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An Analysis of the Extratropical Flow Response to Recurving Atlantic Tropical Cyclones

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AN ANALYSIS OF THE EXTRATROPICAL FLOW RESPONSE TO RECURVING ATLANTIC TROPICAL CYCLONES

By

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Abstract

There is a significant frequency of Atlantic tropical cyclones that complete extratropical transition and recurve in the mid-latitudes. Using a climatological approach, this study will analyze the extratropical flow response to recurving Atlantic tropical cyclones and compare the results to those from the Western North Pacific, as examined by Archambault et al. (2013). This investigation includes 54 recurving Atlantic tropical cyclones occurring between 2007 and 2013. The extratropical flow response will be quantified using potential vorticity. Characteristics of tropical cyclones, the extratropical jet stream, and the dynamical "phasing" of their interaction will be examined to determine the features that lead to significantly amplified extratropical flow. Results show the extratropical flow to be insensitive to the wind speed, latitude, and month of recurvature. However, there is an association between low mean sea level pressure and a larger amplification of flow. Finally, tropical cyclones recurving on the east side of the nearest trough are shown to have "favorable phasing," which yields amplification of the extratropical flow.

1. Introduction

A tropical cyclone (TC) is characterized as a warm-core system that acquires its energy from the heat and moisture of the ocean's surface and from the latent heat produced when evaporated water vapor condenses. An extratropical cyclone is a cold-core, frontal system that forms as the result of temperature gradients and vertical wind shear. A tropical cyclone can become an extratropical cyclone in a process known as extratropical transition (ET). This evolution occurs as a tropical cyclone loses tropical characteristics and takes on extratropical characteristics, including increased vertical wind shear, increased Coriolis parameter, and decreased sea surface temperature (Hart 2003). When a tropical cyclone undergoes extratropical transition, it changes its trajectory and begins to move eastward, as opposed to its original westward direction. This "recurvature" in the mid-latitudes can lead to an interaction between the TC and the extratropical jet stream, which could amplify the extratropical flow of the jet and cause severe weather events a great distance downstream (Archambault et al. 2013).

This chain of extreme weather events is exemplified by the recurvature of TC Hanna in the Atlantic basin. In early September of 2008, TC Hanna completed recurvature and extratropical transition, which is associated with the initiation of amplified extratropical flow leading to high impact weather events. The recurvature of TC Hanna was followed by an evolving upstream extratropical cyclone and the development of a downstream Mediterranean cyclone that caused intense rainfall in Europe (Grams et al. 2011).

This study aims to determine if certain characteristics of recurving tropical cyclones and the large-scale flow influence extratropical flow amplification.

Classification of the interaction between the TC and the jet will be labeled as the "phasing" of the interaction, which will stem from the position of the tropical cyclone at recurvature in relation to troughs on the jet stream. This study will also investigate whether the phasing between the recurving TC and the jet plays a significant role in the extratropical flow amplification. Identifying these characteristics will provide insight that can be used to more accurately forecast the extratropical flow response and the consequent downstream severe weather events.

The forecasting issues associated with extratropical transition result from the mid-latitude westerly winds that contribute to a rapid increase in forward speed of the cyclone, decreasing the warning time of high-impact weather (Jones et al. 2003). This study not only fills an important gap within tropical meteorological research, but also is important to greater society. Better characterization and understanding of the factors contributing to amplification of the jet stream can lead to improved forecasting methods to predict similar extreme weather events. Enormous amounts of rainfall, severe flooding, wind gusts, landslides, and high seas are just a few of the consequences that occur downstream of an amplified jet stream (Jones et al. 2003). These weather events are serious atmospheric phenomena, which pose safety risks for people all around the world. This study will help to more accurately forecast the location and intensity of these severe weather events and give people in danger increased warning time to evacuate to a safer place.

In order to forecast these extreme weather events, it is critical to understand the characteristics of the TC's interaction with the extratropical jet that yield favorable conditions for amplification of extratropical flow. Characteristics of the TC, the large scale flow pattern, and the phasing between their potential interaction are investigated, as they are all factors that impact the extratropical flow response downstream of the TC, yet these have only been studied within the context of the North Pacific basin by Archambault et al. (2013).

A main objective is to analyze the climatological relationship between extratropical transitioning tropical cyclones and waves on the extratropical jet in the Atlantic basin. These results will be compared to those from the North Pacific (Archambault et al. 2013). Investigation will begin by examining characteristics of tropical cyclones, the extratropical jet stream, and their possible interaction to determine the features that lead to significantly amplified extratropical flow. A related objective is to discover a configuration of optimal phasing between the jet and the tropical cyclone that yields significantly amplified flow. This study will then examine whether the results are sensitive to the metrics used to characterize jet strength and the disturbance. Explicit testing and calibration of the metrics will be performed using Hurricane Hanna as a test case.

This remainder of this study is organized as follows. Section 2 describes the datasets, the methods used to determine storms of interest and climatology, and methods of evaluating the extratropical flow response. Section 3 provides a motivation for the selection as Hanna as the test case and examines Hanna using the created metrics. Section 4 presents a climatology of recurving tropical cyclones, followed by the characterization of the jet stream in section 5. Section 6 evaluates the extratropical flow response and section 7 briefly describes the key conclusions.

2. Data and Methodology

a. Data

The analysis of tropical cyclones relies on the Hurricane Database (HURDAT2) from the National Hurricane Center's data archive (Landsea and Franklin 2013). This dataset is a post-storm analysis from the National Hurricane Center, which includes all observations, even those unavailable at real-time. HURDAT2 is an updated version of the HURDAT dataset to include changes to the file's content since 2012. HURDAT2 contains reanalysis data from all known tropical cyclones occurring in the Atlantic Basin from 1851-2013, including best track data on location, pressure, size, and winds at six-hour intervals (Landsea and Franklin 2013).

Information about the extratropical jet is obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) analyses. These analyses are acquired from the THORPEX Interactive Grand Global Ensemble (TIGGE) Data Retrieval archive, which includes data starting in 2006. TIGGE also contains historical forecasts from several operational centers, which could be used in a future study to evaluate the accuracy of the differing forecasts. However, this study will only utilize analyses from ECMWF. The model forecasts are conducted in global domains and can make predictions up to two weeks in the future. The dataset includes standard meteorological variables, such as forecast winds, temperature, humidity, pressure, vorticity, and divergence (European Centre for Medium-Range Weather Forecasts 2014).

b. Identification of Storms of Interest

Tropical cyclone recurvature will be defined as a change in the cyclone's trajectory—from initially moving westward to moving eastward, while the cyclone continues to travel poleward. The point of recurvature will be selected as the western-most point reached by the cyclone. The time variable will be defined such that the time of recurvature occurs at 0 hours. Due to differences in time intervals between the data (6 hour intervals for HURDAT2 and 12 hour intervals for TIGGE), if the time of recurvature falls at a time not present in the TIGGE data, the point of recurvature will be represented by the previous time step in HURDAT2. Time before recurvature will appear as negative values representing hours before recurvature. After the time of recurvature, the time values will increase to indicate the number of hours since recurvature.

In order to have a comprehensive set of data for both the TC and the extratropical jet, only storms occurring between 2007 and 2013 will be included in this study. Furthermore, this study will only focus on those cyclones that recurve, cyclones that are at least classified as tropical storm intensity, and cyclones that undergo extratropical transition to become extratropical cyclones. In order to only consider recurving storms that have a potential interaction with the extratropical jet, this study will only include storms that recurve above a latitude of 20 degrees North. Implementing the previously stated conditions leaves 54 tropical cyclones to analyzed.

c. Climatological Analysis

Each tropical cyclone will be classified by intensity and wind speed. A tropical cyclone will be considered “strong” in intensity if its mean sea level pressure (MSLP) is in the bottom quartile of all recurving tropical cyclones, and a tropical cyclone will be considered “weak” if its MSLP is in the top quartile. Similarly, for wind speed classification, tropical cyclones will be categorized as “strong wind” if their wind speed at recurvature is within the top quartile of all recurving tropical cyclones and "weak wind" if their recurvature wind speed is within the bottom quartile.

The month of year and the latitude of recurvature will be used to characterize the large-scale flow pattern. For this study, the months of interest are those between May and November, so only storms occurring during these months will be considered. Each month will serve as its own climatological category. As for the latitude of recurvature, the storms fitting the previously stated criteria recurved between the latitudes of 20 degrees North and 45 degrees North. For classification purposes, this range of latitudes will be broken up into 5 different bins each containing 5 degrees of latitude.

The characterization of the phasing between the tropical cyclone and the jet will be determined by whether the tropical cyclone interacts with the extratropical jet on the east or west side of the nearest trough at the time of recurvature. A trough is a region of comparatively low atmospheric pressure. In the Northern Hemisphere, air travels in the counterclockwise direction around a low-pressure system. Therefore, when examining pressure contours, or even the jet stream flow pattern, the "dips" in the contour with the counterclockwise flow are representative of troughs (see Figure 1). The amplitude of a trough is essentially the departure of the "dip" from the average line.

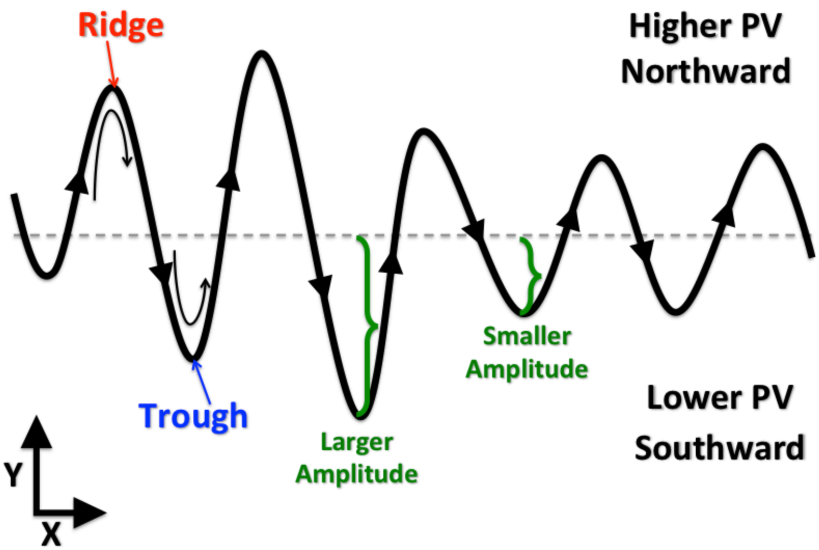


Figure 1. This is a schematic diagram of the 1.5 PV Contour used to describe the jet stream. The black, wavy line is the PV contour that represents extratropical flow pattern, with the flow direction shown by the arrowheads. The grey, dotted line is used to represent the zonal average PV. The northern side of the 1.5 PV contour has higher PV values and the southern side has lower PV values. Ridges are areas of clockwise rotation and defined with negative vorticity. Troughs are areas of counterclockwise rotation and defined with positive vorticity. Two of the troughs have labeled amplitudes to give a visual depiction of an amplified trough.

A goal is to determine if there is a configuration of "favorable phasing" between the TC and the extratropical jet that enhances the amplitude of the extratropical flow, downstream of the initial trough's longitude and at 24 hour time intervals after the time of recurvature. Conversely, a TC classified to have "unfavorable phasing" with the extratropical jet will represent an interaction that does not result in amplified extratropical flow.

d. Method of Analyzing Extratropical Flow

Potential vorticity (PV) is a derived quantity that combines the absolute vorticity (measure of an object's rotation) with static stability. Absolute vorticity is a vector quantity that incorporates both the earth's planetary vorticity and the relative vorticity. Counterclockwise rotation yields positive relative vorticity, while clockwise rotation yields negative relative vorticity. Unlike relative and planetary vorticity, potential vorticity is conserved along frictionless, adiabatic flow and is therefore a convenient tracer for large-scale flow, especially on an isentropic surface (Hoskins et al. 1985). Rossby waves are waves in potential vorticity that owe their existence to gradients in potential vorticity. Therefore, PV is ideally suited for analyzing Rossby waves and the extratropical jet. The static stability term of potential vorticity is useful in differentiating between the troposphere and the stratosphere. The stratosphere is incredibly stable, allowing it to attain static stability values much higher than those in the troposphere. Since the Northern part of the Northern Hemisphere is colder, the tropopause dips lower in altitude in the North, allowing stratospheric air to penetrate towards lower altitudes. Therefore, when examining an isentropic surface, higher PV values are found in the North. The 1.5 Potential Vorticity Units (PVU) contour can be used to trace the tropopause, with higher PV values on the Northern side indicating stratospheric air and lower PV values towards the south signifying tropospheric air. The jet stream is positioned at the point where the temperature gradient switches from decreasing with height (troposphere) to increasing with height (stratosphere). Therefore, the jet stream is situated just under the tropopause and follows the general pattern of the tropopause (Hoskins et al. 1985).

The extratropical flow will be traced using the potential vorticity values along the 320 Kelvin isentropic surface between the latitudes of 40 degrees North and 60 degrees North. Between the band of 40 degrees North to 60 degrees North, a meridional average of potential vorticity is calculated for each longitude within the Atlantic Basin (-100 degrees West and 50 degrees East). Minute fluctuations in PV, due to PV streamers and sub-synoptic scale waves, are smoothed by applying a moving average function. Finally, results are displayed as anomalies from the average PV in the Atlantic basin. At the longitude location of a trough, the latitude of the tropopause on an isentropic surface is displaced equatorward. This causes the higher valued PV contours originally towards the pole to move southward, creating a meridional column with a higher average PV at the longitudes associated with the trough. The local maximum of PV will then be situated at the trough axis.

At the time of recurvature, the longitudes of troughs within the Atlantic basin are compared to the longitude of the tropical cyclone's recurvature. The trough of interest is selected as the trough closest to the recurving cyclone, as determined by the smallest absolute value of the difference between the longitude of the trough and the recurvature longitude of the cyclone. Similarly, the phase of the interaction is determined by subtracting the TC's recurvature longitude from the longitude of the axis of the trough of interest, as shown in Figure 2. If the tropical cyclone recurves on the east side of the trough (downstream), the phase value will be negative. However, if the TC recurves on the west side of the trough axis (upstream), the phase value of this interaction will be positive. Whether this phase value is positive or negative will create two climatological categories, useful for evaluating whether positive or negative phasing is associated with a stronger extratropical flow response.

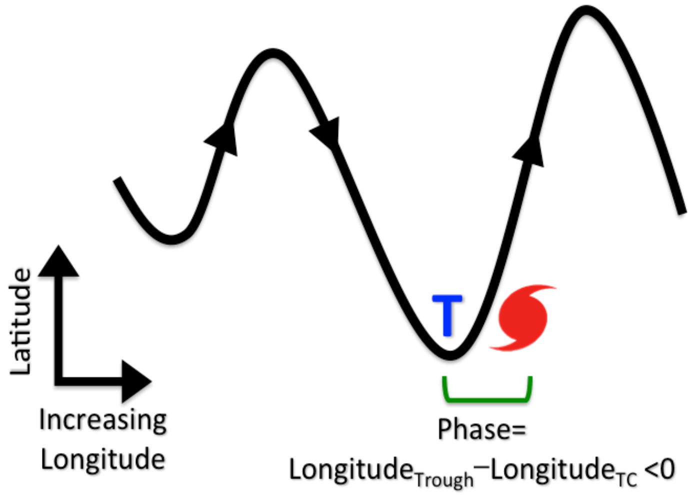


Figure 2. This schematic gives a visual representation of the phase of the interaction between the TC and the extratropical jet. The black line represents the flow of the jet stream, with a blue "T" marking the trough of interest. The TC shown in red undergoes extratropical transition on the east side of the trough of interest, yielding a negative phase value.

The amplitude of the trough of interest provides a comparison point for the downstream troughs at later time steps. At 24 hour intervals after the time of recurvature, the downstream trough within the Atlantic Basin with the largest amplitude is compared to the amplitude of the initial trough of interest. The change in amplitude is calculated by subtracting the initial trough's amplitude from the trough's amplitude at the time after recurvature. This change in amplitude calculation is computed for 24, 48, 72, and 96 hours after the time of TC recurvature.

Using statistical techniques, it can be determined if the extratropical flow pattern becomes significantly amplified. The sample mean and standard deviation of the change in trough amplitude will be computed as a climatological reference point. One sample t-tests will be used to determine whether the change in trough amplitude is statistically greater than zero. A one sided t-test will evaluate the null hypothesis that the change in trough amplitude is equal to zero versus the alternative hypothesis that the change in trough amplitude is greater than zero. The null hypothesis will be evaluated using the p-value. A p-value is the probability of obtaining an observation at least as extreme as the value in question, while assuming that the null hypothesis is true. To present results with 95% confidence, p-values will be compared to an alpha value of 0.05. Low p-values suggest that there is low probability of obtaining the observed value if the null hypothesis is true. Therefore, p-values lower than 0.05 are statistically significant, signifying that there is sufficient evidence to reject the null hypothesis. Accepting the alternative hypothesis indicates a significantly amplified extratropical flow response and favorable phasing between the TC and the extratropical jet. Conversely, a high p-value suggests that there is strong enough evidence to conclude the null hypothesis. In this case, a high p-value shows that the difference in amplitude is not statistically different from zero. In other words, the difference between the initial trough and the downstream trough is insignificant, and does not indicate favorable phasing.

3. Test Case: Tropical Cyclone Hanna

As Atlantic TC Hanna moved into the mid-latitudes she transitioned into an extratropical cyclone and experienced recurvature. At the time of recurvature, Hanna interacted with the extratropical trough that advanced from the west. This interaction was a possible trigger of the reintensification of the extratropical storm Hanna and the formation of a ridge closely downstream of Hanna's low pressure center (Grams et al. 2011). Also at the time of extratropical transition, but at a greater distance downstream, a trough amplified, which initiated the development of another extratropical cyclone. Forty-eight hours after extratropical transition, the northern sector of Hanna's trough moved cyclonically, causing the close downstream ridge to move towards the northern side of extratropical Hanna. Also associated with the cyclonic flow is the generation of an extratropical cyclone, upstream from extratropical Hanna. As the northern sector of Hanna's trough moved, the southern sector of Hanna's trough elongated until it broke off as a PV streamer. Slightly in front of the PV streamer, a cut-off low formed and initiated the origin of a Mediterranean cyclone, which prompted convection, severe thunderstorms, and heavy rainfall in Western Europe (Grams et al. 2011).

The ECMWF forecasts experienced difficulty quantifying the amplitude of the downstream trough. The main sources of uncertainty stemmed from the progression of the mid-latitude extratropical flow following the extratropical transition of TC Hanna. The linkage between Hanna's recurvature, Hanna's potential interaction with the extratropical jet stream, and the subsequent extreme weather events, which had low predictability, makes Hanna an ideal test case for this study. After the extratropical transition of TC Hanna, the extratropical flow becomes significantly amplified, making this a good storm to explicitly test the metrics used in this study.

Hanna developed on the 28^{th} of August 2008 and recurved at 0Z on September 6^{th}, 2008. Hanna's pressure at recurvature was 980 mb, putting Hanna in the lowest quartile of recurvature MSLP and classifying her as a "strong" storm. Hanna recurved with winds of 60 knots, which fell into the highest quartile of wind speed at recurvature and makes Hanna a case with "strong winds." The location representing Hanna's point of recurvature lands at coordinates of 31.5 degrees North and -79.3 degrees West.

Characterization of the large-scale flow pattern begins with plotting the 1.5 PVU contour over a map of the Atlantic Basin. This 1.5 PVU contour represents the location of the tropopause, which can be used to trace the extratropical jet stream. When considering the flow direction along the jet stream, vorticity is maximum at the location of a trough axis and minimum at a ridge axis. Therefore, at the location of a trough, the 1.5 PVU contour will be pulled southward, creating a dip in the contour, in order to bring in values of higher vorticity from the north. If a ridge is present, the opposite occurs, pushing the 1.5 PVU contour northward, producing a hump in the contour and denoting lower values of vorticity. As explained in section 2d, at the time of recurvature, an amplitude is calculated for each longitude to represent the large-scale extratropical flow. Due to the maximum vorticity at a trough, the calculated amplitude is a local maximum at each trough's longitude.

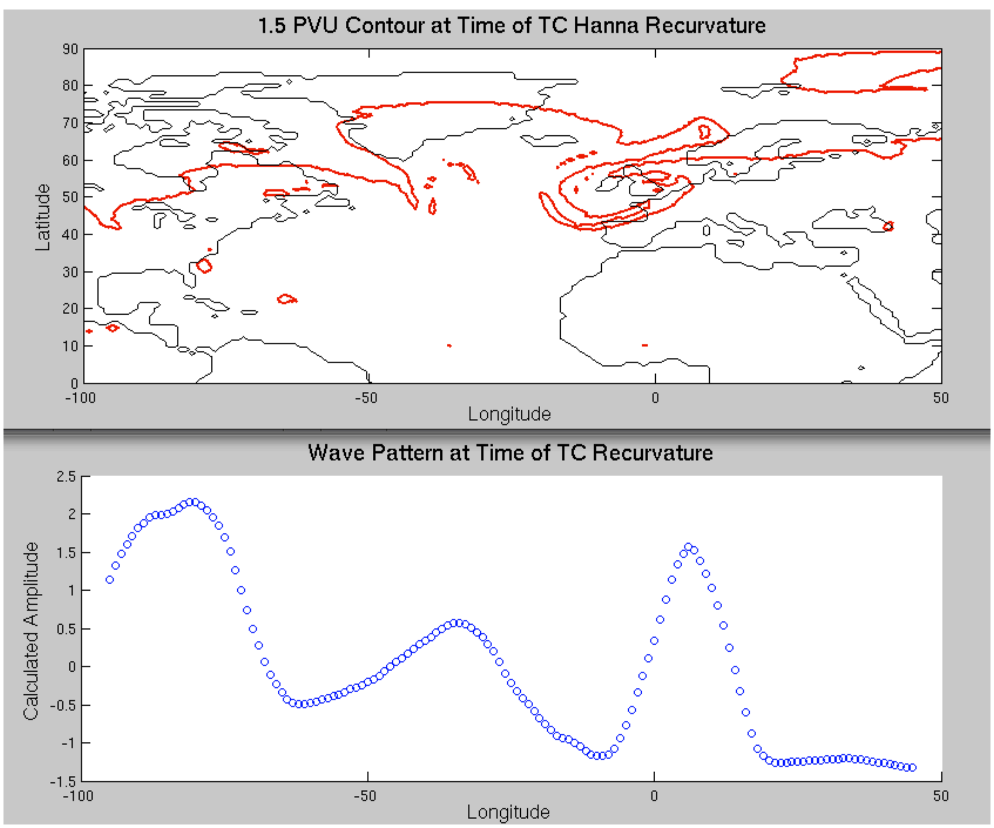


Figure 3. These plots compare the 1.5 PVU contour representative of the jet stream (top) with the wave pattern of the amplitude calculated by a moving average of potential vorticity that is used to describe the dynamics of the jet stream (bottom). As seen in the top figure, a dip in the contour represents a trough on the jet stream and is reflected by a local maximum in amplitude on the bottom plot.

Since the amplitude metric is critical to this study, it is crucial that the calculated amplitude is an accurate representation of the large-scale flow. For ease of comparison, Figure 3 stacks the 1.5 PVU contour with the wave pattern of the calculated amplitude. As seen in the top of Figure 3, troughs appear as dips in the 1.5 PVU contour, which correspond to humps in the calculated amplitude (bottom plot) at the same longitude location. This consistency is provided as evidence that to justify using this particular diagnostic to characterize the amplitude and longitude of downstream troughs in the statistical analysis that follows in section 7. It is also important to note that this metric can adequately identify troughs and their amplitude, but ridges are not captured as accurately.

Comparing the recurvature longitude to the longitudes of the multiple troughs present in the Atlantic basin at the time of recurvature, the closest trough is located at -81.0 degrees West. Hanna's phase is represented by -1.7, indicating that Hanna recurved on the east side of the trough, slightly downstream of the trough axis, shown in Figure 4. The calculated amplitude for the trough of interest at the time of recurvature is 2.159 PVU, as illustrated in Figure 4. Examining downstream troughs at 24 hours after recurvature, the largest trough is positioned at -71 degrees West with an amplitude of 1.883 PVU. This amplitude is smaller than the amplitude of the trough at recurvature, signifying that the extratropical flow is not amplified one day after recurvature. However, 48 hours after recurvature, the largest trough is located at a longitude of -74 degrees West, having an amplitude of 2.626 PVU. The amplitude metric of the extratropical trough two days after recurvature is larger than the amplitude of the initial trough, showing amplification of the extratropical flow and favorable phasing. As presented in the Grams et. al. (2011) study, it is 48 hours after extratropical transition that Hanna's trough travels cyclonically, causing movement of the downstream ridge, and the generation of a downstream cyclone. The amplitude metric applied in this study captures the amplification of extratropical flow at 48 hours, confirming that the methods implemented to calculate the amplitude metric carry enough sensitivity to detect significant changes in the amplitude of the extratropical jet.

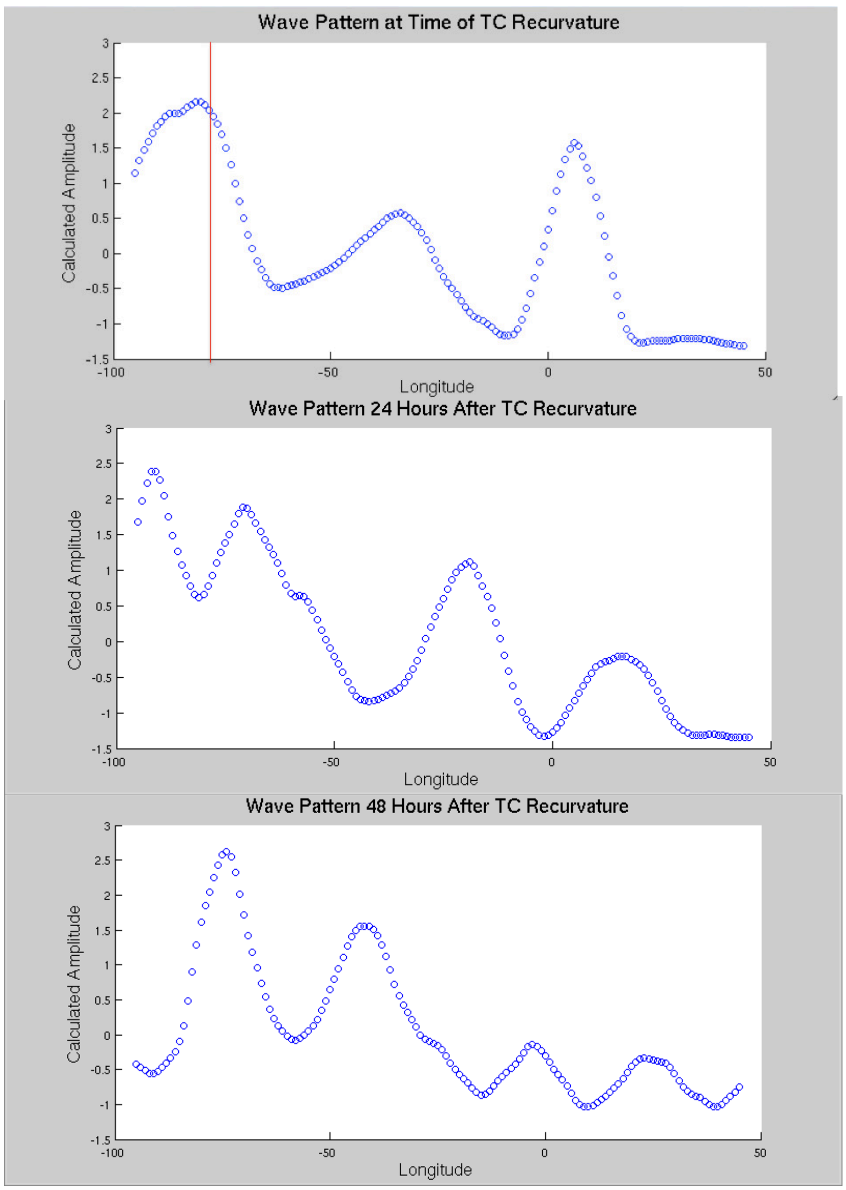


Figure 4. This figure shows a comparison of the amplitude of the extratropical jet at the time of recurvature (top), 24 hours after recurvature (middle), and 48 hours after recurvature (bottom). The longitude of TC Hanna at the time of recurvature is represented by the red line to illustrate Hanna's phase and to reveal the closest trough at the time of recurvature. At 24 hours after recurvature, the largest downstream amplitude does not exceed the amplitude of the initial trough of interest. At 48 hours after recurvature, the trough at a longitude of -74 degrees West possesses an amplitude greater than the initial trough of interest.

In summary, the test case of TC Hanna revealed amplified extratropical flow stemming from a tropical cyclone characterized by strong intensity and strong winds, an extratropical jet characterized by the month of September and a latitude of 31.5 degrees North, and a TC—jet interaction described by a negative phase value (TC recurving downstream of the trough). These climatological categories only yield the amplification of the jet stream for this particular case. A complete climatology analyzing the characteristics leading to significantly amplified flow is presented in the following sections.

4. Climatology of Recurving Tropical Cyclones

Recurving cyclones included in this study recurve with MSLPs that range from 935 mb to 1013 mb. The overall mean recurvature MSLP is 992.65 mb, which is close to the median of 997.5 mb. In order to classify the storms by intensity, the four quartiles of the overall distribution are calculated. "Weak" TCs will be classified as those with a recurvature MSLP greater than 1006 mb and TCs with "strong" intensity will be those with a recurvature MSLP less than 986 mb.

Examining the recurvature MSLP as a function of the month of year in Figure 5 shows that recurving TCs in the Atlantic basin tend to recurve at a lower pressure and higher intensity during the peak of hurricane season, as opposed to the recurving storms towards the beginning or end of hurricane season, which are revealed to recurve at a higher pressure. These results are compared to TC recurvatures in the Western North Pacific to find roughly the same pattern. The Western North Pacific TCs recurving between September and November have a significantly lower average MSLP than TCs that recurve between June and August (Archambault et al. 2013). The main difference between these datasets is centered around the month of August. In the Atlantic basin, August is considered to be a month with a large amount of intense cyclones at recurvature, whereas recurving TCs in the Pacific during the month of August are considered to be weaker, on average.

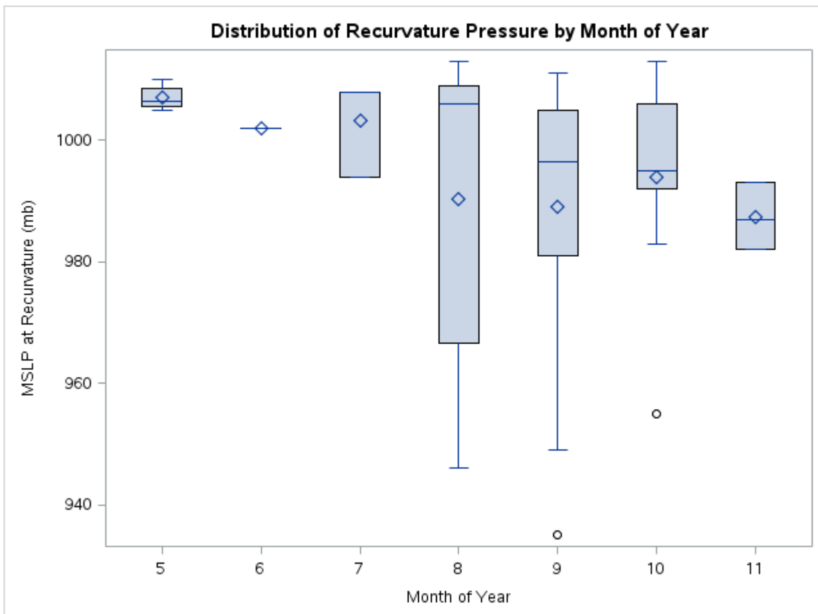


Figure 5. This plot shows boxplots of the distributions of mean sea level pressure (mb) at recurvature for each month included in this study. The upper and lower bounds of each box represent the 75th and 25th percentiles, respectively. The bar inside the box denotes the median, while the diamond indicates the mean. The whiskers extending from the box report the minimum and maximum values, with outliers shown as circles beyond the whisker.

Recurving cyclones are also classified according to their wind speed at recurvature. Wind speed is another valid measure of intensity, as it is typically inversely proportional to MSLP. Classically, a storm with high intensity will have faster wind speeds and lower MSLP. The average wind speed at recurvature for these Atlantic TCs is 50 knots, with a close median of 45 knots. The range of recurvature wind speeds stretches from a minimum of 20 knots to a maximum of 115 knots. Calculating the quartiles of the distributions creates the threshold of a TC with strong winds to have a recurvature wind speed greater than 60 knots. TCs considered to have weak winds will recurve with wind speeds less than 35 knots.

Figure 6 breaks down the recurvature wind speed by month of year. As expected, this plot is almost an exact inverse of the similar plot of MSLP by month. The TCs that recurve with the greatest wind speed are generally storms that occur during the middle of hurricane season, with the slower average wind speeds falling towards the beginning months of hurricane season. The intensity inferred from the plots of MSLP and wind speed is mostly consistent between the two. The only minor discrepancy occurs between the months of August and September. MSLP by month shows the August distribution to extend furthest into highest intensity, while wind speed by month shows the September distribution to extend towards the highest intensity.

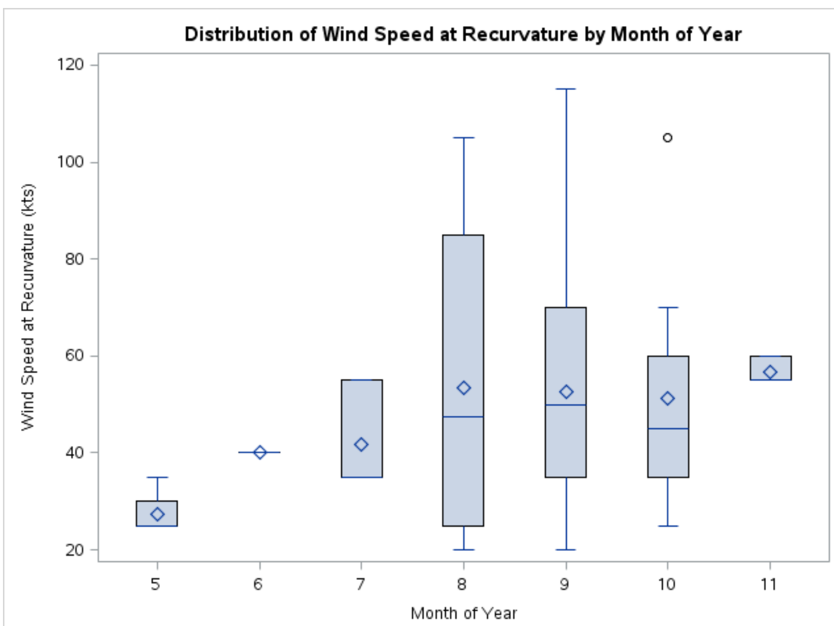


Figure 6. This plot shows boxplots of the distributions of wind speed (knots) at recurvature for each month included in this study. The upper and lower bounds of each box represent the 75th and 25th percentiles, respectively. The bar inside the box denotes the median, while the diamond indicates the mean. The whiskers extending from the box report the minimum and maximum values, with outliers shown as circles beyond the whisker.

5. Characterization of Extratropical Jet Stream

The location of the jet stream is highly sensitive to the time of year. The jet stream shifts seasonally as the elevation of the sun also changes throughout the year. During the Northern Hemisphere's summer months, the sun has a high elevation angle, causing the jet stream to move poleward. As winter approaches, the sun's elevation angle decreases and the jet stream veers towards the equator. This seasonal pattern makes the month of the year and the recurvature latitude valid classifications for describing the jet stream.

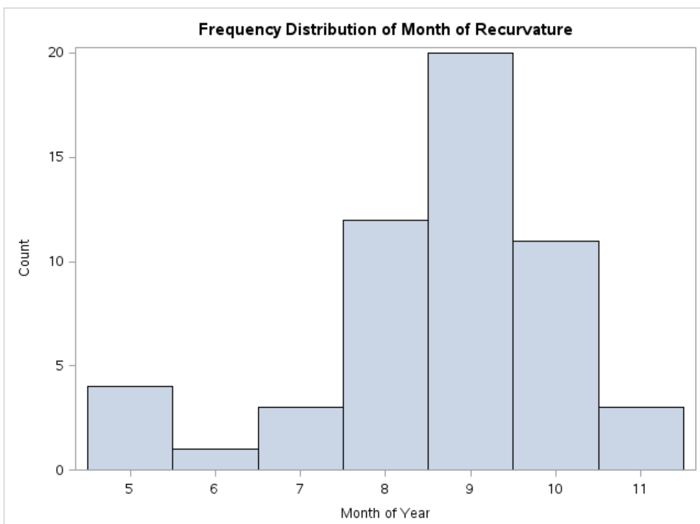


Figure 7. This histogram displays the frequency of Atlantic tropical cyclones recurving each month.

The average month of recurvature is calculated to be 8.63, which is approximately half way through August, though the range of recurvature months spans from May to November. As shown in Figure 7, the frequency distribution appears to be somewhat skewed to the left, but the median month is August (8), which is slightly less than the average. More than half of the storms included in this study recurve between August and October, with the most frequent recurvatures occurring during September. This frequency distribution is consistent with both Hart and Evans' (2011) analysis of recurving Atlantic

TCs from 1899-1996 and the Archambault et. al. (2013) analysis of Western North Pacific cyclones dated between 1979 and 2009. All three time periods in comparison show the peak frequency of recurving TCs to be during the month of September, with a relatively high count also occurring in August and October, but dropping off during the early and late parts of hurricane season.

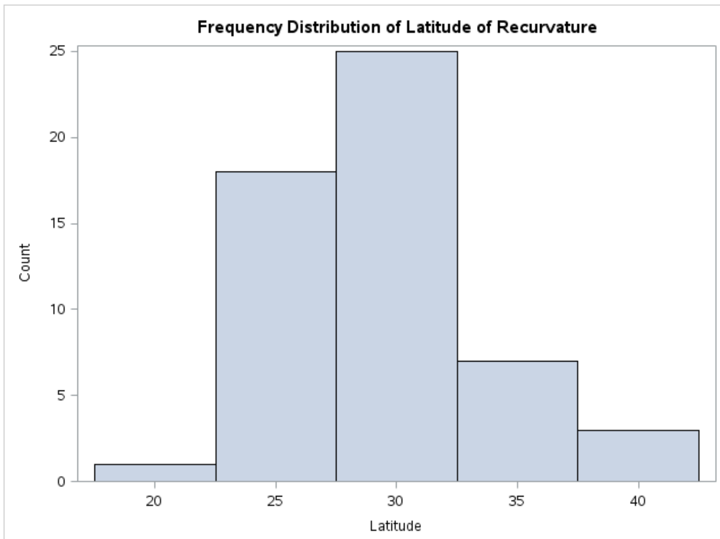


Figure 8. This histogram displays the frequency of Atlantic tropical cyclones recurving within each latitude bin. The bins each contain 5 degrees of latitude and are labeled by the lowest latitude contained in the bin. The 5 latitude bins are as follows: 20°N-24°N, 25°N-29°N, 30°N-34°N, 35°N-39°N, 40°N-44°N.

Coupled with the statistics describing the month of recurvature, the mean latitude of recurvature falls within the mid-latitudes at 29.06 degrees North. The histogram in Figure 8 shows the approximately normal distribution of the recurvature latitude. The minimum recurvature latitude of storms included in this study is 20.20 degrees North with a maximum at 40.60 degrees North. The median recurvature latitude occurs at 29.45 degrees North, almost exactly matching the mean latitude value, as expected from a normal distribution. Nearly half of the storms recurve at latitudes within the 30-34 degrees North bin.

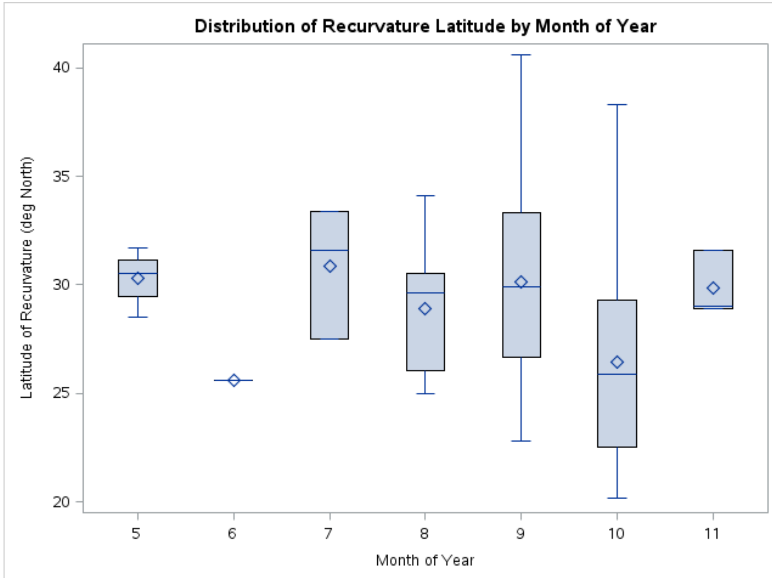


Figure 9. This plot shows boxplots of the distributions of latitude of recurvature for each month included in this study. The upper and lower bounds of each box represent the 75th and 25th percentiles, respectively. The bar inside the box denotes the median, while the diamond indicates the mean. The whiskers extending from the box report the minimum and maximum values, with outliers shown as circles beyond the whisker.

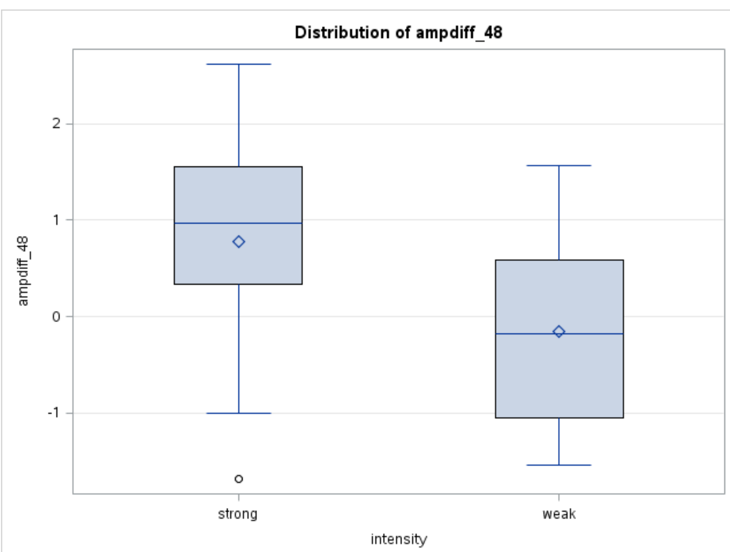
In order to show the correlation between the month of recurvature and the latitude position of the jet stream, Figure 9 is included. When considering each monthly distribution, the mean latitude does not vary much from month to month. This result is slightly different from those presented by Hart and Evans (2001), which showed a monthly deviation in recurvature latitude. The months with a greater frequency of recurving storms seemed to be correlated with a higher latitude of recurvature, while the months with less recurving storms also had a lower recurvature latitude (Hart and Evans 2001). Results from the Western North Pacific also show a strong association between recurvature month and recurvature latitude. Between the months of July and September, the recurvature latitude is typically higher, while lower latitude recurvatures are expected in May and from October to December (Archambault et al. 2013).

Again, a link between the month and latitude of recurvature can be traced back to the shifting of the jet stream throughout the year. As winter approaches (November), the jet stream is stronger and positioned closer to the equator causing TCs to recurve at lower latitudes (Archambault et al. 2013). The summer months feature a weaker jet stream shifted towards the pole, resulting in TC recurvatures at higher latitudes (Archambault et al. 2013).

6. Evaluation of the Extratropical Flow Response

a. Examination of Tropical Cyclone Characteristics

With the main goal of determining specific characteristics that lead to significantly amplified extratropical flow, investigation will first begin with an examination of recurvature MSLP of the tropical cyclones. TCs have already been categorized into "strong" and "weak" storms, so an analysis of variance (ANOVA) test will be executed to determine whether the intensity of the TC plays a significant role in amplifying the extratropical jet stream. ANOVA tests evaluate the hypothesis that the mean response for each category equals the mean response for every other category versus the alternative hypothesis that at least one mean is different from the others. In this case, the response is the difference in amplitude between the trough closest to the recurving TC and the largest trough downstream at a later time. Beginning with the difference in amplitude 24 hours after recurvature produces a p-value of 0.0899. This probability is greater than an alpha of 0.05, giving sufficient evidence to accept the null hypothesis (with 95% confidence) and conclude that at 24 hours after recurvature, whether the TC was strong or weak at the time of recurvature is insignificant in determining whether the extratropical flow is amplified. However, at 48 hours after recurvature, the ANOVA test calculates a p-value of 0.0205. This p-value is smaller than the threshold 0.05 alpha value, yielding the conclusion that the mean difference in trough amplitude is not equal for strong and weak TCs. The ANOVA test is useful to determine if there is exists a difference between the means, but it does not describe which means are different from the others, or how the means are different (larger or smaller). Therefore, a Tukey test is executed in order to determine exactly how the means differ. For this study, a higher response (larger difference between downstream amplitude and initial amplitude) is desirable for finding the optimal characteristics that produce amplified extratropical flow. The Tukey test, illustrated in Figure 10, shows that strong storms produce a difference in amplitude 48 hours after recurvature that is statistically greater than that produced by a weak TC. Similar to the 48 hour ANOVA test, 72 hours and 96 hours after recurvature yield low p-values from the ANOVA test, 0.0058 and 0.0154 respectively. These Tukey tests also mimic the results that TCs categorized as strong in intensity produce a statistically larger difference in trough amplitude than weak TCs.



Means with the same letter are not significantly different.			
Tukey Grouping	**Mean**	**N**	**intensity**
A	0.7788	15	strong
B	-0.1541	17	weak

Figure 10. These figures show the results of the Tukey test. The left figure uses boxplots to show distributions of the difference between downstream trough amplitude and initial trough amplitude for both strong and weak storms. The right figure gives the Tukey groupings for strong and weak tropical cyclones. Different letters indicate statistically different categories.

Comparing these statistical conclusions from the Atlantic basin to those from the Western North Pacific basin return many similarities. TCs of both strong and weak intensity in the Pacific can be linked to significantly amplified extratropical flow; however, strong TCs tend to lead to a larger flow amplification (Archambault et al. 2013), which is the concluded result from the Atlantic, as well.

ANOVA tests were also executed to determine the significance of wind speed at recurvature when examining the difference in trough amplitude between the initial trough and the downstream trough at later times. The categories for this test are strong and weak wind, as classified in section 4. ANOVA tests were implemented for 24, 48, 72, and 96 hours after recurvature and the resulting p-values are 0.1513, 0.1101, 0.0610, and 0.0647 respectively. All four of these p-values are greater than 0.05, leading to the conclusion that weak versus strong wind is not a statistically significant factor in determining the amplification of the extratropical flow.

b. Examination of Extratropical Jet Characteristics

The extratropical jet has been characterized by both month of year and latitude. ANOVA tests are also appropriate for these characteristics in order to determine if month or latitude plays a significant role in the difference in trough amplitude between the time of recurvature and downstream at a later time. Beginning with month of year, each month will serve as its own category. The ANOVA test analyzes the null hypothesis that the mean difference in trough amplitude is equal for months ranging from May to November versus the alternative hypothesis that there is at least one month that has a statistically different average difference in trough amplitude. The ANOVA test is performed using the responses from 24, 48, 72, and 96 hours after recurvature which produce p-values of

0.9104, 0.2087, 0.2611, and 0.2696 respectively. These are all very high p-values, yielding high confidence that the amplification of extratropical flow is not dependent upon the month of year. This result, however, is not consistent with results from the Western North Pacific. The North Pacific results revealed that during the months August through November, the extratropical flow was more likely to be amplified, whereas May and June experienced conditions less favorable for extratropical amplification (Archambault et al. 2013).

ANOVA tests require categorical input, so the latitude bins each containing 5 degrees (created in section 5) will be used as the groupings for this analysis. Here, the ANOVA test analyzes the null hypothesis that the mean difference in trough amplitude is equal for each latitude bin versus the alternative hypothesis that there is at least one latitude bin that has a statistically different average difference in trough amplitude. The resulting p-values from these tests are 0.2746, 0.6884, 0.7668, and 0.8073 for the differences in trough amplitude between the initial trough amplitude and 24, 48, 72, and 96 hours after recurvature, respectively. At all times, the p-value is much greater than an alpha value of 0.05, so it can be concluded that, at each time, the means for each latitude bin are statistically equal. In other words, the latitude of recurvature is not a significant characteristic in determining the amplification of the extratropical jet stream. This result, though, is not supported by the results from the North Pacific. North Pacific TCs that recurve at lower latitudes are shown to be less favorable for amplified extratropical flow when compared to recurving TCs at higher latitudes (Archambault et al. 2013).

c. Phasing Between the Tropical Cyclone and Extratropical Jet

The final objective is to discover if there exists a configuration of optimal phasing between the jet and the tropical cyclone that yields significantly amplified flow. Since primary interest regards how the extratropical flow evolves after TC recurvature, the metric representing the change in amplitude (subtraction of the initial trough's amplitude from the downstream trough's amplitude at the time after recurvature) will be utilized. If this change in amplitude is positive, the downstream trough has a greater amplitude than the initial trough, indicating amplification of the extratropical flow. The dataset is sorted into two groups, according to phase, which can either be positive (TC recurved upstream/west of trough) or negative (TC recurved downstream/east of trough). One sided, one sample t-tests assess the null hypothesis for both positive and negative phase and at each time step after recurvature. In this case, the null hypothesis is that the mean change in amplitude equals zero, whereas the alternative hypothesis is that the mean change in amplitude is greater than zero.

At 24 hours after recurvature, TCs recurving west of the trough produce a p-value of 0.0693, while TCs recurving east of the trough produce a p-value of 0.0370. The null hypothesis should be accepted for storms recurving west of the trough, but rejected for storms recurving east of the trough. (See Figure 11) At 24 hours after recurvature, storms recurving west of the trough do not result in a significantly amplified jet, but cyclones recurving on the east side of the trough appear to have favorable phasing to yield significantly amplified extratropical flow.

At 48 hours after recurvature, the p-value for storms recurving to the west of the trough is 0.3225, while the p-value for storms recurving on the eastern side is 0.0029. For storms recurving on the western side, the p-value is greater than 0.05, lending sufficient evidence that, with 95% confidence, the change in amplitude could equal zero, signifying that the extratropical flow is not amplified. This upper 95% confidence interval is shown in Figure 11. Zero is included within the shaded region for storms recurving to the west, but zero falls outside the confidence interval for storms recurving to the east. Furthermore, the p-value for storms recurving on the east side of the trough is low, so the null hypothesis should be rejected. TCs recurving on the east side of the trough produce a change in the amplitude of the extratropical jet that is statistically greater than zero. Consistent with 24 hours, at 48 hours after recurvature, only TCs recurving on the east side of the trough yield favorable phasing for amplified extratropical flow.

Similar results occur at 72 and 96 hours after recurvature, also shown in Figure 11. TCs recurving on the west side of the trough result in high p-values of 0.2542 and 0.1929 for 72 and 96 hours after recurvature, respectively. Again, these p-values lead to the conclusion that TCs recurving west of the trough do not significantly amplify the extratropical flow. Conversely, TCs recurving downstream (east) of the trough yield statistically significant p-values of 0.0070 and 0.0347 for 72 and 96 hours after recurvature, respectively. Consistent with the previous time steps, there is enough statistical evidence to conclude that, for TCs recurving on the eastern side of the trough, the change in trough amplitude is greater than zero indicating favorable phasing for amplification of the extratropical flow.

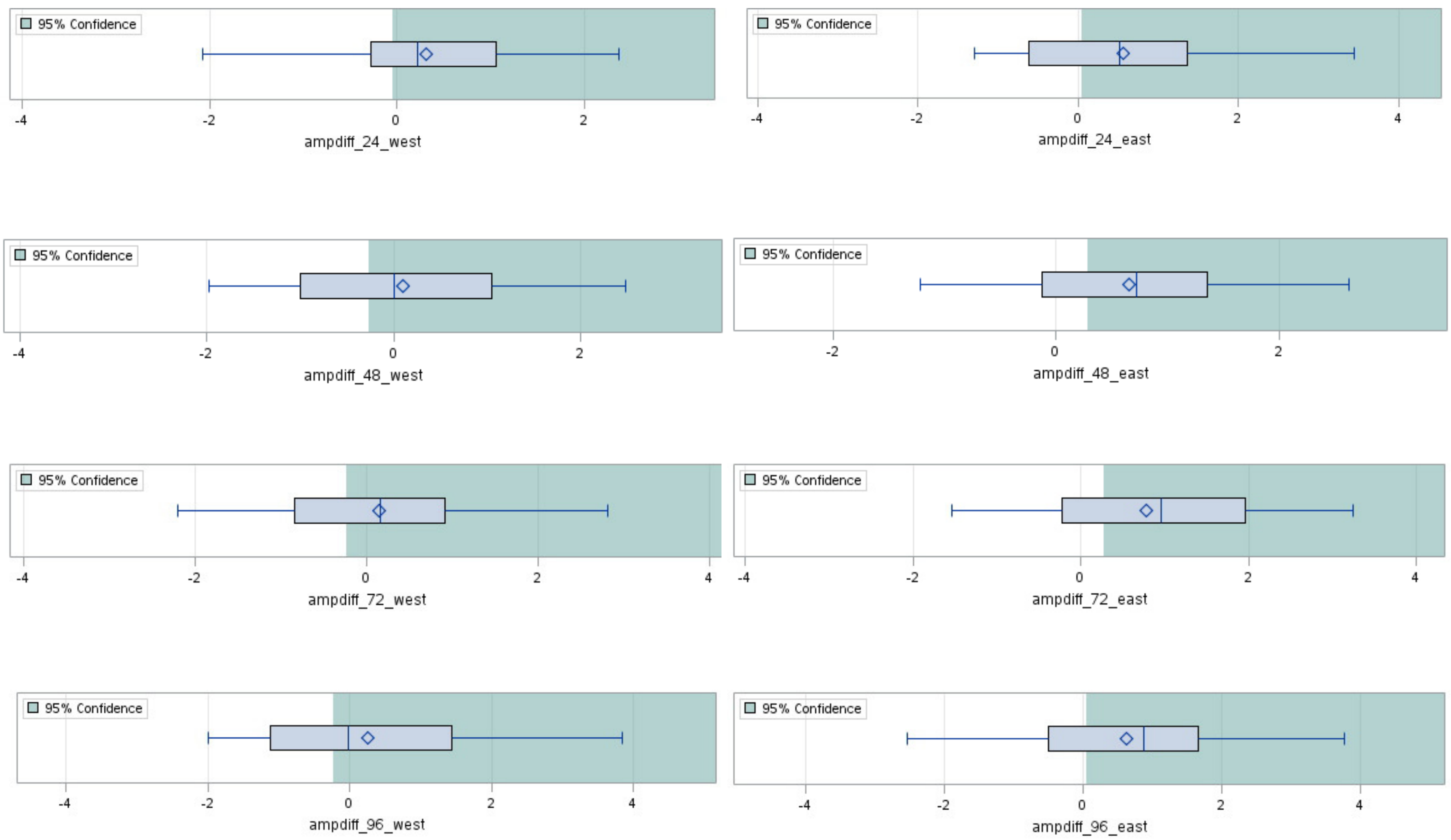


Figure 11. This figure uses a boxplot to show the distribution of the difference in amplitude between the amplitude of the initial trough of interest and the largest downstream trough at 24 (first row), 48 (second row), 72 (third row), and 96 (fourth row) hours after recurvature. The left column displays distributions from TCs that recurved on the west side of the trough of interest and the right column displays distributions of storms that recurved on the east side of the trough of interest. The right and left bounds of each box represent the 75th and 25th percentiles, respectively. The bar inside the box denotes the median, while the diamond indicates the mean. The whiskers extending from the box report the minimum and maximum values. The shaded region is the upper 95% confidence interval. If zero is contained within this shading, there is sufficient evidence to conclude that the extratropical flow is not amplified at the specified time. If zero is not contained within the upper confidence interval, then there is enough evidence to conclude that the difference in amplitude is greater than zero, indicating amplified flow at the given time.

7. Conclusion

The discoveries of this Atlantic study can be added to the results of the Archambault et al. (2013) study of the extratropical flow response in the Pacific to enhance the current knowledge of the extratropical flow response to recurving tropical cyclones. This study presents a climatological analysis of the characteristics of tropical cyclones, the extratropical jet stream, and the phasing between the two in order to identify which features optimize amplification of the extratropical jet stream after tropical cyclone recurvature.

After comparing the amplitude of the extratropical jet stream at the time of TC recurvature to the amplitude at 24 hour intervals from one to four days after recurvature, characteristics of the jet are not found to be statistically significant in affecting the change in amplitude. Neither the month of year nor the latitude of recurvature appeared to be factors that significantly affected amplification of extratropical flow. Examining the affects of the tropical cyclone characteristics on the amplification of flow leads to the conclusions that wind speed at recurvature does not have a significant influence on the amount of extratropical flow amplification. However, classifying intensity by MSLP leads to an association between a larger amplification for TCs of strong intensity. Finally, an analysis of the phasing between the tropical cyclone and the extratropical jet shows that storms recurving west of a trough do not yield significantly amplified extratropical flow. Conversely, tropical cyclones recurving on the east side of the nearest trough have favorable phasing and are more likely to be associated with amplification of the extratropical flow.

These results are significant from a forecasting prospective because the predictability (whether weak or strong) associated with tropical cyclones will be inherited by the extratropical waveguide. This causes a significant problem for medium range numerical weather prediction, especially given the frequency of recurving tropical cyclones throughout hurricane season.

Future directions to continue this study include additional classifications to characterize the tropical cyclone and the jet stream. The complex structure of a tropical cyclone has only been characterized by mean sea level pressure and wind speed, but it could also be described by size, mass divergence at upper levels, and net heating within the cyclone. The extratropical waveguide could be quantified using a contour displacement diagnostic. Another future objective is examining how well this extratropical flow amplification is forecasted, which involves identifying the key physical processes that are responsible for error growth and skill degradation within numerical weather prediction models.

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