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Hurricanes: A Primer on Formation, Structure, Intensity Change and Frequency

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About the Author

Dr. Robert Hart is an Assistant Professor in the Department of Meteorology at Florida State University. His research interests include: cyclone genesis and development (tropical and extratropical), hybrid cyclone structure, cyclone structural transition (including tropical and extratropical transition) and predictability, synoptic meteorology and weather forecasting, statistical and numerical weather prediction, ensemble forecasting and visualization techniques. He holds a PhD from Pennsylvania State University. He is the 2006 American Meteorological Society Banner I. Miller Award winner for outstanding contribution to the science of hurricane and tropical weather forecasting.

Foreword

The 2005 hurricane season visited major destruction on the United States. The devastation of the Gulf Coast, the loss of life, and dislocation of hundreds of thousands is a tragedy that we will not soon forget.

Unfortunately, last year's experiences are also being used to advance claims about climate change. It has been widely asserted that warming global temperatures are producing more frequent and more intense tropical storms. Overly focusing on that linkage detracts from serious consideration of what can and should be done to mitigate the damage from similar storms in the future.

This paper explains how hurricanes form and the challenges faced in predicting where they go, how strong they are, and how frequently they will occur. It describes the limits of the observational record. Given those limits, the pronouncements of those who claim that human activities are causing more frequent and more intense hurricanes should be reviewed with a critical eye.

With more and more people moving to coastal regions, bringing with them greater and greater wealth, damage from future hurricanes will only continue to grow. The nation will be served well by focusing on ways to mitigate the impact of those storms on property and devising more effective evacuation plans for use when necessary. Those are the true lessons for the 2005 hurricane season.

Wise climate policy will flow from improved understanding of what science can and can not explain. This paper also advances that cause as well.

We thank Dr. Robert Hart for preparing this paper.

— Jeffrey Kueter, President, George Marshall Institute

Hurricanes: A Primer on Formation, Structure, Intensity Change and Frequency

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The 2005 hurricane season devastated the lives of thousands of people on the Gulf Coast. Financial losses related to the hurricanes far exceeded previous records and the loss of life was the largest in the United States since the Florida Keys hurricane of 1928. This record-breaking activity has led to increased discussion of hurricane science. This primer examines the fundamentals of tropical cyclone formation, structure, movement, and frequency to better inform future discussions of hurricanes, their causes, and effects.

1. Tropical cyclone structure and formation

A cyclone is a circulation in the atmosphere with lower atmospheric pressure that rotates counter-clockwise in the northern hemisphere and clockwise in the southern hemisphere. We define a tropical cyclone as a non-frontal [absence of the warm and cold fronts typically associated with winter-type storms], "warm-core" storm with a sustained wind speed of at least 34 knots (kt) or 39 mph that forms in or near the tropics. "Warm-core" means that, on average, the temperature near the center of the cyclone is warmer than the surrounding environment. A tropical cyclone's strongest wind speeds are generally located about 1500 feet above the surface and the strength of the wind decreases both above and below that level (Franklin et al. 2003). However, it remains strong enough at the surface to be able to cause considerable damage. This wind structure—stronger winds in the lower atmosphere than in the upper atmosphere (upper troposphere)—is a direct consequence of the warm-core structure.

Tropical cyclones usually form within 25° of the Equator, but they can form as far as 40° from the Equator (Elsberry 1995), which is as far north as New York City or as far south as Melbourne, Australia. Regardless of where it originates, in order to form a tropical cyclone requires a relatively small, closed circulation, that is, a low-pressure area less than 500-1000 km in diameter, within 5000 feet of the surface that has a substantial concentration of thunderstorms inside it. It is not currently well understood what quantifies "substantial concentration of convection" in terms of its extent over time or space. Frequent thunderstorms day after day within this closed circulation concentrate precipitation and the formation of precipitation itself heats the atmosphere. If the closed circulation is sufficiently strong and small and the thunderstorms occur close enough to its center, the heat is focused within the circulation by both the rotation of the circulation itself and the rotation of the Earth (Coriolis deflection). This precipitation-induced heating lowers the surface pressure and strengthens the winds of the closed circulation. Wind rushes inward toward the strengthening low pressure system which causes evaporation of warm ocean water into

* *The views expressed by the author are solely his own and may not represent those of any institution with which he is affiliated.*

the atmosphere. This evaporation moistens and cools the lower atmosphere, but strong heating by the ocean typically counteracts the evaporative cooling. Heat flux off the warm ocean can also overcome the cooling caused by downdrafts from the thunderstorms. If other conducive conditions are in place, such as weak winds between 20,000 and 30,000 feet, minimal dry air (which dissipates thunderstorms), and sufficiently warm (on average 75-85°F) ocean temperature (Gray 1968), this process can lead to a runaway intensification (Emanuel 1986) stopped only by strong winds aloft, landfall, cooler waters, or friction with the land or water (Bister and Emanuel 1988). However, this maximum "potential" intensity (Emanuel 1988) is rarely attained by a hurricane, since one of the previously mentioned factors typically weakens the storm before it can reach its theoretical limit.

In the Atlantic basin, the source of the tropical cyclone is typically an atmospheric wave (usually called an easterly wave) that forms over northern Africa (5-15° latitude) and moves westward into the Atlantic. Once the wave moves over sufficiently warm water, a tropical cyclone can arise in the process described above. How quickly this happens depends on how warm the ocean water is, which depends on the time of year, the latitude at which the wave leaves the African continent and enters the Atlantic, and the other atmospheric parameters described above. Another source of tropical cyclones is cold fronts that move into the lower latitudes and then stall, creating regions in which thunderstorms can focus (e.g., Hurricane Erika in 2003). A third source is a fall/winter-type cyclone that moves equatorward into the lower latitudes and, if over warmer water for a sufficiently long time, can transition into a tropical cyclone (e.g., Tropical Storm Ana in 2003). A fourth source is a complex of thunderstorms that forms over land, organizes a circulation, and then moves over water (e.g., Hurricane Danny in 1997). These latter three formation methods are less common than the easterly-wave formation source in the Atlantic, but not rare. In addition, more than one genesis method may act at once to produce a tropical cyclone. There are also other formation methods peculiar to other basins of the world that will not be discussed here.

At a sustained wind speed of 64 kt (74 mph), the tropical cyclone becomes a hurricane in the Atlantic and east Pacific basins, a typhoon in the western Pacific basin, and acquires the name tropical cyclone in the Indian Ocean. Numerical model prediction of the formation of tropical cyclones is not very accurate, but has improved in the past decade due to better satellite technology, numerical forecast models and their use of the satellite data, and human forecaster experience with both. The Saffir-Simpson intensity scale ranks a hurricane in one of five categories based upon its maximum sustained wind speed. Although Category 1 and 2 hurricanes make landfall regularly in the United States, higher intensity hurricanes (Categories 3 through 5) make landfall less frequently than Category 1 or 2 hurricanes (Neumann et al. 1993; Landsea 1993; Elsner and Kara 1999). Only three hurricanes have made landfall as Category 5 intensity (Labor Day Hurricane of 1935; Camille in 1969; Andrew in 1992). As intense as Rita and Katrina were in 2005, they thankfully weakened well below Category 5 prior to landfall.

2. Tropical cyclone motion prediction

Tropical cyclones move under the influence of the wind field in which they are embedded and also under the influence of more complex factors not to be discussed here (Elsberry 1995). Hurricane track prediction is usually carried out using a combination of numerical computer models that simulate the atmosphere and attempt to predict where the storm will go. Occasionally the track forecasts are relatively easy, for example, when the wind surrounding the storm is uniform speed and direction and is observed well by satellites. However, hurricanes are often located in regions where the wind strength and direction varies with height above ground, called wind shear. In such a situation, which is more typical, the direction the storm will move depends on the tropical cyclone's intensity (Velden 1993). Further, we may not fully observe the actual wind surrounding the storm and computer models may incorrectly forecast the storm track. However, there have been considerable advances in the past two decades in tropical cyclone track prediction (McAdie and Lawrence 2000), largely resulting from increased satellite observations of the atmosphere (Velden et al. 1997), their incorporation within numerical models (Velden et al. 1998), improved computer power, and accounting for established model biases (Krishnamurti et al. 2000). Some of the most challenging tracks to forecast occur when a frontal system approaches a tropical cyclone and forecasters are unsure whether the front will pull the storm out to sea to the higher latitudes or if the front will pass by the storm, leaving it in the tropics. In these situations, track forecasts can be off by several hundreds of miles after a few days (e.g., Hurricane Alberto in 2000). Naturally, the intensity of the storm depends upon where the storm ends up moving since that determines the ocean temperatures, among other things. Thus, track and intensity are often, but not always, related. It is important for the public to realize that although track forecasts typically represent a line on a map, there is a great uncertainty about that line and that uncertainty grows quickly with forecast length. The public should not focus so much on the line itself, but rather on whether they are within the cone of uncertainty attached to that line—which should also be graphically portrayed by private and public forecasters alike.

3. Tropical cyclone intensity prediction

It is exceptionally difficult to predict hurricane intensity accurately. The Achilles' heel of computer models is thunderstorms and their prediction; tropical cyclones are primarily driven by thousands of thunderstorms and their interaction. Although hurricane intensity forecasting has improved somewhat over the past few decades, it has achieved nowhere near the rate of improvement of track forecasting (http://www.nhc.noaa.gov/verification). Forecasters have considerable success in predicting intensity when all atmospheric and oceanic conditions are conducive and the tropical cyclone is already intense. In such a situation, continued intensification is often correctly forecast. Even in those situations, however, the *rate* of intensification is often underestimated (e.g., Hurricanes Katrina, Rita, and Wilma in 2005). Processes within the interior of the storm itself, such as eye size and eyewall evolution, are believed to be key to short-term forecasting of intensity. However, it is not well-understood how to forecast these short-term changes since not all intensifying storms have dramatic changes in eye size. Further, unless the storm is close to land and within radar or airplane coverage, it is often difficult to observe the details of the storm core.

Occasionally there are tornado outbreaks within tropical cyclones at landfall (Gentry 1983; Spratt et al. 1997). The introduction of a land surface, often warmer and with higher friction, under part of the tropical cyclone can lead to localized spinup of convection into tornados. The forward quadrant right of motion is most favored for this occurrence, although tornados can occur in other quadrants, especially when the land distribution is focused within that quadrant. During very intense landfalling hurricanes, such as Andrew, the eyewall can often produce tornados from the sudden increase in friction (Wakimoto and Black 1993; Willoughby and Black 1996). The damage in the region of tornado occurrence is often a Saffir-Simpson category higher than those without tornados. However, it should be noted that tornado occurrence for any given location is very rare and that the majority of observed hurricane wind damage does not occur from tornados but rather from the hurricane wind itself.

Considerable work has been performed on statistical prediction of hurricane intensity change (Jarvinen and Neumann 1979; DeMaria and Kaplan 1999; Krishnamurti et al. 2000). Through an examination of the current storm intensity, the oceanic temperatures, the wind speed and wind direction at 20,000-30,000 feet, and interaction with nearby atmospheric features (fronts, other cyclones), forecasters are able to make forecasts of possible intensity from 12 hours to several days. However, the skill of these forecast intensities decreases rapidly as one goes further into the future. *Users of tropical cyclone track and intensity forecasts, regardless of the source, should be keenly aware that forecast error beyond 2-3 days can be extreme and great caution should be used. The public should not focus on the infinitely thin track line or single intensity value that is forecast, but instead focus on whether their own location of interest is within the cone of possible landfall alone. This cone becomes larger as forecast length increases. The public should be aware that intensity forecasts can be in error by far more than one Saffir Simpson category, even if the track forecast is correct.* This uncertainty in track and intensity is a well-accepted fact of scientific understanding and is true regardless of the source of the forecast, academic, private, or government.

4. Cycles of tropical cyclone frequency

There are often dramatic changes in tropical cyclone frequency from year to year or decade to decade within a given region, for example, the Atlantic Basin or Pacific basin. Although 2004 and 2005 were exceptionally active years in the Atlantic basin, they were considerably below average activity in several other basins around the world, such as the Pacific. The decades from the late 1930s through the early 1960s were above average for tropical cyclone occurrence in the Atlantic, while the 1970s through early 1990s were below average decades. Preliminary research suggests that since 1995, the Atlantic basin has returned to the more active phase of the seemingly natural cycle, possibly similar to the 1930s-1960s. Indeed, there does appear to be a multidecadal frequency of tropical cyclone occurrence in the Atlantic basin. Previous research has attributed this multidecadal oscillation in the Atlantic basin to rainfall across the Sahel of Africa (Landsea and Gray 1992) or the strength of the slow-moving oceanic currents that transport colder freshwater (from melted snow) toward the equator and warmer ocean saltwater toward the poles (Gray and Sheaffer 1997). However, it is important to note that the period of record is short and that the record of tropical cyclone occurrence prior to 1960 is quite likely incomplete due to the lack of satellites to observe tropical cyclones at sea. It is also important to note that globally there has been no dramatic change in net (global) hurricane frequency over the past few decades (Henderson-Sellers et al. 1998; Emanuel 2005).

Pioneering work by Prof. William Gray has lead to seasonal forecasting of hurricane frequency in the Atlantic basin as early as the winter preceding the hurricane season. These forecasts are made possible through an increased understanding of the factors globally that affect the probability of hurricane formation in the Atlantic, such as El Niño/La Niña. By winter or spring of the year preceding the hurricane season, many scientists and organizations globally now produce their individual forecasts of the number of hurricanes (both major and total) and tropical storms overall to form in each basin. It must be noted, however, that it does not take an active season overall to produce a catastrophic amount of damage and loss of life. Hurricane Andrew (1992) occurred during one of the least active Atlantic hurricane seasons on record. Further, the question of forecast skill of these seasonal forecasts has been brought into question since preliminary results (Holland et al. 2006) showed that a short-term climatology (previous five year hurricane frequency mean) outperformed many seasonal forecasts examined.

Unfortunately, the vast growth of coastal population occurred during (and perhaps was associated with) a time when the Atlantic basin was undergoing a minimum of hurricane activity (1970s-early 1990s) (Pielke and Landsea 1998). Thus, the percentage of U.S. population that experienced the maximum of hurricane activity in the 1930s-1960s is decreasing rapidly, producing a population that at least by age has not experienced what history had to offer in terms of hurricane threat (Elsner and Kara 1999).

5. Long-term trends of tropical cyclone activity

In addition to the multidecadal trends previously discussed, there has been considerable discussion in the scientific community lately questioning whether, in light of the events of 2004 and 2005, global warming has contributed to a long-term increase in hurricane activity and whether this long term trend would lead to a dramatic increase in hurricane intensity in the coming century. The first observationally-based scientific evidence of increasing hurricane destructiveness over the past three decades was published in the past year (Emanuel 2005; Webster et al. 2005; Hoyos et al. 2006). These three studies argued that there has been a substantial increase in the frequency of intense hurricane existence since 1970 (globally and within the Atlantic basin) and that it is primarily due to ocean temperature increases over that same period. However, when such hurricane activity is measured at landfall points only (J.J.

O'Brien, personal communication; K. Emanuel, ***http://wind.mit.edu/~emanuel/anthro2.htm***; Landsea 2006), the dramatic hurricane frequency increase found in the three prior studies greatly decreases or becomes nonexistent. Although these latter results may be viewed by some as more reliable since a hurricane's intensity and location are far more reliably measured at landfall than while at sea, the number of landfalls is smaller in comparison to the total number of hurricanes overall, and thus the landfall significance becomes less reliable for long-term trend calculations.

Recent climate modeling studies have predicted a general intensification of hurricanes in a globally-warmed climate, but also predict that the total number of hurricanes globally will not increase (Knutson and Tuleya 1999; Knutson and Tuleya 2004). These modeling studies have also been brought into question. In particular, some scientists have noted that these and other hurricane models also generally either vastly overpredict or underpredict the intensity of hurricanes in the current climate. Thus, the general lack of forecast skill in model forecast hurricane intensification in the current climate may decrease the validity of intensification forecasts based upon future climate change. Despite the disparate scientific opinions on these studies, these studies all represent the first solid attempts at quantifying a trend and answering a question that has remained subjective and purely theoretical for some time.

As alluded to, the results found in the previous studies have been met with great controversy, and some scientists have raised concerns about the conclusions found in those studies based upon the evolving observational record. In particular, it has been suggested there has been a dramatic increase in the number and quality of observations of tropical cyclones over the past century (Landsea 2006). During the first half of the century, a tropical cyclone was only observed if it struck land in populated regions or if a ship encountered it at sea and survived to report it (e.g., the 1938 New England hurricane). Accordingly, several scientists note that it is quite likely that during the first half of the century the record underestimates the total number of tropical cyclones that occurred within the Atlantic basin and perhaps all basins. With the advent of the space age in the 1960s, satellites for the first time photographed cyclones at sea. As satellite coverage increased, hurricanes were far more likely to be observed. Further, more reliable intensity estimates have been available since the 1980s, when a method was established to estimate hurricane intensity from the hurricane's structure on the satellite image (Dvorak 1984). Thus, the historical record is likely more complete for the recent period. However, previous research has also suggested that airplane flights into hurricanes may have overestimated the intensity of hurricanes in the 1960s and 1970s, based upon the less reliable equipment then used and the lesser understanding of hurricane structure at the time (Landsea et al. 2004).

The result of all of these caveats is that the historical record of hurricane occurrence and intensity—although the most complete available—is replete with uncertainties, holes, changing biases, and probable errors that may be obscuring a potential signal of long-term increase. It has been noted that several other atmospheric events (e.g., tornadoes) and atmospheric-related events (airplane delays) have seen a dramatic increase in occurrence over the past several decades, almost exclusively the result of population (and, thus, observational) increase. Presumably the tornado trend has not been tied to climate change since their observational biases over the past decades are even more striking than that for hurricanes.

In summary, estimates of long-term changes in either hurricane frequency or hurricane intensity using the basin total occurrence may be prone to considerable error, given that the long-term changes in observation method are so large. Future studies will hopefully be able to refine the analyses published over the past two years as the record grows and becomes more uniform. It should be noted that there have been considerable efforts recently to improve the quality of the historical hurricane record in the first half of the century by applying today's technology and knowledge to the datasets from that period (Landsea et al. 2004; J. Kossin, personal communication). Although this hurricane "reanalysis" has improved the quality of the Atlantic database, it is still far from perfect and this reanalysis does not yet extend to other basins. Despite the aggressive efforts to improve the database, there will always be hurricanes missing in the historical record prior to the launch of satellites, especially hurricanes far at sea.

6. Closing

It is worthwhile to note in closing that if we were to adequately prepare our homes and lives for the worst-case-scenario, based upon the *past 100 years*, we would be adequately prepared for any increase in intensity that may result from global warming. *The greatest threat to life and property results not from the increase in tropical cyclone intensity that may result from global warming, but instead from the inexperience, apathy, and disbelief we have about our own current and past vulnerability.* A 5 or 10 mph increase in hurricane intensity (such as that which may result from climate change) should not make the difference for how the public prepares for a hurricane. Would the residents who were affected by Katrina, Rita, and Wilma in 2005 act any differently if the forecasts had been decreased or increased by 5 or 10 mph? Should the residents of New England have taken the devastating 1938 hurricane less seriously at the time because it preceded the global warming era?

Further, despite the dramatic activity of this past year, the percentage of land areas and population that have experienced hurricane or major hurricane (115mph or greater) force winds is astonishingly small. For example, during Hurricane Andrew, a Category 5 hurricane at landfall, Fort Lauderdale, which was only 65 miles from the center, experienced a maximum gust of only 61mph, well short of hurricane force. Although Andrew was a Category 5 hurricane, downtown Miami and the airport experienced Category 2-3 winds and Miami Beach experienced Category 1-2 winds. Hurricane Andrew was a truly devastating storm in areas close to the center (e.g., Homestead), but we must realize the vast majority of southern Florida experienced Category 2 or (considerably) less winds from Andrew. Although Andrew (1992; Category 5) was far more damaging in total than Hurricane Wilma (2005; Category 3), a far greater number of people experienced hurricane force winds during Wilma given its larger size. This likely explains, in part, why much of southern Florida was surprised by the strength of the wind when it came. Many people thought they had already experienced a major hurricane wind with Andrew, but the vast majority had not, given Andrew's small size. In short, even though hurricanes severely affected many of the Gulf coastal population in 2004 and 2005, the percentage of people that experienced true hurricane force winds was minimal. That is to say, just because someone was affected by Hurricane Andrew or Rita or Katrina does not mean that she or he experienced the full strength of hurricane force winds, as those winds are confined close to the center of the storm.

After 50-100 years of additional hurricane record, we may at last know the magnitude, if it exists, of the impact of global warming on hurricane occurrence. Let us be hopeful that, regardless of this magnitude, the increased public attention produced by the recent scientific studies will lead to an increase in preparedness and a decrease in the loss of life. Whether or not global warming is increasing hurricane intensity and frequency should not be the immediate focus for public preparedness. Intense hurricanes have occurred frequently in the past, are occurring now, and will continue to occur in the future. As coastal property becomes more valuable, and coastal population more dense, damages and loss of life will continue to grow.

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