The Structure and Complexity of the Eye of a Hurricane

Dustin E. Maddox
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Fall 2001 Semester, Dr. Droegemeier
University of Oklahoma
Norman, OK 73019

1. Introduction

In studying the dynamics and mechanics that go into the formation of one of the most incredible structures in meteorology, the eye of a hurricane surpasses the ideal weather system. A hurricane, in all definitions, is truly a machine that has puzzled meteorologists and weather-watchers for centuries. Numerous research has been done to study and help predict the paths, intensity, and structure of these monsters from the sea. If one was to glance at a satellite picture of a large, major hurricane, they are instantly drawn to the center feature, the majestic eye. This paper will examine in-depth the structure and complexity of the mysteries of the eye of a hurricane as well as to speculate on how the eye behavior could perhaps better predict intensity and the future track of a particular tropical cyclone.

First, we must have some background on how a tropical system first forms. An average of 75-100 tropical waves move off of the African coast each year however only about 10-15% of the waves go on to become tropical depressions. Some of these go on to become tropical storms with winds over 39mph. Still a fewer number of these tropical storms go on to actually become hurricanes. To be designated a hurricane, the system must have winds exceeding 74mph. At this point, a hurricane is ranked on the Saffir-Simpson scale, with a Category 1 hurricane capable of “minimal” damage and up to Category 5 hurricane capable of “catastrophic” damage. A hurricane is named a “major” hurricane once it attains Category 3 strength wind winds in excess of 115mph. The most spectacular eye visualizations and structures coincide with these major hurricanes. (Simpson, 122)

Several parameters are essential for the growth and development of tropical cyclones. They include, but are not limited to, warm sea surface temperatures of at least 80°F, open water free from the friction of land, and weak vertical shear in the upper atmosphere. Once a major hurricane is born, it is an intense weather engine that can sustain itself for many days and even up to a week given certain, favorable conditions. On average, the Atlantic averages 2.1 major hurricanes a year whereas the northwest Pacific averages 7.5 major typhoons a year. Last century, only 22 hurricanes in the Atlantic basin attained Category 5 or Super-Hurricane status. Of these 22, only 8 of these made landfall as a Category 5 hurricane and only two of these occurred in the United States – the Florida Keys hurricane of 1935 and Hurricane Camille (MS) in 1969. They are rare indeed. (Mccown)

However, when doing research, it is always best to look at the classic, textbook structure of a particular system, as well as to study abnormalities that occasionally occur. Meteorology is never an exact science and there are always rules to be bent. Most of my analysis, thus, will be based on well-studied and researched hurricanes of our age. Through the extensive data provided by satellite imagery, NOAA Air Force reconnaissance planes (hurricane hunters), and, most recently real-time radar imagery, meteorologists are closer than ever in decoding and deciphering the mysteries and secrets that the eye of a hurricane holds. By analyzing the structure and complexities of the eye of a hurricane, perhaps better forecasting will eventually lead to a better warning system for the public, which, of course, is always the ultimate goal.
2. Structure

The eye of a hurricane, first and foremost, serves as the center of rotation of the weather system. In the Northern Hemisphere, tropical cyclones rotate counterclockwise and in the Southern Hemisphere, they rotate clockwise. Famous Finnish meteorologist Erik Palmen first made the observation that hurricanes were heat engines, that is they transfer the heat of the ocean surface to the top of the troposphere in a continuous cycle. The spiraling clouds surrounding a hurricane literally feed into the center of the eye of the cyclone. This air converges sometimes hundreds of miles from the center of rotation. (Fitzgerald, 74)

Meteorologist Robert Simpson took part in a revolutionary task by flying into the eye of a hurricane. In 1947, he boarded a B-29 hurricane hunter and gave the most descriptive detail to date about the structure of the eye. Despite earlier belief, Simpson noted that both at the surface and at the flight level, the winds were both spinning in a counterclockwise direction. He also noted that the outflow of the system was more concentrated and defined than previously thought. “Shafts of supercooled water...rose vertically and passed out of sight overhead,” reported Simpson in his log. (Simpson, 174)

At times, the wings of the airplane accumulated so much ice that the pilot had to slip down in altitude for it to melt as it condensed heavily at such a cold temperature. Simpson when on to distinguish that all the feeder bands do not compete for energy but rather work together to form the eyewall. The clouds gather the surface area to converge under them, thus clearing the air between bands, enhancing the updrafts in the existing clouds. Bands are determined by the size of the hurricane.

The eye of the hurricane is really a ring of intense storm activity. (Rosenfeld, 101) In the eye, low pressure draws air down for the cloud tops and the sinking air warms and evaporates tiny vapor droplets, clearing away any stray clouds. This shows that the eye is generally clear to partly cloudy by the displacement of cloud cover. Occasionally, the eye can be filled with some low clouds as in the case of Typhoon Marge. No matter whether an eye is clear or cloud covered, the eye opens when outside spiraling wind contracts and accelerate into a radius. It must be fast enough that the centrifugal effect flinging them outward is strong enough to equal the inner low-pressure system of the eye, thus providing the center of rotation. This balance must equal completely or the tropical cyclone will not have an opportunity to strengthen.

It should be noted that the tallest clouds in a hurricane are found in the eyewall and the immediate bands encircling the eyewall. While not reaching the updraft speeds of tornadoes, air could possibly ascend as fast as 40mph in the eyewall, making the connection between inflow and outflow of a hurricane. Weak vertical wind shear aloft is critical in the development and sustainment of the eyewall structure. If too much shear is present, the eyewall updrafts would not be able to remain upright sufficient to hook in the Earth’s stratosphere. Above 35 degrees latitude, this strong shear is a common occurrence, thus strong hurricanes rarely form or sustain their strength north of this latitude. In the deep tropical Atlantic, however, during late summer, wind blows steadily throughout the troposphere providing very little vertical wind shear and thus supporting hurricane formation and growth.

The low pressure observed in the eye of a hurricane can be quite remarkable. Indeed, the lowest pressures ever recorded on Earth have been measured in the most intense hurricanes. In 1979, extremely large Typhoon Tip recorded this lowest pressure of 25.69
inches of mercury. What causes the center of the hurricane to have such a low pressure? The whirling clouds that circle the eye ascend, and consequently, begin to cool. Ample water vapor condenses rapidly and frees the process of latent heating to take place. This lowers the pressure in the eye. As a rule of thumb, as the pressure of a hurricane drops, the stronger the tropical cyclone becomes. The faster the pressure drops, the quicker the system intensifies. In addition, the closer you approach the eye, the tighter the pressure gradient becomes in almost an exponential fashion. (Helm, 155)

How does a hurricane spin? The Coriolis force, dictated by the earth’s rotation, pertains to the effect of wind direction. In 1835, French scientist G. G. Coriolis observed that because of the earth’s rotation, winds in the Northern Hemisphere are deflected to the right and vice versa in the Southern Hemisphere. This sets the tropical cyclone into motion, rotating about a fixed origin called the eye. (Helm, 87)

Long before satellites gave us a view of what a hurricane actually looks like, scientists theorized what they would look like if observed from out of space. Most meteorologists agreed on the symbol of a doughnut and having the eye serve as the doughnut hole. By relentless research, the average diameter of the eye of a hurricane has been found to be around fourteen miles. However, the eye can be much smaller or must larger depending on some complex factors, which I will try to elaborate on in the next section.

The structure of a hurricane is very vast stretching from the ocean surface up to the upper troposphere. Through the advancement of equipment including dropsondes with sensor packets dropped from hurricane hunters, we now have a nearly complete three-dimensional picture of the texture of a hurricane, including the eye and eyewall. It has shown that as opposed to tropical storms who’s wind fields are spread out over a larger, more vast area, hurricane wind fields are typically more tightly packed in rings immediately surrounding the eyewall. The eyewall is just that – a wall of intense water and wind. Typically, in almost every case, the strongest part of the hurricane is found in the northeastern eyewall or the so-called right-front quadrant of a hurricane. (Simpson, 201)

The temperature inside of the eye is quite warm compared to its immediate surroundings. The reasoning for this is two fold. One reason is the fact that as air pressure sinks and subsides, warm air increases at the surface and especially aloft. In other words, the heat flux from the warm ocean waters compensate for expansional cooling due to lower pressure, thus maintaining warm surface pressure in the storms center. The second reason is the simple fact that if skies go clear in the eye, sunshine filters through and temperatures rise because of lack of cloud cover. Theory suggests that there must be some sort of higher pressure aloft directly above the eye to counteract or balance the warm temperatures present in the eye. Some means is needed to reduce the strong winds of the air encircling the eye to the observed very low speeds inside the eye, which suggests some time of high pressure aloft. (Kossin, 5)

In conclusion to this section, the structure of a hurricane and its eye is really quite simple in the basic understanding. It consists of a whirling mass centered about the origin or eye. Tight, spiral bands of thunderstorms are found surrounding the eye. It is a vast heat engine that thrives on rich, warm ocean waters. By studying the components that make up the tropical cyclone and its respected eye, one can begin to get an understanding of the intricate structure involved on a more scientific level as well. We will now shift our focus to the complexities of the eye of a hurricane.

3. Complexities

As we begin to concentrate on the complexities of the eye itself, even as we speak, new, innovative research is being done on this topic. By looking at eyewall replacement cycles and the concept of concentric eyewalls, we are getting a better understanding of how this affects the strength and motion of a hurricane. Discussed in further detail in the forecasting section, I will provide some background information on observations of both eyewall replacement cycles and concentric eyewalls in this section. Both are highly fascinating yet extremely debatable as well.
a. Eyewall replacement cycles

First believed to be very rare, new research indicates that eyewall replacement cycles occur quite often in intense hurricanes. An eyewall replacement cycle is just what it sounds like. It occurs when an old eyewall of a hurricane is replaced by a new, usually stronger eyewall. This happens in quite a complicated process however. First, another ring of convection forms in stronger hurricanes and a secondary eyewall forms. Outflow at the top of this outer eyewall flows outward as in the first eyewall, however the air flowing inward actually converges over the eye and eyewall and sinks, thus suppressing convection in the eyewall. Slowly, the inner eyewall dies as its updrafts are overtaken by the downmixing of exhaust air from the secondary eyewall. The eye fills in and the storm weakens for a time. (Fulton)

The new, secondary eyewall slowly moves inward in the above process and eventually replaces the eyewall it overtook. The hurricane then begins a restrengthening phase and often intensifies stronger than it had previously been. Eyewall replacement cycles can be as short as a few hours to as long as a day and a strong hurricane can undergo as many as ten cycles in a week’s period. (Fulton) During the process, the minimum central pressure can fluctuate by as much as thirty millibars. In most cases, right after the cycle concludes, a period of rapid intensification occurs. However, in other cases studied, the system may actually weaken, never to return to its original intensity. (Bluestein) Meteorologists are still not certain on what factors contribute in the strengthening or weakening of a tropical system during these eyewall replacement cycles.

Satellite imagery, both infrared and visible has literally been able to shed some light on the mysteries behind this phenomenon. During the time of the replacement cycles, the eye often becomes extremely ragged and undefined, sometimes becoming completely obscured by high clouds. In most cases, smaller hurricane eyes become larger hurricane eyes after an eyewall replacement cycle but this is not always the case.

A textbook example of this is the case of Hurricane Luis in early September of 1995. Called a “doughnut hurricane” due to its characteristically defined eye, these tropical cyclones often have a persistent symmetric ring of deep convection surrounding a larger than normal or normal sized eye, a lack of spiral banding, and intensities of ~85% of the maximum potential intensity with respect to sea surface temperatures. This results in very strong and long-lived hurricanes. They occur under very specific conditions including no upper level trough interactions, weak environmental wind shear from an easterly or east southeasterly direction, and sea surface temperature conditions that are constant or decreasing with time and that are less than 28.6°C and are greater than 25.5°C. (Knaff)

Thus, they are quite rare indeed. They occur as a result of “internal mixing events”, that is, eyewall replacement cycles followed by eye disintegration cycles. This process repeats itself and becomes more rapid, highly energetic eyewall replacement cycles yielding to a much larger eye than the system previously had. Some other doughnut hurricanes of note are Hurricane Edouard (Atlantic, 1996), Hurricanes Darby and Howard (E. Pacific, 1998) and Hurricanes Beatriz and Dora (E. Pacific, 1999).
journey. As the cycle begins, the hurricane, in essence becomes dazed and confused as its eyewalls are replacing one another. This can cause the structure as a whole to oscillate north or south of its projected trajectory. Usually, the wobble is insignificant but occasionally, the wobble can cause a complete overhaul of the direction of the storm’s path, which is extremely hard to forecast. Needless to say, more research needs to be done on this subject matter. I will once again raise this concept of “wobbling” in the forecasting section of this paper.

Of particular fascination in regard to eyewall replacement cycles is the Hurricane Andrew case as it made landfall in southern Florida in the early morning hours of August 24th, 1992. Extensive investigation now seems to indicate that Andrew went through an intense eyewall replacement cycle just prior to landfall, which, conceivably, could have made Andrew stronger than a Category 4 hurricane. Andrew had temporarily weakened but exploded in intensity after it reached the warm Gulf Stream waters which lie immediately off of Florida’s east coast. The eyewall contraction of Andrew caught Dade County at just the wrong moment and caused $25 billion in damage.

In studying the case closer, radar scans ranged from 1,500 to 25,000 feet and showed seven convective cells spin up in the northern eyewall in a 45-minute time spread. Each intense updraft cell circled around the eyewall to the southern edge where it punished Homestead, Florida. Each thunderstorm vortices lasted 10-15 minutes each, and rain fell 50 percent harder it was noted. Local microbursts also may have caused enhanced severe wind damage as the cells rotated within the intense eyewall of Hurricane Andrew. This all begins to shed light on the violent nature a hurricane goes through during the process of an eyewall replacement cycle. In the case of Hurricane Andrew, we are offered a glimpse at what happens when this happens at landfall along the coast. Still, much additional research is needed to accurately predict when and where they will occur.

**b. Concentric eyewalls**

Another term that coincides and is intricately related with eyewall replacement cycles is concentric eyewalls. Concentric eyewalls simply means that more than one eyewall is present. A study by H. E. Willoughby showed that during the development of some intense hurricanes, spiral rain bands for a partial or complete ring of heavy precipitation around the eyewall. This ring usually contains a well-defined wind maxima. This oscillating pattern of inner and outer convective rings is called the concentric walls. Tropical cyclones that display these characteristics often undergo characteristic intensity changes. As previously noted, as the outer eyewall contracts and intensifies, the intensity of the hurricane actually stops increasing and starts to weaken. That is, an increase in the eyewall’s radius, decrease in the maximum tangential wind, and a rise in minimum central pressure. Soon after, the outer eyewall replaces the inner one and becomes a new primary eyewall. After this eyewall succession, intensification may resume. The time in which more than one eyewall is present is the time of concentric eyewalls.

Shangyao Nong from Applied Insurance Research, Inc. in Boston, Massachusetts led an evaluation into the finding of concentric eyewalls. They found that a casual relationship does not always exist between environmental forcing and the formation of a secondary eyewall. In the cases of Hurricanes Allen (1980), Elena (1985), and Opal (1995), they showed a good and clear relationship between their concentric eyewalls and their external forcing mechanisms. Hurricanes Gilbert (1988) and Andrew (1992) showed some degree of casual relationship. Hurricanes Emily (1993) and Gabrielle (1989) showed a weak or close to no casual relationship with its external forcing. They also found that with Hurricane Frederic of 1979 and others, interaction between a hurricane and its upper-level synoptic environment is neither sufficient nor necessary for the formation and development of concentric eyewall cycles in reality. Lastly, the study showed that the maps of isentropic potential vorticity (PV) provide only qualitative information on the occurrence of interaction. The storm-moving coordinate system determines the strength of the interaction quantitatively by the eddy PV fluxes. (Nong)
Nong goes on to hypothesize two mechanisms of genesis. One is the interaction between a tropical cyclone and the ocean underneath. Secondly, is the tilting of high PV inner core with the storm and followed up projection of cyclonic vorticity down to the ocean surface. The findings point to less than conclusive proof that concentric eyewalls are indirectly related to the ocean surface that hurricanes thrive on.

Looking closer at the case of Hurricane Opal in October of 1995, we see that it underwent a very crude eyewall replacement cycle as a Category 5 hurricane in the Gulf of Mexico. Two concentric eyewalls formed and the result actually weakened Opal to a Category 3 hurricane just prior to landfall. As this and other studies indicate, there is not yet an exact correlation between concentric eyewalls ultimately strengthening or weakening a hurricane.

A final case in concentric eyewalls is the recent Hurricane Juliette in the Eastern Pacific. On September 26, 2001, as hurricane hunters flew into the eye, they were treated to a most amazing site – three concentric eyewalls. While not unheard of, it is a rare event. The first, center ring (eyewall) measured 12 miles in diameter. The second eyewall was 20 miles in diameter. The third eyewall was 40 miles in diameter. Juliette was a Category 4 hurricane at the time of the flight. (Hurricane Hunters)

By studying these irregular complexities of the eyes of hurricanes, forecasters will soon be able to make even better predictions of the forecasted path and intensity of these weather systems. Closely researching the eyewall replacement cycle and concentric eyewalls will eventually lead meteorologists to a better understanding of the mechanisms that drive and steer these monsters of nature.

4. Forecasting

As we closely look at the irregular complexities, we begin to see a certain pattern become clear. Both eyewall replacement cycles and concentric eyewalls indicate that the hurricane is going through a state of violent change. Indeed, the hurricane is always in a state of unrest, despite the calmness and beauty that is displayed on satellite imagery. As stated before, the hurricane acts as a machine by constantly feeding off on the warm ocean waters. I would like to suggest that by intently studying these changes within the eyewall, forecasting them is very complicated and we still have no tools to indicate if and when these changes will take place.

Take the case of Hurricane Andrew once more. The eyewall replacement cycle that occurred just prior to landfall was so mesoscale in nature that not until well after the event did we know what indeed had occurred. If we had better equipment and better tools, we could have been able to predict and forecast an intensification period just prior to landfall, which quite possibly could have had a reduction in fatalities as a result.

Furthermore, as these complexities occur within the eyewall, the eye itself tends to “wobble” or slightly alter its course. While these are usually insignificant, occasionally it changes the hurricanes course quite significantly. Possibly by studying this closer, scientists will have a better way of predicting where and when these events will occur and invariably lead to better forecasts of the paths and intensities of hurricanes.
5. Conclusions

In conclusion, hurricanes are intense weather systems that demand our understanding and awareness. The eye of a hurricane is the most intense part in which extraordinary events occur – some of which we do understand and some that we do not. The eye serves as a point of rotation about which the spiral bands swirl. It is a vast heat engine that drives the weather system. The eye itself is constantly changing, never staying in a solitary state for long. That is what makes for difficulty in forecasting.

As we learn more and more about the structure and complexities of the hurricane and its eye by the use of satellite, radar, and aircraft, a cleared picture is beginning to come in focus about how the overall hurricane operates. Research done by countless individuals on hurricanes has greatly impacted our understanding of them. They have no doubt caused a significant reduction in the loss of human life as a result of their findings. As the new century begins, meteorologists continue to question the fundamentals behind weather phenomenon such as the hurricane in order to help better prepare humans for the worst Mother Nature has to offer.

6. REFERENCES


