Increased North Atlantic Hurricane Activity

A Summary of Relevant Literature

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Risk Management Solutions

INTRODUCTION

The North Atlantic has observed a substantial increase in both the number and intensity of tropical cyclones since 1995. The increased frequency and intensity of Atlantic hurricanes has caused a large debate in the tropical research community to determine the primary cause of the elevated activity. One area of research examines whether increasing tropical sea surface temperatures (SSTs) that are thought to modulate on time scales of decades are responsible for more intense and increasing numbers of tropical cyclones. An alternative hypothesis centers on the role of global warming in conjunction with natural variability within the climate system. A third group of researchers are actively investigating the reliability of historical hurricane datasets.

This document provides a brief summary of recent relevant papers surrounding this debate. RMS believes that users of the medium-term view of hurricane frequency issued in RiskLink® and RiskBrowser® 6.0 should have a basic understanding of the debate as to the possible causes of increased hurricane frequency. This document will be updated twice a year to provide the latest information regarding the range of perspectives on this debate.

Knutson, T. R., Tuleya, R. E. 1999: Increased hurricane intensities with CO_2-induced warming as simulated using the GFDL hurricane prediction system. *Clim. Dyn.* **15**, 503-519.

Knutson et al. (1999) explores the impact of a CO_2-induced global warming on the intensities of strong hurricanes by using the Geophysical Fluid Dynamics Laboratory (GFDL) regional high-resolution hurricane prediction system. Fifty-one northwestern Pacific storm cases are selected from the GFDL present day global model and simulated in the regional model with present day conditions. Another 51 Pacific storms are selected from the GFDL global model with increasing CO_2 at a rate of 1 percent per year, which are then simulated in the regional model with high CO_2 conditions. A limitation of the regional model is that ocean coupling effects were not included.

The hurricanes simulated between the present day and prescribed high CO_2 conditions reveal statistically significant differences. The environmental conditions between the two models reveal a warming of about 2.2°C for SSTs, 2.5°C in the lower troposphere, and a warming greater than 5°C in the upper troposphere. Surface wind speed increased 3-7 m/s (5-11 percent) in the hurricanes prescribed with the higher CO_2 environment and a lowering of central pressure by 7-24 mb. The near-storm precipitation is increased by 28 percent and the mean radius of hurricane force winds are increased 2-3 percent both in the high CO_2 model. One characteristic that remained fairly similar between the two simulations were the storm tracks. The authors conclude that in an environment with higher CO_2, strong hurricanes can be expected to be more intense.

Bengtsson, L., 2001: Enhanced Hurricane Threats. *Science*, 293, 440-441.

Bengtsson (2001) provides a general overview of hurricane formation and summarizes and discusses recent scientific publications indicating a potential link between increasing SSTs and the intensity of hurricanes. Bengtsson emphasizes the relatively short period of reliable tropical cyclone (TC) observations (60 years in the Atlantic Ocean and Western North Pacific, and only 30 years elsewhere) globally and the difficulties in determining a trend or reliable low-frequency variation in TC activity. However, in the Atlantic Ocean and Caribbean Sea multi-decadal trends have been observed, which are superimposed by yearly variations caused by El Nino Southern Oscillation (ENSO).

The latter half of the paper addresses how TC frequency and intensity might respond to climate change. Bengtsson states that the literature suggests that increasing SSTs would enhance TC development. TC development in a warmer climate would occur at higher oceanic temperatures, particularly in the case of intense tropical cyclones, because upper atmospheric warming compensates to some extent for the increased energy potential from the warmer ocean, supported by modeling studies. This leads Bengtsson to state that the broad geographical regions affected by tropical cyclones are not expected to change substantially. Although the number of cyclones may not increase substantially, Bengtsson cannot rule out that the strength of the most powerful and dangerous cyclones will remain the same. Given optimal conditions in a future warmer climate with an atmosphere potentially holding more moisture, the development of more intense cyclones cannot be ruled out. Given the large population increases in coastal areas and increasing investment in buildings and extensive infrastructure, there may be risks of high damage costs.

Vitart, F., and J. L. Anderson, 2001: Sensitivity of Atlantic tropical storm frequency to ENSO and interdecadal variability of SSTs in an ensemble of AGCM integrations. *J. Climate*, **14**, 533-545.

Vitart et al. (2001) produce ensembles of simulations with an atmospheric general circulation model (AGCM) to explore the mechanisms responsible for the observed variability in tropical storm activity in the North Atlantic. The investigation is a result of an observed reduction of tropical storm activity over the Atlantic Basin during El Nino and an opposite affect during La Nina events. The number of Atlantic tropical storms also displays an interdecadal variability with more storms in the 1950s and 1960s than in the 1970s and 1980s.

The study investigates interannual variability by prescribing SSTs of the 1980s everywhere except over the tropical Pacific and Indian Oceans where they vary based on an El Nino SST ensemble simulation and a La Nina SST ensemble simulation. When the models were forced by SSTs of an El Nino rather than a La Nina, the ensemble of AGCM integrations simulates significantly fewer tropical storms over the North Atlantic. The authors attribute this decrease in tropical storms to an increased simulated vertical wind shear over the Atlantic. The model ensemble was then forced to SSTs of the 1970s and compared the number of tropical storms to a model ensemble of SSTs of the 1950s. The 1970s' model ensemble demonstrated a significant decrease in the Atlantic tropical storms. These findings coincide with observations allowing the authors to conclude that the AGCM integrations is successful in simulating two examples of Atlantic tropical storm variability.

Solow, A. R., and L. J. Moore, 2002: Testing for a trend in North Atlantic hurricane activity, 1900-98. *J. Climate*. **15**, 3111-3114.

Solow et al. (2002) use the complete record of U.S. landfalling hurricanes back to 1900 to detect a trend in landfalling hurricane activity in the North Atlantic. This research expands upon an earlier paper that extrapolated an exponential linear trend to landfalling hurricanes since 1930. To test for a trend in the U.S. landfalling hurricanes, Solow et al. (2002) made several crude assumptions including: (1) there is no misclassification of hurricanes as tropical storms and vice versa; (2) the record of hurricanes making landfall in the U.S. is complete; and, (3) the probability that a hurricane makes landfall in the U.S. is constant over the period of analysis. With these assumptions in place, the trend is estimated non-parametrically and the hurricane landfalling activity does not reveal an exponential linear trend as seen with prior research using data back to 1930. This result led the authors to conclude that there is little evidence of a trend in overall hurricane activity in the North Atlantic.

Barnet, T.P., D.W. Pierce, K.M. AchutaRao, P.J. Gleckler, B.D. Santer, J.M. Gregory, W.M. Washington, 2005: Penetration of Human-Induced Warming into the World's Oceans. *Science*, **309**, 284-287.

Barnet et al. (2005) investigate the warming observed into the world's oceans by using an upgraded and expanded observed ocean dataset (Letivus, 2005). The authors want to understand the origin of the complex time- and space-dependent signal observed in the vertical temperature structure of the oceans and attribute the warming to either natural internal variability, external natural variability, or forcing arising from human activity. Climate models cannot replicate the warming observed in the past 40 years by only natural internal variability or natural external variability. However, by using five Parallel Climate Model runs with anthropogenic forcing, the authors discovered an ocean-by-ocean and depth-by-depth comparison that revealed very similar results to the observed ocean dataset from the past 40 years. This result led the authors to conclude that human influences are largely responsible for warming signal.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686-688.

Emanuel (2005) uses an approximation of the power dissipation (PD) called the power dissipation index (PDI), which is defined as the potential destructiveness of hurricanes, to estimate how hurricanes destructiveness has changed in the past 30 years. This approximation of the PD was necessary because historical tropical cyclone data is rarely reported with the dimensions of the tropical cyclone. The author makes a case that this PDI is a better method in calculating trends in hurricane intensity with changes in global mean SSTs than analyzing only hurricane frequency because both PDI and monetary loss are correlated to the windspeed. Tropical cyclone variability in the North Atlantic has been attributed to regional climate phenomena such as the Atlantic Multidecadal Oscillation (AMO) and ENSO. Emanuel also discusses how basic theory establishes a limit on hurricane intensity called a *potential intensity*, which through global climate models have shown a substantial increase with anthropogenic warming.

To emphasize long-term trends and interdecal variability, Emanuel accumulated the PDI over an entire year and individually over each of the several major cyclone-prone regions. Additionally, Emanuel statistically smoothed the PDI to minimize the effect of interannual variability. The PDI for the North Atlantic and the September mean tropical SSTs averaged over one of the prime genesis regions in the North Atlantic revealed a strong correlation (r2 = 0.65), suggesting that tropical SSTs exert a strong control on the PDI. Emanuel notes the large upswing in the PDI over the last decade is unprecedented, and probably reflects the effects of global warming. Similarly, the smoothed PDI for the western North Pacific compared against the July through November average SSTs in a primary genesis region for the North Pacific is strongly correlated (r2 = 0.63). Emanuel then calculated the correlation between the annual averaged smoothed SSTs between 30°N and 30°S and the sum of the North Atlantic and western North Pacific smoothed PDI to reveal a strong correlation (r2 = 0.69). The large increase in PDI over the past 30 years may be because storms have become more intense on the average and/or have survived at high intensity for longer periods of time. Emanuel reports that the accumulated annual duration of storms in the North Atlantic and western North Pacific have increased by roughly 60 percent since 1949 and the annual storm peak windspeed has also increased by about 50 percent. Emanuel concludes that only part of the observed increase in TC PDI is directly due to increased SSTs because tropical cyclones do not directly correspond to SSTs. Instead, tropical cyclones are also dependent upon the atmospheric conditions.

Kerr, R.A., 2005: Is Katrina a Harbinger of Still More Powerful Hurricanes. *Science*, **309**, 1807.

Kerr provides a one-page summary of the research being conducted on finding links between global warming and tropical cyclones. A study has found an 80 percent increase worldwide in the abundance of the most powerful TCs in the past 35 years. Kerry Emanuel says that there is a strong suggestion of a link between the growing greenhouse effect and intensifying tropical cyclones. However, he points out that coastal areas have swollen in population in recent decades and that the increase in damage due to demographics has more impact than any sign of increased damage due to storm intensification. Webster et al. (2005) have found no long-term trend in the number of storms per year but have found a sharp increase during the past 35 years in the number of category 4 and 5 TCs. However, Trenberth, Pielke Jr., and Knutson question the trends other researchers are observing.

Kerr, R.A., 2005: Atlantic Climate Pacemaker for Millennia Past, Decades Hence? *Science*, **309**, 41-43.

Kerr provides a two-page summary of the research being conducted to provide a longer view of how the AMO has varied and implications for TCs in the Atlantic Ocean. The Gulf Stream and the rest of the ocean conveyor have caused fluctuations in the Atlantic SSTs, which in turn cause variability in Atlantic TC. The AMO period is approximately a 60- to 80-year cycle over the past few centuries. AMO's cold years have favored less hurricanes making landfall on the U.S. during the years 1903-1925 and 1971-1994 while AMO's warm years have favored a significant increase in landfalling hurricanes in the U.S. from 1926-1970 and 1995-present.

Saunders, M. A., and A. S. Lea, 2005: Seasonal prediction of hurricane activity reaching the coast of the United States. *Nature*, **434**, 1005-1008.

Saunders et al. (2005) uses a statistical model that incorporates July wind anomalies averaged between 925-400 mbars (data from NCEP/MCAR reanalysis) to predict wind energy of U.S. landfalling hurricanes for the following hurricane season. The tropospheric wind anomalies are compared to the U.S. Accumulated Cyclone Energy index (US ACE), which is defined as the sum of the squares of hourly max sustained windspeeds from all tropical cyclones over the U.S. mainland that have wind of at least tropical storm strength.

The authors have found the US ACE index is linked significantly to tropospheric height-averaged wind anomalies occurring over North America, the eastern Pacific, and the North Atlantic. An anticyclonic flow anomaly associated with a strengthened and northward displaced Bermuda high pressure area is a prominent feature found in their analysis. This feature tends to persist and ridge westwards during August and September promoting onshore wind anomalies along U.S. East Coast during August through October. Saunders et al. (2005) then performed statistical analyses of this method to past hurricane seasons to identify the skill of this method. Using the July height-averaged wind index, the US ACE index is predictable from August 1 with a correlation skill of 0.65-0.70, which is an improvement of 36-40 percent over climatology.

Trenberth, K., 2005: Uncertainty in Hurricanes and Global Warming. *Science*, **308**, 1753-1754.

Trenberth (2005) analyzes how the North Atlantic SSTs have varied over the past 130 years and the possible connection to the number of TCs and their intensity. In the North Atlantic Ocean, SSTs and hurricane activity vary widely on interannual and multidecadal time scales attributable to factors such as the ENSO and the thermohaline circulation, referred to as the Atlantic multidecadal oscillation (AMO). Combined with this variability there is a non-linear upward trend in SSTs during the 20th century in the North Atlantic Ocean that has been associated with global warming and attributed to human activity.

Trenberth explores the possibility of having increased SSTs and the implications on the number of TCs and their intensity. Trenberth notes that SSTs are not the only variable influencing hurricane activity. However, higher SSTs increase the water vapor in the lower atmosphere. Since 1988, the amount of total column water vapor over the oceans has increased by 1.3 percent per decade. The combination of the higher SSTs and increased water vapor increases the energy for convection.

Trenberth invokes a term called the Accumulated Cyclone Energy (ACE), which is a measure of regional storm activity. Since 1995, the ACE index has been above normal except for two seasons that have been normal and that were linked to El Nino years. Trenberth states that "despite enhanced activity, there is no sound theoretical basis for drawing any conclusions about how anthropogenic climate change affects hurricane numbers or tracks, and thus how many hit land." However, Trenberth concludes that although the variability in SSTs is large, trends associated with human influences are evident where hurricanes form, which suggests the intensity of and rainfalls from hurricanes are probably increasing but the effect on hurricane numbers remain unclear.

Webster, P. J., G. J. Holland, J. A., and H.-R. Chang, 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, **309**, 1844-1846.

Webster et al. (2005) have examined the variations in hurricane characteristics for each ocean basin in the context of the ocean basin SSTs variations for the satellite era (1970-2004). Ocean SSTs have increased 0.5°C between 1970 and 2004. A Kendall trend analysis was used and trends in each ocean basins are significantly different from zero at the 95 percent confidence level or higher except for the southwestern Pacific Ocean. However, the time series for the global number of TCs and number of TC days for 1970 2004 do not show a trend that is significantly different from zero. The authors do note that there are substantial decadal-scale oscillations that are observed especially in the number of TC days. The only ocean basin that exhibits a statistical difference to the global averaged time series is the North Atlantic, which exhibits an increasing trend in frequency and duration that is significant at the 99 percent confidence level.

The authors note that against a background of increasing SSTs, there has been no global trend that has emerged in the number of TCs. Only the North Atlantic has shown a statistical significant increase in the number of TCs, which commenced in 1995. However, there has been a substantial change in the intensity distribution of hurricanes globally. The number of category 1 hurricanes has remained approximately constant but has decreased monotonically as a percentage of the total number of hurricanes through the 35-year period. In contrast, the number of category 4-5 hurricanes has almost doubled in number and in proportion in all ocean basins. Thus, the authors conclude that the global TC dataset indicates a 30-year trend toward more frequent and intense hurricanes in the future.

Chan, J. C. L., 2006: Comment on "Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment", *Science*, **311**, 1713b.

Chan (2006) comments on the Webster et al. (2005) study by utilizing an analysis of TC records from the western North Pacific from 1960-2004. Chan examined the potential destruction index (PDI) and the number of category 4-5 hurricanes. The data reveals that the recent increase in occurrence of intense typhoons is not a trend. Chan demonstrates that the number of intense typhoons numbers shown in Webster (2005) is part of large interdecadal variation similar to variations in the atmospheric environment. Furthermore, Chan argues that local SSTs, which have been increasing since the 1970s, cannot explain the fluctuations in typhoon activity.

Enfield, D. B., and L. Cerrano, 2006: Projecting the risk of future climate shifts. *Int. J. Climatol.*, **26**, 885-895.

Enfield et al. (2006) has developed a method to estimate probability distribution functions from a long climate index series that can calculate the probability of a future decadal-to-multidecadal regime shift. The authors test their method on the AMO because of recent paleoclimate research that has extended the AMO index back to the late 1500s. They find the AMO to have been nonstationary over the last half millennium and the associated uncertainty in probability is approximately 2-5 percent. Lastly, the authors comment on how global climate change may affect future climate regime characteristics. They note that if the true future distribution parameters are different from those in the past, the effect on risk projection is to shift all probabilities in the same direction and by similar amounts.

Hoyas, C.D., P.A. Agudelo, P.J. Webster, J.A. Curry, 2006: Deconvolution of the Factors Contributing to the Increase in Global Hurricane Intensity. *Science Express,* 16 March 2006.

Hoyas et al. (2006) addresses the contributions of natural internal variability on decadal and shorter time scales compared to a longer term trend and identifying the importance of SSTs in causing the increase in number of category 4-5 hurricanes, relative to other known variables that influence hurricane intensity. To address these issues the authors describe the time series of SSTs, specific humidity in the layer 925-500 mb, wind shear between 850 and 200 mb, and the 850 mb zonal stretching deformation between 1970 and 2004 globally. The authors use a methodology called *information theory* that isolates the trend from the shorter term natural modes of variability. In the long term category 4-5 hurricane trend, SSTs dominate all other variables and are statistically significant. This indicates that the increasing number of category 4-5 hurricanes is directly linked to the trend in tropical SSTs. Other variables responsible for hurricane formation influence shorter term variation and do not contribute significantly to the global trend of increasing hurricane intensity.

Klotzbach, P.J., 2006: Trends in global tropical cyclone activity over the past twenty years (1986-2005). *Geophys. Res. Lett.*, **33**, L10805, 1-4.

Klotzbach (2006) investigates worldwide TC frequency and intensity to determine trends in activity over the past 20 years during which there has been an a 0.2° – 0.4°C warming of global SSTs. Klotzbach uses "best track" data sets from 1986-2004 for all TC basins, which is the best estimate of the locations and intensities of TCs at 6-hour intervals produced by international warning centers. The data indicates a large increasing trend in TC intensity and longevity for the North Atlantic Basin and a decreasing trend for the Northeast Pacific. The North Atlantic Basin TC increase has been attributed to an increase in strength of the Atlantic thermohaline circulation. The remaining basins demonstrate a small trend.

Klotzbach reveals that there has been no significant change in global net TC activity and only a small increase in category 4-5 hurricanes when comparing data from 1986-1995 to 1996-2005. Klotzbach attributes this small increase to improved observational technology. However, the North Atlantic Basin has seen an increase in category 4-5 hurricanes by approximately 250 percent in the past 20 years. Klotzbach performed a Student's t-test between SSTs and observed TC intensity. A statistically significant relationship between SSTs and Accumulated Cyclone Energy (ACE) as well as SSTs and category 4-5 hurricanes exist for both the North Atlantic and Northeast Pacific. However, these correlations only explain 25-30 percent of the variance, indicating that large amounts of variance are unexplained. Klotzbach states that atmospheric and oceanic features are also critical for TC development and intensification besides warmer SSTs.

Mills, T. C., 2006: Modeling Current Trends in Northern Hemisphere Temperatures. *Int. J. Climatol.*, **26**, 867-884.

There is little consensus on which statistical method is appropriate to fit a trend to a dataset. Mills (2006) considers a range of trend extraction techniques and uses them to estimate the trend of annual mean Northern Hemisphere temperatures. This study compares four trend techniques: the AutoRegressive Integrated Moving Average (ARIMA) decomposition, parametric techniques, non-parametric regression, and the Hodrick-Prescott and Butterworth low-pass filtering techniques, none of which require padding out the series beyond the end of the available observations.

A comparison of trends estimated from the Northern Hemisphere temperature dataset from 1856-2003 provides a robust indication of the likely range of current trend temperature increases. The parametric trends have an advantage because the trend can estimate the precision with which the trend and its slope are estimated and can be calculated. In all trend extraction techniques the trend is characterized as having long waves about an underlying increasing level with peaks around 1873 and 1948 and troughs around 1909 and 1970. Since around 1970, all techniques display a pronounced warming trend with the period since 1970 having been twice as fast as that of the earlier warming period between 1910 and 1948.

Sriver, R., M. Huber, 2006: Low frequency variability in globally integrated tropical cyclone power dissipation, *Geophys. Res. Lett.*, **33**, L11705

Tropical cyclone intensity and frequency distributions are hypothesized to be modulated by a number of natural phenomenon and also controversially to trends in tropical SSTs associated with global warming. To investigate the correlation between trends in tropical SSTs and trends in TC frequency and intensity, Sriver et al. (2006) calculated an annually integrated power dissipation (PD), a measure of the potential destructiveness of a TC based on surface windspeed and storm duration, globally from 1958-2001 by using near-surface wind data from the European Centre for Medium-Range Weather Forecasts' 40-Year Reanalysis (ERA-40). The PD was then compared to ERA-40 2-meter air temperatures and SSTs. Their approach complements previous estimates by using a different data source, adopting a more objective analysis approach (they do not correct data), and making fewer assumptions. A drawback to this method is that they are not able to identify shorter varying processes such as ENSO.

The ERA-40 PD correlates with 2-meter air temperatures (r2 = 0.34) and the correlation improves (r2 = 0.40) when PD is compared to mean annual tropical SSTs. This indicates to the authors that a substantial potion of the low frequency variance in globally integrated PD can be attributed to changes in mean tropical SSTs. A regression fit was calculated between SSTs and PD and demonstrates that a 0.25°C increase in mean annual tropical SSTs corresponds roughly to a 60 percent increase in global PD. They conclude that PD is an important quantity that appears to correlate with trends in tropical temperatures and may be an important feature for understanding the long-term evolution of integrated TC intensity.

WEBSTER, P. J., J. A. CURRY, J. LIU, G. J. HOLLAND, 2006: RESPONSE TO COMMENT ON "CHANGES IN TROPICAL CYCLONE NUMBER, DURATIONS, AND INTENSITY IN A WARMING ENVIRONMENT", *Science*, **311**, 1713C.

Webster et al. (2006) respond to comments made by Chan (2006). The authors argue that there are unquestionably complex and strong signals of natural variability in both the hurricane statistics and SSTs in the western North Pacific. However, they point out that the main conclusion in Webster et al. (2005) (there is a shift in the distribution of hurricane intensity with increasing SSTs) is not refuted by the data presented in Chan (2006). Webster et al. (2006) argue that the percentage of the number of category 4-5 hurricanes is a far better indicator than the number of category 4-5 hurricanes because the latter is dominated by the large natural variability. The correlation of the percentage of the number of category 4-5 hurricanes with SSTs is clearly seen on a multidecadal time scale since 1960. The authors conclude should SSTs continue to rise under anthropogenic forcing, it is reasonable to expect that this relationship will be maintained and that there will be an associated increase in the intensity of typhoons.