for making a forecast for U.S. hurricane landfalls for 2011-2016:

- Continuation of the warm phase of the AMO, with elevated frequency of total hurricanes, landfalls and major landfalls.
- Continuation of the cool phase of the PDO, with a dominance of La Nina events.
- Warm AMO/cool PDO is associated with (relative to the 110 year climatology) an increased frequency of landfalls along the Atlantic seaboard, but likely fewer landfalls within the US portion of the Gulf of Mexico.
- Increased chances of El Nino Modoki events relative to canonical El Ninos, with increased landfalls for all portions of the US coast in years they occur.
- Since the recent climate shift to cool PDO, global temperatures have not been warming, and there is no apparent reason to factor in any global warming impact (relative to the last 15 years) during this period.

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