Observations of Wind Asymmetries in Atlantic Tropical Cyclones

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ABSTRACT

Most major cities are located on coastlines, vulnerable to the direct impacts of tropical cyclones. Therefore, it is critical to understand and improve prediction of these storms in order to make communities more resilient. Though hurricane warning systems have improved in recent years, these warnings are insufficient, because they fail to account for an indication of tropical cyclone wind asymmetry, or the radial extent of maximum winds in different locations within the cyclone. This study explored the wind asymmetry (defined by magnitude and orientation) among 337 Atlantic tropical cyclones from 1988-2012, utilizing the National Hurricane Center’s (NHC) Extended Best Track Dataset (EBT) and Statistical Hurricane Intensity Prediction Scheme (SHIPS). Asymmetry was defined as the magnitude of the largest difference in the radius of gale-force wind across opposing quadrants, normalized by the average of the four wind radii. The asymmetry orientation pointed along the axis of maximum asymmetry toward the quadrant with the greater gale radius. Relationships between wind asymmetry and various storm characteristics such as geographical location, storm life cycle, intensity, size, storm motion, and vertical wind shear were examined. The magnitude of asymmetry increased in higher latitudes and along coastlines, particularly in smaller storms. Asymmetry was higher at the beginning of a storm’s life, possibly owing to a less well-organized structure, and higher near the end of a storm’s life, coinciding with an increase in vertical wind shear and translation speed. Results from this study may allow for improved tropical cyclone forecasts and warnings to help protect seaside communities.

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1. Introduction

Winds in tropical cyclones (TCs) are a critical factor in determining the storm’s intensity and they provide the basis for issuing appropriate warning systems. Despite recent advances in forecasts and warning systems (Lubchenco & Hayes 2012), winds in tropical cyclones continue to result in a huge amount of destruction, both to economy and human life (Blake, Landsea, & Gibney 2011). From 1988-2012, tropical cyclones resulted in approximately $3.6 trillion in damage and 20,375 fatalities in the United States alone (Weather Underground). Thus, a better understanding of these powerful storms is essential, especially regarding the structure and behavior of wind in TCs.

Though warning systems focus mainly on a TC’s maximum wind speed, current studies suggest that the distribution of wind speeds within a TC provide a more comprehensive illustration of the storm’s unique behavior (Uhlhorn et al. 2014; Rogers & Uhlhorn 2008; Kimball & Mulekar 2004). This differential distribution of wind speeds, known as wind asymmetry, has been explored in order to understand how a given TC’s structure and intensity change based on environmental factors. For example, Uhlhorn et al. (2014) found that the amplitude of wavenumber-1 flight-level (700mb) wind asymmetries increased with storm translation speed and that flight-level asymmetry amplitudes were about 50% greater than those at the sea surface. Rogers & Uhlhorn (2008) similarly found a relationship between the asymmetric wavenumber-1 parameter and storm motion and shear in Hurricane Rita. The amplitude of asymmetry in Rita evolved from displaying a maximum to the right of the storm track at both flight and surface level on the first day to exhibiting a right of storm track at flight-level and left of storm track at surface level (Rogers & Uhlhorn 2008). Both Uhlhorn et al. (2014) and Rogers & Uhlhorn (2008) suggest a number of factors, such as vertical wind shear,
storm translation speed, and storm motion, contributing to observed wind asymmetries, as characterized by the wavenumber-1.

While previous studies examining wind asymmetry have relied on aircraft reconnaissance data, this study will utilize the National Hurricane Center’s (NHC) Extended Best Track (EBT) dataset and the Statistical Hurricane Intensity Prediction Scheme (SHIPS). The EBT is advantageous in providing consistent 6-hr observations of TC structure and intensity over the Atlantic from 1988-2012, yet the main limitation present is the considerable deal of uncertainty in the many of the parameters. The main contribution to uncertainty is the collection of data from numerous sources, such as satellite, aircraft reconnaissance, and surface measurements (among land-falling TCs). The uncertainty is especially notable when it comes to the gale-force (34-kt) wind radii measurements, used to define TC wind asymmetry, with uncertainty measures from 25-40nm (Figure 1). In using the gale-force wind radii, this study is also limited to observing those wind radii in four-quadrants only (Landsea & Franklin 2013).

![Figure 1](image.png)

**Figure 1.** Figure from Landsea & Franklin (2013) of the extended best-track gale-maximum wind radii uncertainty, stratified by measurement type and tropical cyclone intensity.
Despite the drawbacks in using the EBT dataset, the consistent and detailed observations were useful for exploring Atlantic TC wind asymmetries from 1988-2012, which was the goal of this study. Wind asymmetry was defined in various ways, such as normalized magnitude, directional orientation, and storm relative orientation, all based off of the radial extend of gale-force winds among four quadrants. Relationships were then examined between asymmetry metrics with other TC characteristics, including geographic location, storm life cycle, vertical wind shear, and storm translation speed. In section 2, TC data and methodology for defining asymmetry metrics will be discussed. Section 3 will include results of asymmetry metrics, while section 4 will present a discussion of the results, and section 5 will provide conclusions and directions for future work.

2. Methods

Tropical Cyclone Data

Atlantic tropical cyclone (TC) data from 1988-2012 were obtained via the Tropical Cyclone Extended Best Track Dataset (EBT) version 2.01 (last updated February 22, 2013). The data are based on the National Hurricane Center’s (NHC) Atlantic TC dataset, extending back to 1851, known as HURDAT. The EBT includes the 6-hourly observational data from HURDAT, and is derived from a number of sources, such as ships and surface stations, satellites, and aircraft, all of which are associated with some degree of error and uncertainty (DeMaria et al. 2013, Landsea and Franklin 2013). The EBT also contains six additional parameters determined by the NHC: eye diameter, radius of maximum wind (RMW), radii of the 34, 50, and 64-kt winds in four quadrants (northeast, southeast, southwest, northwest), and the pressure and radius of the outer closed isobar (DeMaria et al. 2013).
To ensure the data adhered to logical physical properties of TCs, a quality check was performed. Cases in which the RMW exceeded the radii of 34-kt winds in all quadrants, or minimum pressure was greater than the pressure of the outer isobar were excluded from analysis (Kimball & Mulekar 2004). Other data excluded from analysis include observations with missing wind radii data, TC landfall cases, and cases in which dates and times for a specific storm in the EBT dataset and the 850-200mb vertical shear data did not match. After quality check and exclusion of unwanted data, cases remained out of the initial 10860.

The vertical wind shear data comes from NHC’s Statistical Hurricane Intensity Prediction Scheme (SHIPS), which is a statistical-dynamical forecast model, used to predict TC intensity (NHC 2009). For the purposes of this project, however, SHIPS data was used for retrospective analysis of TC asymmetry rather than for forecasting purposes (RAMMB 2014).

Metrics of Asymmetry

Before the 34-kt wind radii ($R_i$) were utilized as TC asymmetry measurements, the wind radii in each quadrant were normalized in the following manner:

$$R_{1n} = \frac{R_1}{\text{mean}(R_1, R_2, R_3, R_4)}$$  \hspace{1cm} \text{Eqn. (1)}

Where $R_{1n}$ is the normalized 34-kt wind radii in the northeast quadrant and $R_1, R_2, R_3,$ and $R_4$ are the raw 34-kt winds in the northeast, southeast, southwest, and northwest quadrants, respectively. Normalization of the wind radii was performed to remove the bias of larger TCs displaying larger asymmetries.

Following normalization, wind asymmetry ($A$) was calculated by finding the maximum difference between opposing quadrants, given by the following equation:
\[ A = \max(|R_{1n} - R_{3n}|, |R_{2n} - R_{4n}|) \]

Eqn. (2)

Where \( A \) is asymmetry (unitless). This yielded a range of asymmetry values from 0 to 4, with 0 indicating a symmetric TC in which the normalized 34-kt wind radii in 4-quadrants were all equal, and 4 indicating an asymmetric TC in which the 34-kt wind radius is present in only 1 of the 4 quadrants.

Another measure of TC asymmetry is wind orientation (\( O \)), defined as the axis along which \( |R_i - R_{(i+2)}| \) is larger, pointing towards the quadrant with the larger of the two radii. For cases in which \( R_n \) is equal among all quadrants, \( O \) is zero. Cases in which \( R_n \) was equal among both set of opposing quadrants were assigned to two orientation values. For example, if \( R_{1n} = R_{4n} \) and \( R_{3n} = R_{2n} \) and \( R_{1n} \) is greater than \( R_{3n} \), then the orientation would be assigned both 1 (northeast) and 4 (northwest).

Procedure

TC asymmetry was examined both temporally, by analyzing the changes in asymmetry over the TC’s life cycle, and spatially, by examining changes in asymmetry with regard to geographical location. A TC’s life was defined (relative to each storm) by assigning each storm a normalized start time of 0, a normalized maximum intensity (based upon the maximum wind) time of 1, and a normalized end time of 2. Times between a TC’s start to maximum intensity ranged from 0 to 1 in 0.1 increments. Times between the maximum intensity and end of a TC ranged from 1 to 2 also in 0.1 increments. The range and median of TC asymmetry for each normalized time were then calculated and analyzed by a box-and-whisker plot. The same procedure was repeated for vertical wind shear and translation in order to examine the impacts of these variables on asymmetry (Rogers & Uhlhorn 2008, Uhlhorn et al. 2014).
TC translation speed was calculated by determining the distance traveled, using change in latitude and longitude and the Pythagorean theorem. The change in distance was divided by the change in time (hours) from one observation to the next for each TC to yield a translation speed. Finally, the translation speed was converted into m/s to be analyzed over the course of a TC’s life cycle.

To analyze asymmetry by geographic location, each TC case was placed into a 10°x10° (latitude x longitude) location bin. For example, if a TC was located at 72’W 26’N, it would be placed in the 70’W 20’N location bin. All other storms located between 70-79’W and 20-29’N would consequently be placed in the same location bin. This was repeated for all TC cases for each unique location in the northern Atlantic. TCs were then categorized as large (greater or equal to 90nm) or small (less than 90nm) storms, with the categories determined by calculating the median size of all TCs in the dataset. For each storm size, the median magnitude of asymmetry was calculated, plotted, and visually evaluated for each of the 54 location bins. In a few cases, there were locations not containing any small or large storms.

3. Results

Life Cycle Analysis

Results from the life cycle analysis of TC asymmetry in 337 TCs from 1988-2012 show that the asymmetry changes over the course of a storm’s life (Figure 2). At the beginning of a storm (normalized time =0), asymmetry is high, with a median around 1, and a large range as well as interquartile range (IQR) is present. As the storm intensifies towards the maximum intensity (normalized time=1), the median, IQR, and range of asymmetry decrease to approximately 0.5, 0.4-0.6, and 0-1.1, respectively, at normalized time = 0.9. However, at the
time of maximum intensity, there is an increase in the IQR and range to 0.3-0.85 and 0-1.7, respectively. After the storm reaches maximum intensity, at normalized time =1.1, the median asymmetry reaches a minimum value around 0.4, while the IQR and range decrease to 0.3-0.6 and 0-1.15, respectively. Nearing the end of a storm’s life (normalized time=1.2-1.9), the median, IQR, and range of asymmetry are relatively constant with each time, varying between 0.45-0.55, 0.3-0.95, and 0-1.7, respectively. At the very end of a storm’s life (normalized time=2), the median, IQR, and range of asymmetry noticeably increase, to values of 0.85, 0.4-2, and 0-4, respectively. What this means is that asymmetry values were found to be higher in TCs before maximum intensity than after, with the exception of the very end of a storm’s life, and that asymmetry value reach a minimum right before and after the time of maximum intensity.
**Figure 2.** Box-and-whisker plot of the life cycle of tropical cyclone asymmetry, starting at the beginning of a storm’s life (normalized time=0), to the end of a storm’s life (normalized time=2), with the storm’s maximum intensity located in the middle of the life cycle (normalized time=1). The magnitude of asymmetry is the maximum difference in the radial extent of gale-force winds between any two diagonal quadrants when the storm is split up into four quadrants and is a normalized value to accounts for storm size. Circles outside of the box-and-whisker plot denote outliers during each stage.

Additionally, the magnitude of shear (850-200mb) also varies over the life cycle of TC, however in a different manner than asymmetry (Figure 3). From the beginning of a storm’s life, up to maximum intensity (normalized times = 0-0.9), the median, IQR, and range of shear is relatively constant, around 10kts, 8-20kts, and 0-35kts, respectively. A sudden increase in shear occurs at the time of maximum intensity, with a median of 14 kts, IQR from 9.5-21 kts, and a range from 1-46 kts. For the most part, from the time of maximum intensity to the end of a storm’s life, the median of shear for each time increases to approximately 22 kts. The IQR and
range of shear fluctuate somewhat between this same time, and at the very end of a storm’s life (normalized time=2), the IQR and range increase considerably, with values of 14-33 kts and 1.5-60 kts, respectively. In general, shear is relatively constant before the time of maximum intensity, then increases markedly at maximum intensity, and continues to increase until the end of storm’s life cycle.

**Figure 3.** Box-and-whisker plot of the life cycle of tropical cyclone vertical wind shear (850-200mb), starting at the beginning of a storm’s life (normalized time=0), to the end of a storm’s life (normalized time=2), with the storm’s maximum intensity located in the middle of the life cycle (normalized time=1). Circles outside of the box-and-whisker plot denote outliers during each stage.

The life cycle of translation speed shows similar variation to the life cycle vertical wind shear, yet there are some notable differences. For most of the storm’s life, translation speed is relatively constant, with median values between 5-6m/s, IQR between 2.5-7.5 m/s, and ranges from 0-13 m/s (Figure 4). As the storm approaches the end of its life cycle (normalized time 1.5-
2), the translation speed increases in its median, IQR, and range, obtaining maximum values of 7.5 m/s, 4.5-12 m/s, and 1-24 m/s, respectively, at a normalized time of 1.9. At the very end the life cycle (normalized time=2) the median, IQR, and range actually decrease slightly, though still exhibit higher than those found earlier in the storm’s life cycle.

**Figure 4.** Box-and-whisker plot of the life cycle of tropical cyclone translation speed, starting at the beginning of a storm’s life (normalized time=0), to the end of a storm’s life (normalized time=2), with the storm’s maximum intensity located in the middle of the life cycle (normalized time=1). Circles outside of the box-and-whisker plot denote outliers during each stage.

**Geographical Analysis**

In examining the magnitude of TC asymmetry by location, general trends were examined. Spatial patterns in asymmetry in both small (<90nm) and large storms (>= 90nm) were studied to identify similarities, and then differences in asymmetry between small and large storms were analyzed. Note that median asymmetry values among the various locations are only representative of TCs over water, as those making landfall have been excluded.
In looking at the distribution of small storm asymmetry by geographic location, there are distinct areas where the median asymmetry values are notably higher than others (Figure 5). For reference, the median of asymmetry for all locations in small storms is 0.86. Between 40-50°N is one such area in which asymmetry values are higher, especially between 10-40°W and 60-80°W, in which the median of asymmetry is between 1-2. Median asymmetry values are also higher near landfall, with the exception of TCs in the 80-100° W and 10-20°N range. Along the coast of South America, North America, and islands in the Caribbean, the median of asymmetry ranges from 1-1.6, except for one storm, Hurricane Beryl in 1988 (DeMaria, M., J. Pennington, and K. Williams 2013), found between 90-100° W and 30-40° N that exhibited an asymmetry of 2. From 10-50° W and 0-40° N, excluding the point at 50-60°W and 0-10°N, median asymmetry values fall at or below the median for small storms, ranging from 0 to 0.9.

Generally, median values of both large and small storm asymmetry display similar spatial patterns, with asymmetry values higher above 40° N and along land (Figures 5&6). However, there are specific locations where these patterns are not consistent. For example, above 40°N between 20-40°W, large storm asymmetry is equal to or less than median for all large storm locations (0.44), while the small storm asymmetry is higher than the median of all small storm locations (0.86). Between 40-60° W and above 40°N, asymmetry in large storms is higher than the median for all locations, while small storms asymmetry is less than the median for all small storm locations. Another discrepancy occurs at 90-100°W and 10-20°N, where large storm asymmetry is higher than its overall median, yet small storm asymmetry is lower than its overall median.

Perhaps the most apparent disparity between the asymmetry values of small and large storms is that large storms exhibit a lower asymmetry in nearly all locations compared to small
storms (Figures 5&6). While small storm asymmetry ranges from 0 to 2, with many locations displaying median asymmetry values beyond 1, large storm asymmetry only ranges from 0 to 1.1 and most locations contain median asymmetry values less than 0.7. Exceptions to this trend do exist though, markedly in the lower longitudes. Specifically, between 40-50°W and 10-20°N, 20-30°W and 20-30° N, as well as 30-50°W and 30-40°N, the median asymmetry values for those locations range from 0-0.4 in both small and large storms. On the whole, asymmetry values are lower in large storms compared to small storms, but both show higher asymmetries above 40°N and near land.

![Map of storm asymmetry values](image)

**Figure 5 (left) and 6 (right):** Median asymmetry values representative of tropical cyclones in each 10’x10’ location bin for small (less than 90 nm) and large (90nm) tropical cyclones.

4. Discussion

_Life Cycle Asymmetry_

The general trends exhibited by TC asymmetry over its life cycle suggest that asymmetry has some relationship to intensity changes in the storm. The overall higher asymmetry exhibited at the beginning of the storm’s life as it is intensifying could be due to the storm being less
organized (Kimball & Mulekar 2004). Conversely, this trend could be attributed to the manner in which asymmetry is defined, in that smaller storms, which are generally intensifying, may only have a 34-kt wind radii present in only 1 quadrant (Kimball & Mulekar 2004). This would result in an asymmetry value of 4, which is the maximum that can be achieved, based upon how wind radii were normalized for size and asymmetry was calculated. In larger storms, it is possible that there are fewer cases in where 34-kt wind radii are missing, given that larger storms in the northern Atlantic were found to be more intense (Kimball & Mulekar 2004). Therefore, it is possible that the high asymmetry in intensifying storms/storms at the very end of life could be due to a less organized structure (Kimball & Mulekar 2004) in combination with intensifying storms/storms at the very end of life being more sensitive to the calculation of asymmetry. Conversely, the relatively constant values of asymmetry in weakening (usually larger) storms could be owed to a more organized structure than intensifying storms (Kimball & Mulekar 2004) in conjunction with larger storms having less sensitivity to the calculation of asymmetry, except for storms at the very end of their life.

Fluctuations in the life cycle of TC asymmetry could also be attributed to vertical wind shear and TC translation speed. For instance, at the time of maximum intensity (normalized time =1), a noticeable increase in shear occurs (Figure 3) while the IQR and range of asymmetry (Figure 2) also increases at this time as well. Similarly, at the very end of storm’s life (normalized time=2), both shear and translation increase dramatically (Figure 3&4) as asymmetry rises (Figure 2). Based upon previous studies, it has been found that TC translation speed and vertical wind shear increase TC asymmetry, thus results are consistent with expectations (Emanuel 2005; Wang & Wu 2003, Uhlhorn et al. 2014). However, it is interesting that shear and translation speed increase notably before the very end of storm’s life, from

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normalized time = 1.8-2, yet an increase in asymmetry does not accompany this change. The reason for this is unknown, however, since weakening storms are generally larger (Kimball & Mulekar 2004) and larger storms are more immune to the effect of shear (DeMaria 1996), it is possible that storm asymmetry in the life cycle between 1.8-2 are less affected by shear and translation speed as they are when they are at their weakest stage (normalized time = 2). Other factors could be contributing to trends in the life cycle of TC asymmetry that have not directly been studied in this project, such as eyewall replacement cycles and sea surface temperatures (Emanuel et al. 2004).

Geographic Asymmetry

Among both large and small storms, asymmetry is higher above 40°N and near landfall (Figures 5&6), which is consistent with expectations and previous studies. Higher asymmetry above 40°N could be attributed to higher vertical wind shear at higher latitudes and storms weakening at this location (Kimball and Mulekar 2004). As storms are usually at the end of their life above 40°N and asymmetry is higher at the very end of a storm’s life, higher asymmetries above 40°N supports the life cycle analysis of asymmetry (Figure 2). Elevated asymmetry along the west coasts of North and South America also supports the idea that as TCs near landfall, they begin to experience different surface frictional forces (Wong & Chan 2007), possibly attributing to higher asymmetry.

Locations of lower asymmetries are relatively similar among small and large storms, generally occurring in eastern longitudes. Between 30°N-40°N, east of 50°W, small and large storms both have median asymmetry values between 0-0.4, which could be indicative of most storms in this area, regardless of size, being in their weakening stages as Kimball and Mulekar
(2004) found. The only exception is between 10-20°W and 30°N -40°N in the large storm geographic plot, which has a median asymmetry value of 1. As larger storms are more often weakening than intensifying (Kimball & Mulekar 2004), it could be that a greater number of large than small storms are approaching the end of their life than small storms, resulting in a higher asymmetry value. Below 30°N, it is a bit less evident why asymmetries in small and large storms are lower. Though at these locations, TCs are mostly intensifying or at steady-state (Kimball and Mulekar 2004), depending on the time of year and particular TC track (NHC 2014). TCs in the open water between 10-50°W and 0-30°N could be just forming or in later stages of intensifying. If TCs are just forming in this region, higher asymmetry would be expected, possibly shown by the furthest east location between 10-20°N having moderate asymmetries around 0.8 in small and large storms. Moving further west and north between 10-50°W and 0-30°N, median asymmetry values decrease to 0-0.4 in large storms, but range from 0-0.9 in small storms. Given that the median value for all locations among large and small storms is 0.44 and 0.86, respectively, asymmetries in this location for both small and large storms range in value from below-median to median (Figures 5 & 6). This suggests that storms in this area may not be at the very beginning or end of their life, as those times exhibit high asymmetry, but instead somewhere in the middle. Also, given that the geographic plots represent all times of the year, less concrete remarks can be said about locations of TC formation and intensification.

What remains less clear are the discrepancies between large and small storm asymmetries, as there are many variables potentially contributing to the observed results. Higher asymmetry in small storms, compared to large storms, could also be a result of resistance to wind shear and state of intensification. As large storms are more resistant to the effects of vertical wind shear (DeMaria 1996), increased resistance likely results in lower asymmetry. Another
theory is that because asymmetry is higher in intensifying storms, and intensifying storms tend to be smaller (Kimball and Mulekar 2004), asymmetry is inherently higher in smaller than larger storms.

5. Conclusion

In exploring the magnitude of TC asymmetry in the Atlantic from 1988-2012, asymmetry was found to change both on a temporal and spatial scale. In the life cycle analysis, of both small and large-scale storms, asymmetry was highest at the start and end of a TC’s life, with a slight increase in asymmetry at the time of maximum intensity relative to the times directly before and after. State of intensification, TC size, magnitude of vertical wind shear, and translation speed seem to account for fluctuations in the life cycle of TC, although numerous other variables not directly studied could also be contributing factors (eyewall replacement cycles and lower SSTs; Emanuel et al. 2004). Furthermore, the method in which TC asymmetry was calculated could also account for some changes in TC asymmetry, posing a possible limitation to the study.

The geographical analysis between small and large storms showed some consistent spatial patterns in the median asymmetry values, with higher asymmetry values above 40°N and near landfall, and lower asymmetry values below 30°N and between 10-50°W. However, there were differences between the two geographic plots, with smaller storms exhibiting higher asymmetry than larger storms and specific locations exhibiting higher asymmetry in one plot and lower in the other. Much like the life cycle plots though, factors potentially contributing to asymmetry include state of intensification, storm size, vertical wind shear, and additionally, and proximity to landfall.

From these results, we can gather that TCs in the Atlantic have particular stages in their life cycle and location in which asymmetry is preferentially higher. It would be useful to perform
statistical analyses and modeling work to more concretely see what factors may contribute most to TC asymmetry, however these results still offer useful information. Finally, results from this study would be beneficial in assisting forecast and warning-system application to better communicate to the public where to expect the highest winds in a given TC.

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http://www.wunderground.com/hurricane/hurricanearchive.asp?&MR=1