Atmospheric Rossby Waves in Fall 2011: Analysis of Zonal Wind Speed and 500hPa Heights in the Northern and Southern Hemispheres

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ABSTRACT

This study is an analysis of atmospheric waves using 500hPa heights as well as 500hPa and 300-150hPa zonal winds. Data was collected from September 7, 2011, to November 11, 2011, in order to relate real-time atmospheric waves with barotropic Rossby wave theory. Collected data included wave number, average wave amplitude, wave speed, and zonal wind calculations from the 500hPa and 300-150hPa layers. In general, observations did not follow theory except for one case in the Northern Hemisphere. The waves in this study exhibited decreasing wave speed as wave number decreased. In addition, wave number increased as amplitude decreased.

1. Introduction

Large-scale atmospheric wave motions are an integral part of everyday weather. Whether it is sunny or raining, atmospheric waves play an important part in determining it. Atmospheric waves are wavelike disturbances or fluctuations of different variables in the atmosphere, such as pressure and temperature. Through quasi-geostrophic theory, forecasters can project future weather events using these wave motions. Equations have been derived using atmospheric waves to forecast where and at what magnitude upward motion will occur, which can lead to understanding where precipitation occurs. The predictability of waves can therefore be used to forecast the weather.

The goals for this study are to analyze relationships between the data recorded and Rossby wave theory. Over sixty-six days from September 7, 2011, to November 11, 2011, data was collected from both hemispheres, including wave number, average amplitude of the waves, wave speed, and two zonal wind calculations from the levels of 500 hectopascals (hPa) and

300hPa-150hPa. Analyses were performed on the data to find correlations, if any, with barotropic Rossby wave theory.

2. Data

The data used in this research is from the Iowa State University Meteorological Products website. The products given are the 8-day Northern and Southern Hemisphere 500hPa analysis and the 8-day global zonal wind average. The 500hPa analysis is imaged from the North Pole (Northern Hemisphere) or South Pole (Southern Hemisphere) to the equator. Lines of latitude are drawn every ten degrees from the pole to the equator, and lines of longitude are drawn every ten degrees around the Earth starting at the Prime Meridian. The global zonal wind average is created by averaging wind speed at a given latitude over the entire globe at every pressure level. Data was collected from September 7, 2011, to November 11, 2011.

The data provided in the Northern Hemisphere 500hPa analysis is more accurate than the Southern Hemisphere 500hPa Analysis due to weather station availability. The Northern Hemisphere is more populated, and has more access to weather stations that provide data such as temperatures, winds, and propagations of waves. The Southern Hemisphere is more difficult to provide accurate data because of fewer weather stations, and due to greater area of ocean it is hard to find a stable station to give accurate data.

Using these products we collected five variables: wave number (N), wave amplitude (A), wave speed (C), zonal wind speed at 500hPa (U500), and the zonal wind maximum in the 300-150hPa level (Uupper). Each variable is calculated for both the Northern and Southern Hemispheres. The data collected from the images were submitted into a Google Spreadsheet that was shared with the group through Google Docs. Each group member was responsible for recording their variables for the day and the duration of the project.

3. Methods

Multiple data fields were gathered from the 500hPa height analysis and global zonal wind average images retrieved from the Iowa State University Meteorological Products webpage. These include wave number, wave amplitude, wave speed, and the zonal wind speeds at the 500hPa layer and the 300-150hPa layer. Each of these variables required a method for determining or calculating their values.

The first step in determining many of the variables is to choose a target contour in each hemisphere to follow as the data progresses in time, as well as a target latitude on which to record data. For the northern hemisphere, the 5580 m contour was an appropriate target contour. The 5580 m contour separates yellow and orange/brown color-filled regions. In the southern hemisphere the 5280 m contour, separating green and blue color-filled regions, is the target contour used in this study. The target latitude is 50°N in the northern hemisphere and 50°S in the southern hemisphere because it is approximately halfway between the poles and equator and clearly marked on the data images. Both the 5580 m contour and the 5280 m contour are well-chosen because they frequently cross the 50° latitude line.

a. Wave Number, N

$$N = \frac{number\ of\ times\ target\ contour\ crosses\ target\ latitude}{2} \qquad (1)$$

Wave number is the simplest calculation. Simply begin at a point on the 50° latitude line and progress completely around the circumference of the earth on that latitude line. Count the number of times the target contour crosses the latitude line. This always gives an even number. Finally, divide the value by two to get the actual wave number.

b. Wave Amplitude, A

$$A = \frac{AvgMax - AvgMin}{2} \tag{2}$$

Waves are composed of troughs and ridges; therefore, calculations of the wave amplitude must take both troughs and ridges into account. At the pinnacle of each trough and ridge around the 50° latitude line, calculate the height of the 500hPa layer. Average the maximum values and the minimum values, subtract the average minimum from the average maximum, and divide by two. This will give the average amplitude of the waves on a given day.

c. Wave Speed, C

$$C = \frac{LON(day + 1) - LON(day - 1)}{2} \tag{3}$$

Wave speed is the physical speed of the waves, not necessarily the group velocity. In this case, the two are not equal, as will be discussed in later sections. To calculate wave speed, use the data images from the days before (day – 1) and after (day + 1) the day for which wave speed is being calculated. Mark the longitude where the target contour crosses the 50° latitude line on (day – 1), move forward to (day + 1), and mark the longitude where the same target contour now crosses the 50° latitude line. Calculate the difference in longitude and divide by two to get the wave speed.

d. 500hPa Zonal Wind Speed, U500

Zonal wind speed is determined simply by reading the wind speed value off the global average zonal wind data images. For U500, mark the locations of the 50° latitude line in each hemisphere, move upward on the graph to the 500hPa line, and read the wind speed value. Positive values indicate westerly winds, whereas negative values indicate easterly winds.

e. 300-150hPa Zonal Wind Speed, Uupper

Calculating Uupper is equivalent to calculating U500, except for the pressure level at which the wind speed is determined. Instead of reading the wind speed off at 500hPa, look for the maximum wind speed value in the 300-150hPa layer and record that value.

As always, with human calculations comes error. In calculating wave amplitude and wave speed, it was necessary to estimate the 500hPa heights and the longitude at which the target contours cross the 50° latitude line. In calculating zonal wind speed, the horizontal axis (latitude) was not marked so the 50° N and 50° S latitude lines were also estimated. However, the researchers were consistent in their calculations of each variable.

Finally, in the data analysis some fields were averaged in order to compare values. Linear regression was used with scatter plots to model the relationship between multiple variables.

4. Results

a. Speed of wave patterns

Over the period of data collection, wave speed decreased slightly with time in both the Northern and Southern Hemispheres (Figure 1).

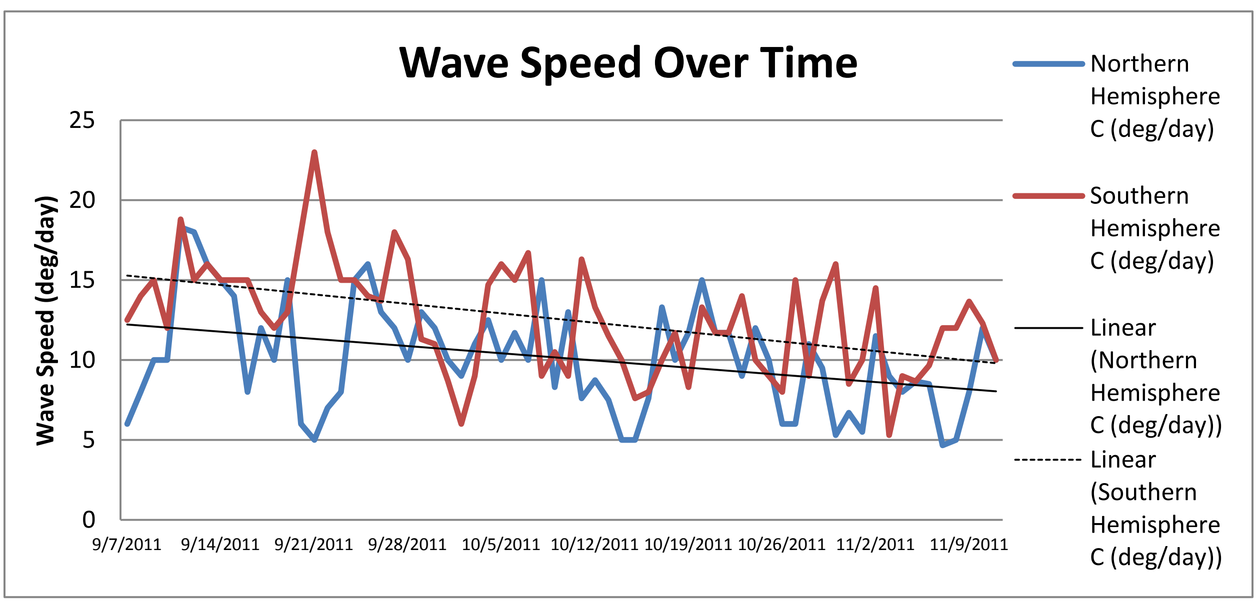
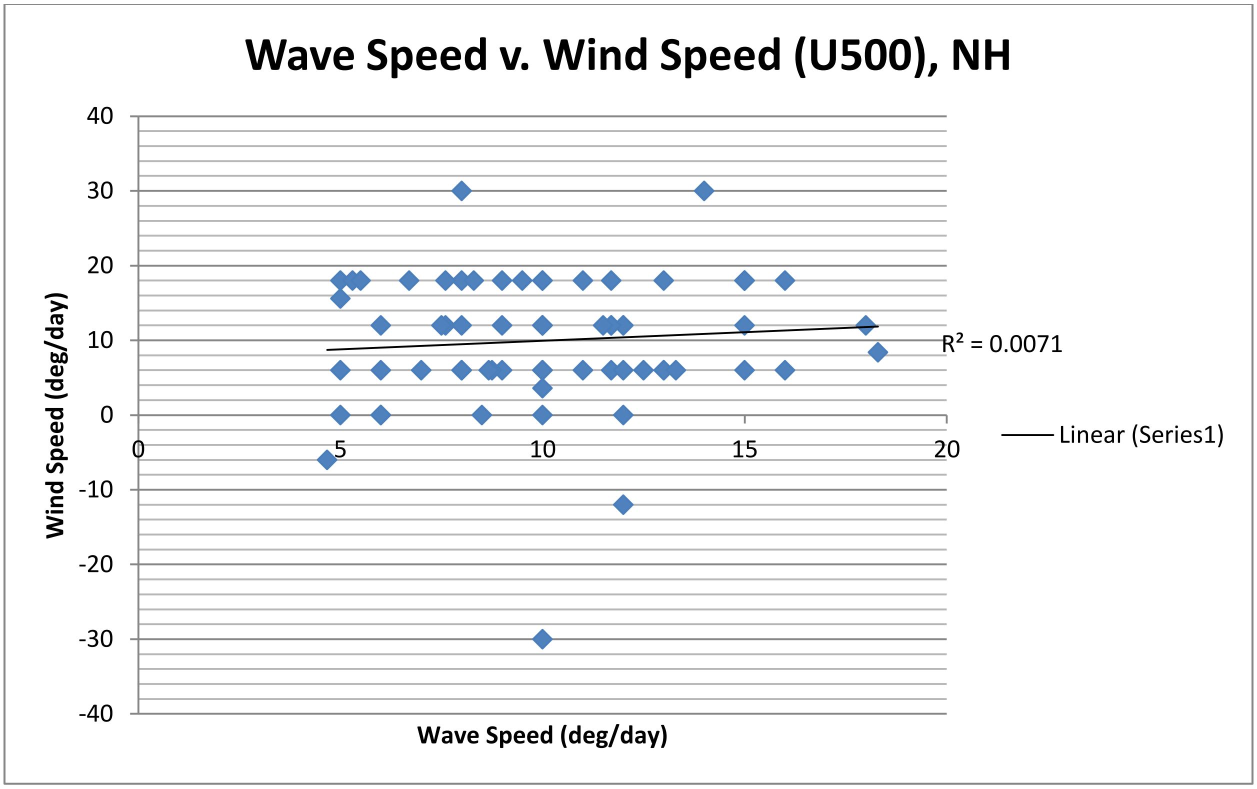


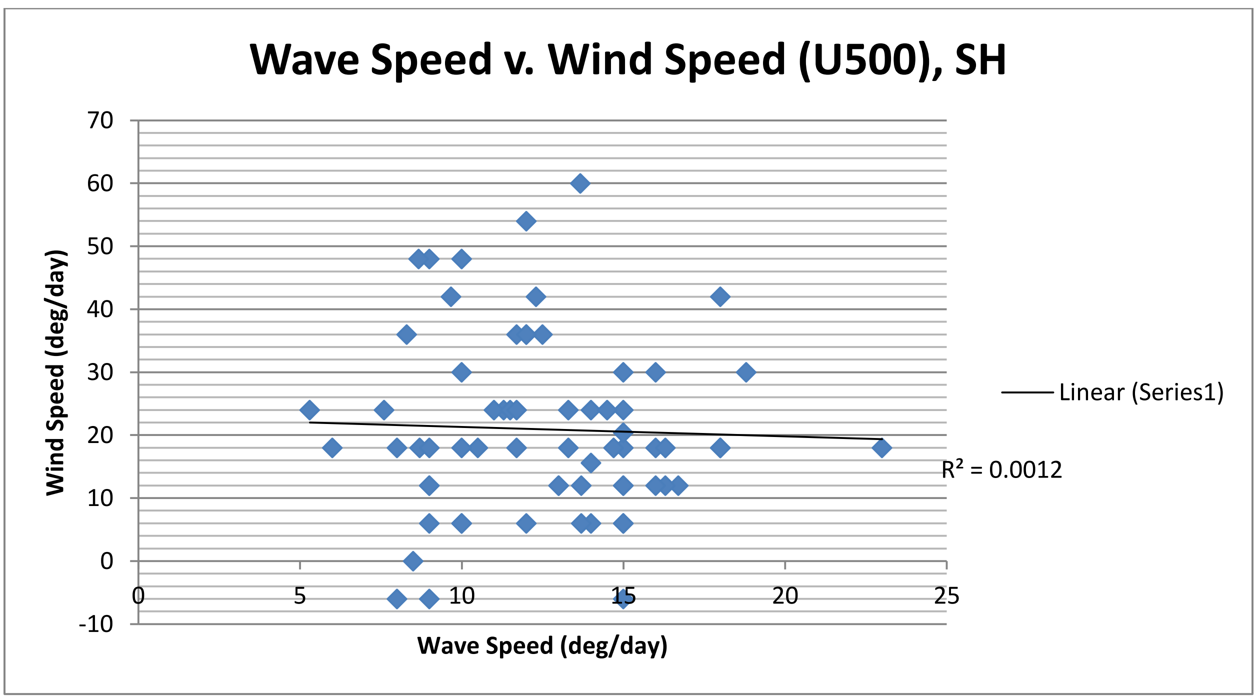
Figure 1: Wave speed versus time with linear regression trend lines

At the beginning of the period, wave speed was, on average, 14 deg/day, whereas at the end of the period, average wave speed was 9 deg/day. Waves moving at 14 deg/day take approximately 25 days to circumvent the globe, while waves moving at 9 deg/day traverse the Earth in approximately 40 days. The synoptic timescale, or the time that synoptic features last in the atmosphere, is 2-3 days. Therefore, the waves studied in this project will not survive to travel around the globe.

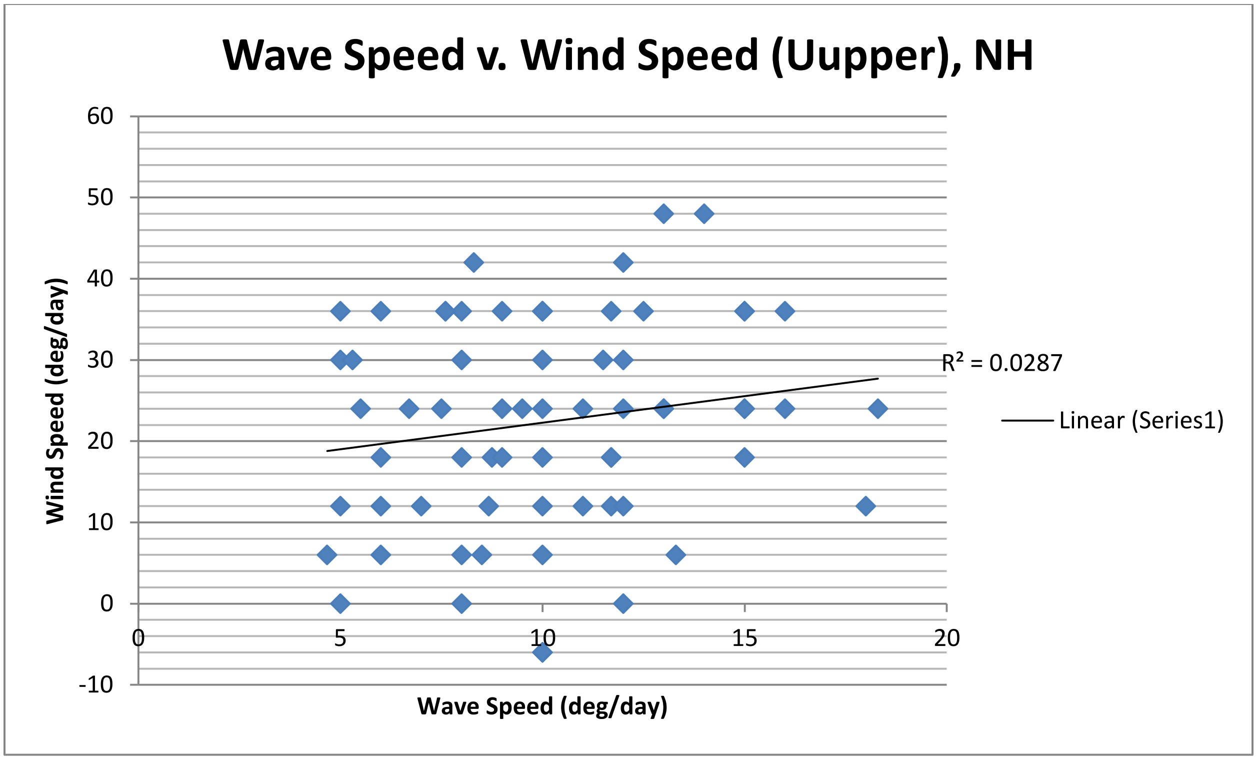
b. Relationship between zonal wind speed and wave propagation

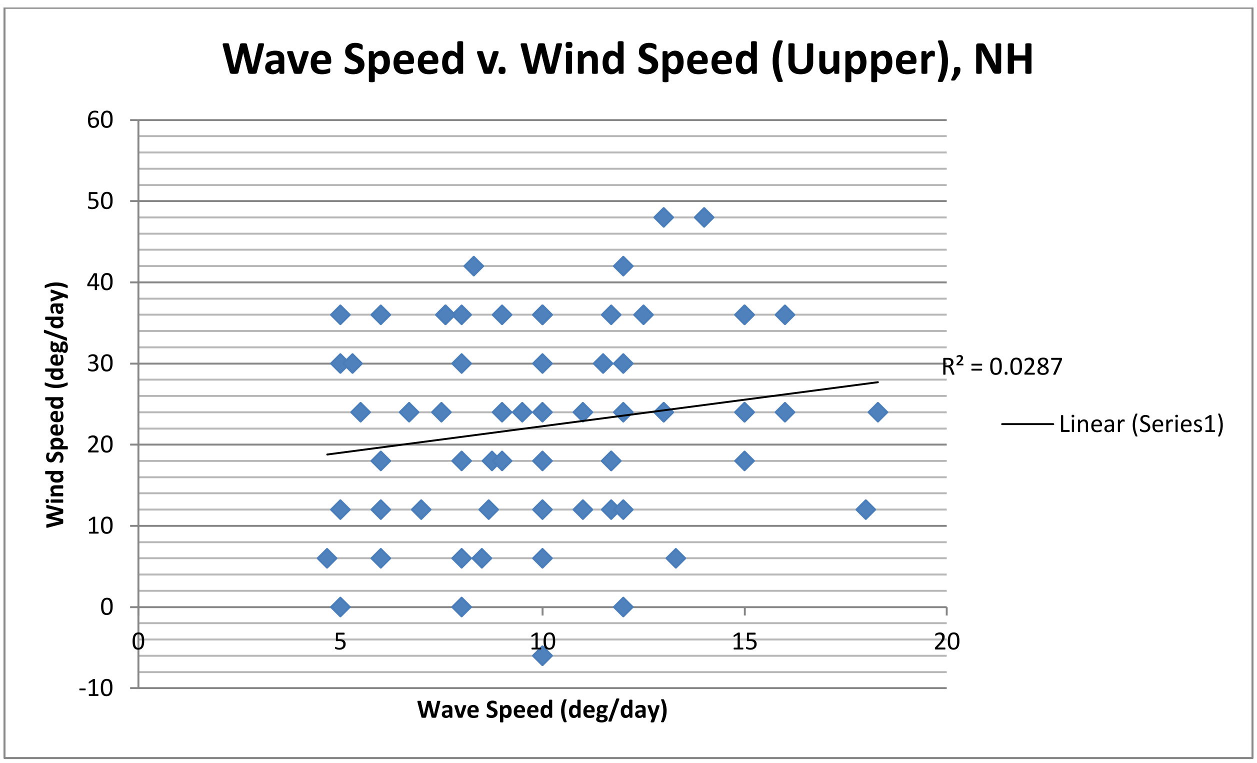
Little to no correlation exists between wave speed and wind speed at 500hPa (U500) in both hemispheres (Figures 2, 3). The same is true for wind speed at upper levels (Uupper) in the Southern Hemisphere (Figures 4, 5); however, there is a slight correlation between wave speed and Uupper in the Northern Hemisphere with a correlation coefficient $R^2 = 0.0287$. According to Rossby wave theory, without any background flow (U500 or Uupper) Rossby waves propagate in the opposite direction of zonal flow. It is only due to background winds that they propagate with the flow. Therefore, we expect to see wave speed increasing as zonal wind speed increases, and indeed that is the case in both hemispheres with Uupper and the Northern Hemisphere with U500.





Figures 2 and 3: Wave speed versus wind speed at 500hPa in the Northern (Figure 2) and Southern (Figure 3) Hemispheres with linear regression trend lines





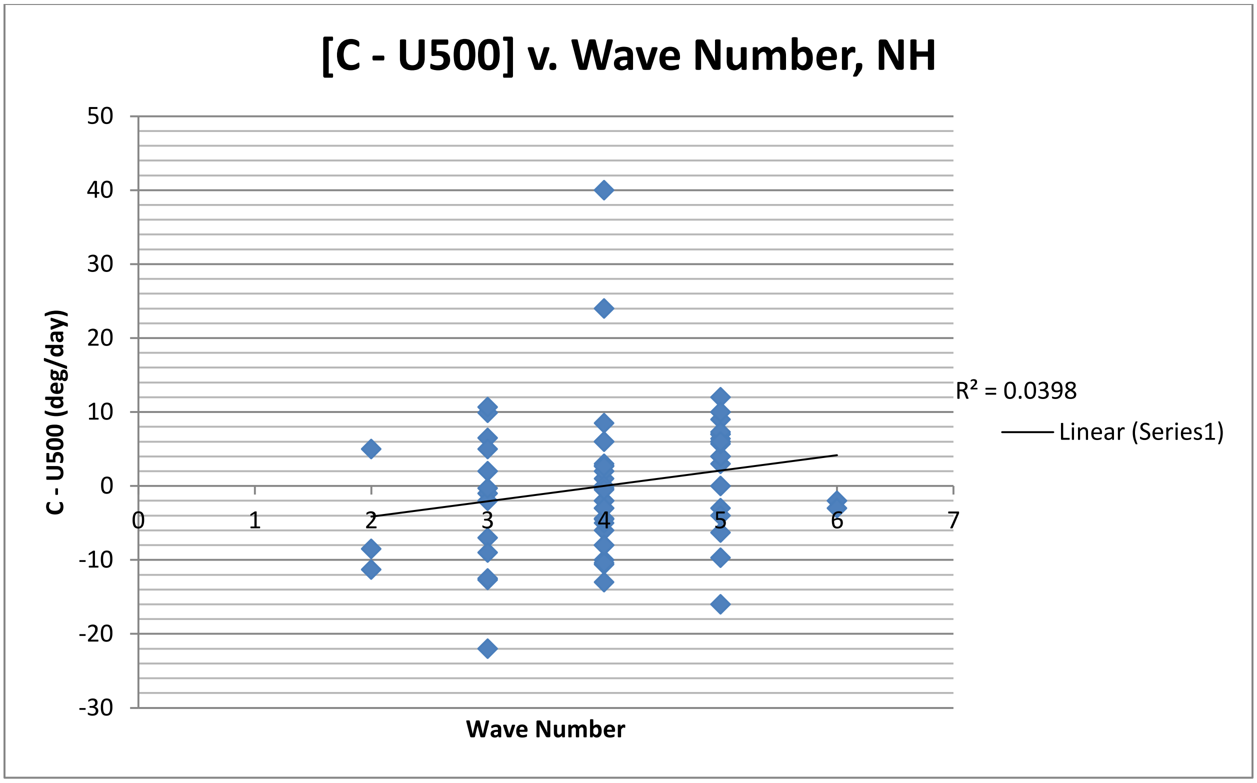
Figures 4 and 5: Wave speed versus wind speed in the 300-150hPa layer in the Northern (Figure 4) and Southern (Figure 5) Hemispheres with linear regression trend lines

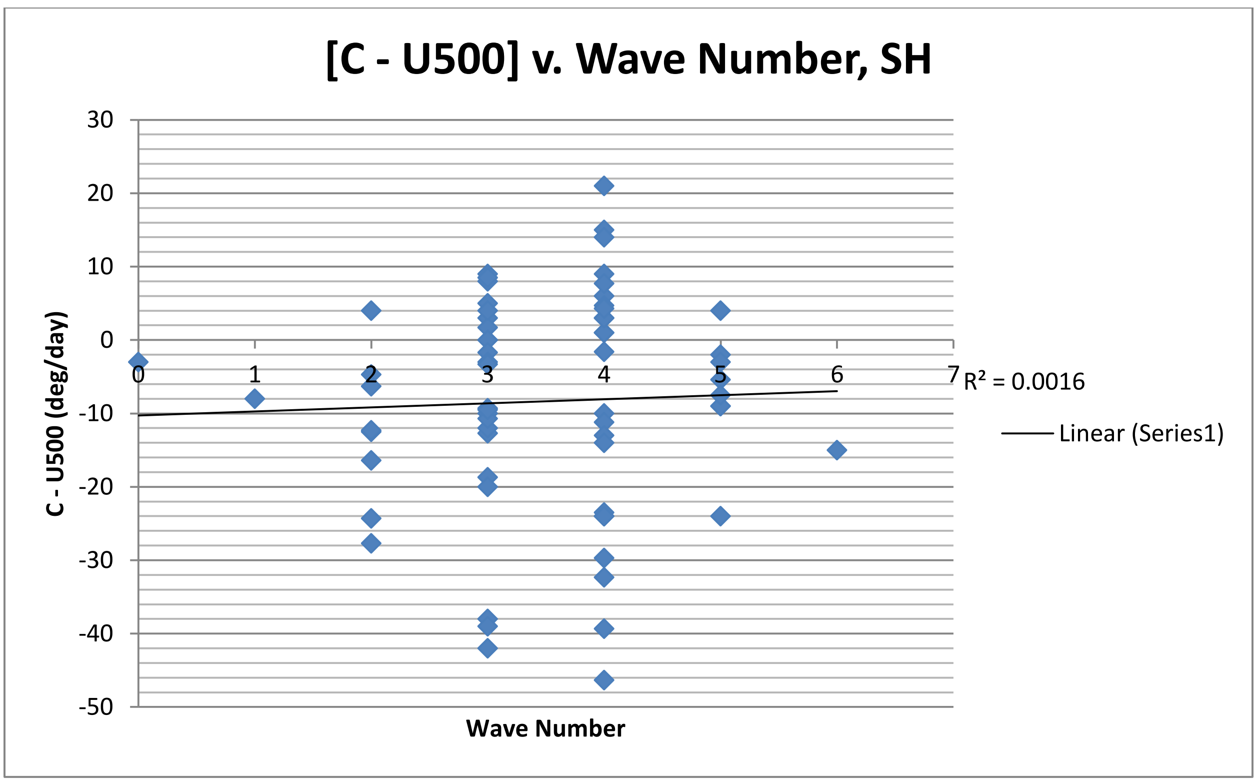
In addition, according to Rossby theory we expect to see wind speed greater than wave speed, on average, in order to account for the movement of waves with the zonal flow. In the Southern Hemisphere, the average zonal wind speed at 500hPa (U500) is 20.9 deg/day while the average wave speed is 12.5 deg/day. This agrees with Rossby wave theory. However, in the Northern Hemisphere the average wind speed is 10.0 deg/day, while the average wave speed is 10.1 deg/day. This does not comply with Rossby wave theory, but the values of U500 and wave speed C are very close.

The wave speed C calculated here is the speed that Rossby waves move as observed by humans. However, the wave speed $c_x - u$ is the speed at which waves propagate without any background zonal flow. This wave speed $c_x - u$ is given by

$$c_x - u = \frac{\beta}{k^2 + l^2} \qquad (4)$$

where u is the background zonal flow, β is a constant, and k and l are representative of the wave number. Therefore according to theory, $c_x - u$ should increase as wave number decreases. The data collected in this study does not support the theory, as seen in Figures 6 and 7. The Northern Hemisphere plot has a larger correlation coefficient than the Southern Hemisphere, but neither plot correlates well. The disagreement with theory is likely due to human measurement error when measuring wave speed and/or wind speed.





Figures 6 and 7: Wave speed minus wind speed at 500hPa versus wave number in the Northern (Figure 6) and Southern (Figure 7) Hemispheres with linear regression trend lines *c. Temporal scale of waves*

On average, a dominant wave number in both hemispheres persists for 4-5 days and ranges from 3-7 days with occasional anomalies. This is visible in Figure 8. As stated previously, the synoptic timescale is 2-3 days. The time in which a dominant wave number persists exceeds the synoptic timescale in most cases.

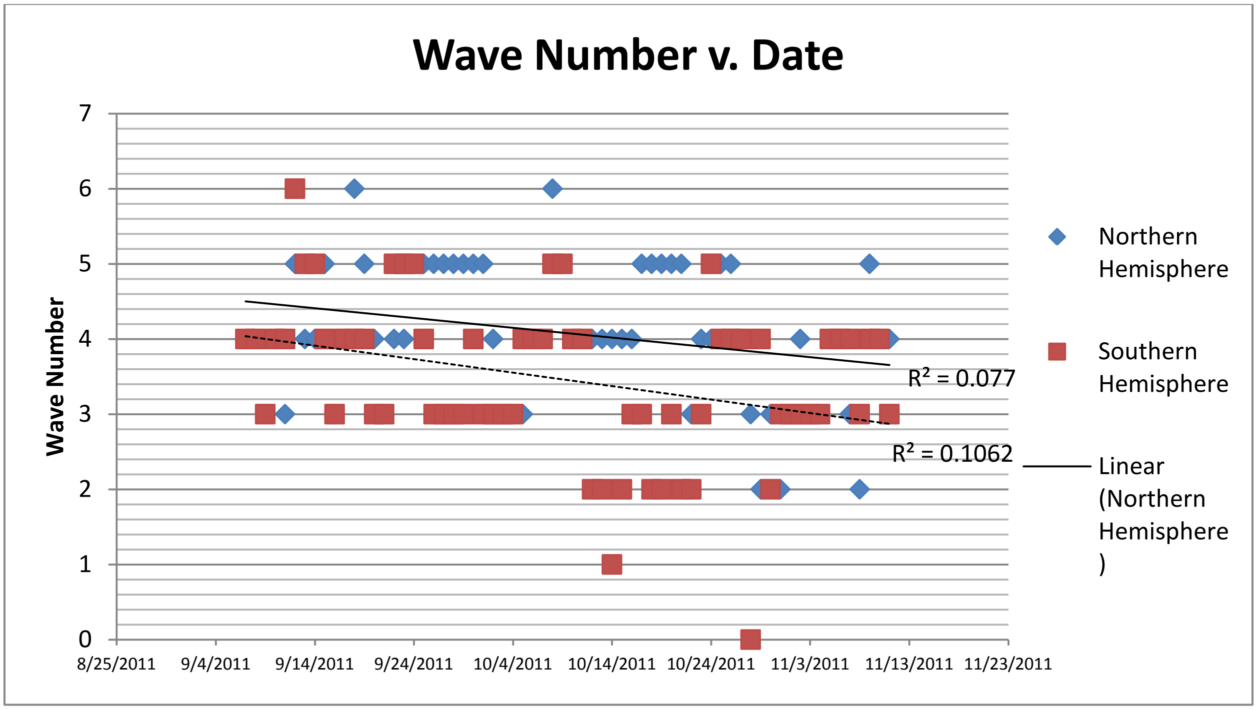
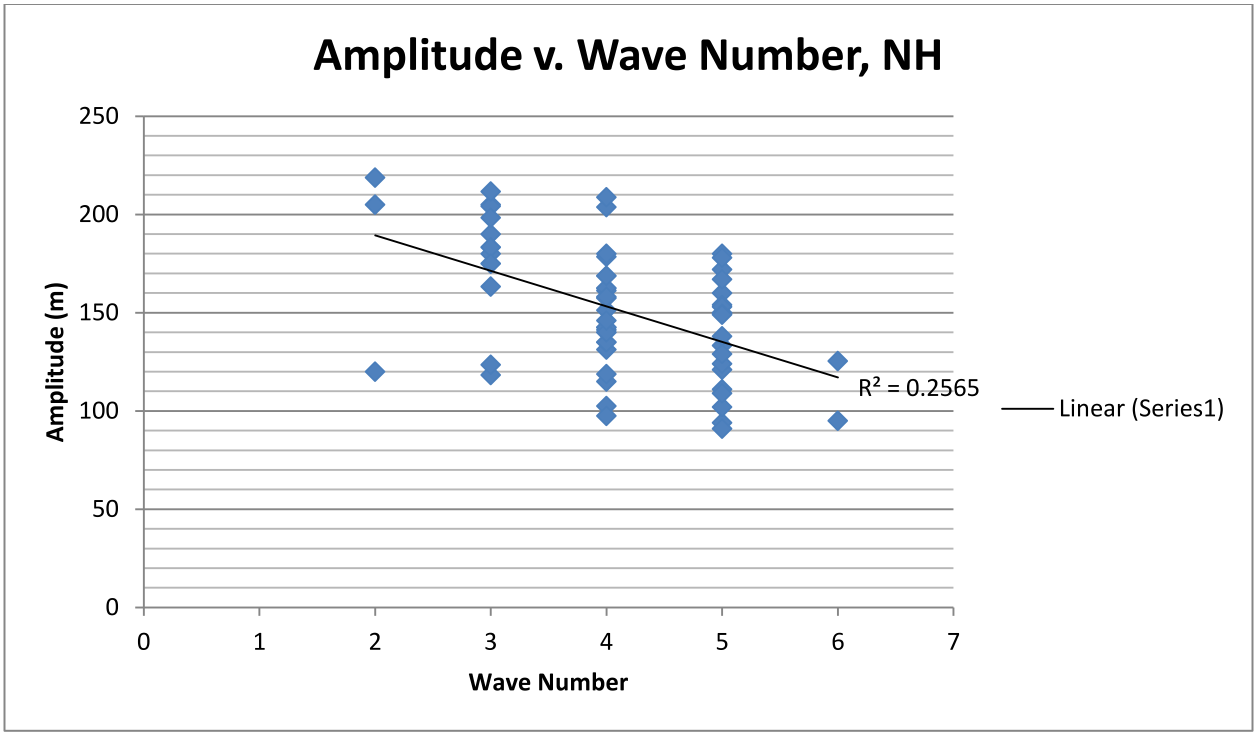
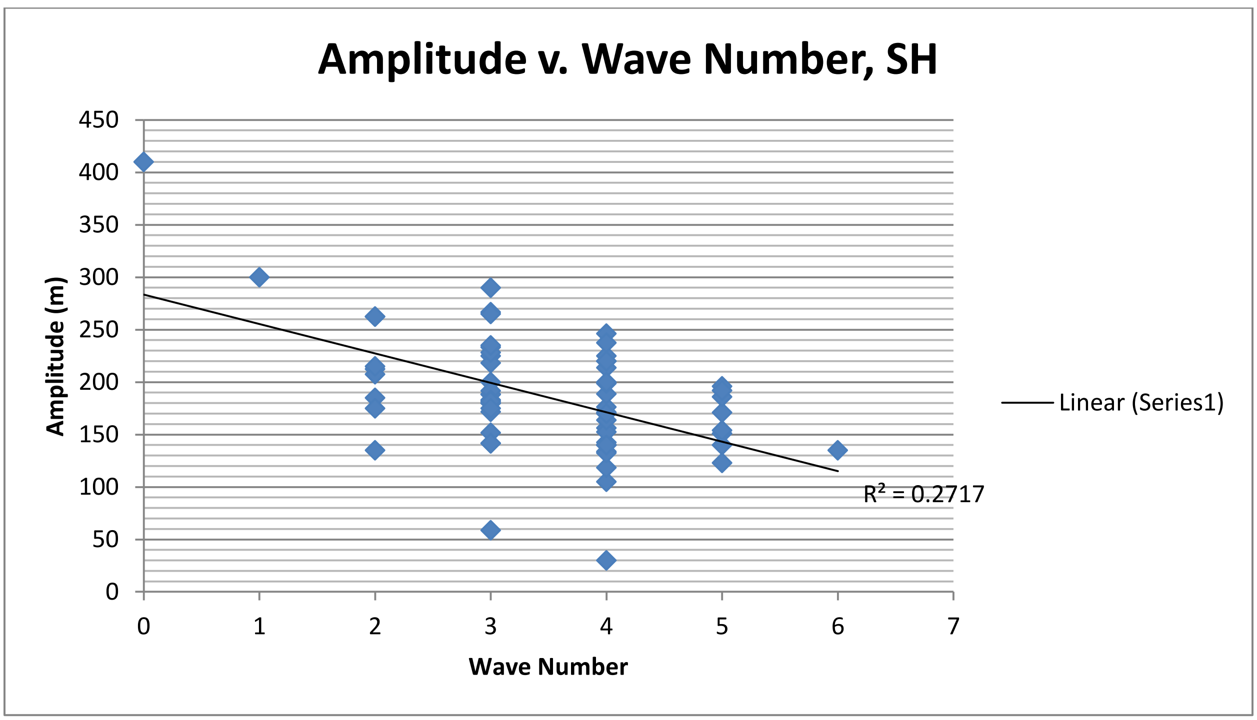


Figure 8: Wave number versus time for both the Northern and Southern Hemispheres with linear trend lines

In addition, Rossby wave theory states that higher wave numbers (or shorter waves) lead to larger amplitudes, based on calculations using Equation 4 above. According to Figures 9 and 10, in which wave amplitude A is plotted against wave number N, as wave number increases wave amplitude decreases in both hemispheres. Observations from the past few months do not follow Rossby wave theory. It is also notable that the correlation coefficients in these two graphs are two of the highest R^2 values seen in any graphs in this study.





Figures 9 and 10: Wave amplitude versus wave number in the Northern (Figure 9) and Southern (Figure 10) Hemispheres with linear trend lines *d. Changes in wave amplitude*

Wave amplitude increased over time in both the Northern and Southern Hemispheres. The increase was greater in the Southern Hemisphere. In the Northern Hemisphere, periods of growth lasted 2-3 days and periods of decay lasted 4-6 days. On average, wave amplitude increased by 73% and decreased by 40%. This matches the linear regression fit in Figure 11 which shows an increasing trend. In the Southern Hemisphere, periods of growth lasted 5-7 days while periods of decay lasted 3-4 days, which is the opposite of periods of growth and decay in the Northern Hemisphere. Wave amplitude increased by 95% and decreased by 63% on average. This agrees with the linear fit in Figure 12 showing increasing amplitude with time.

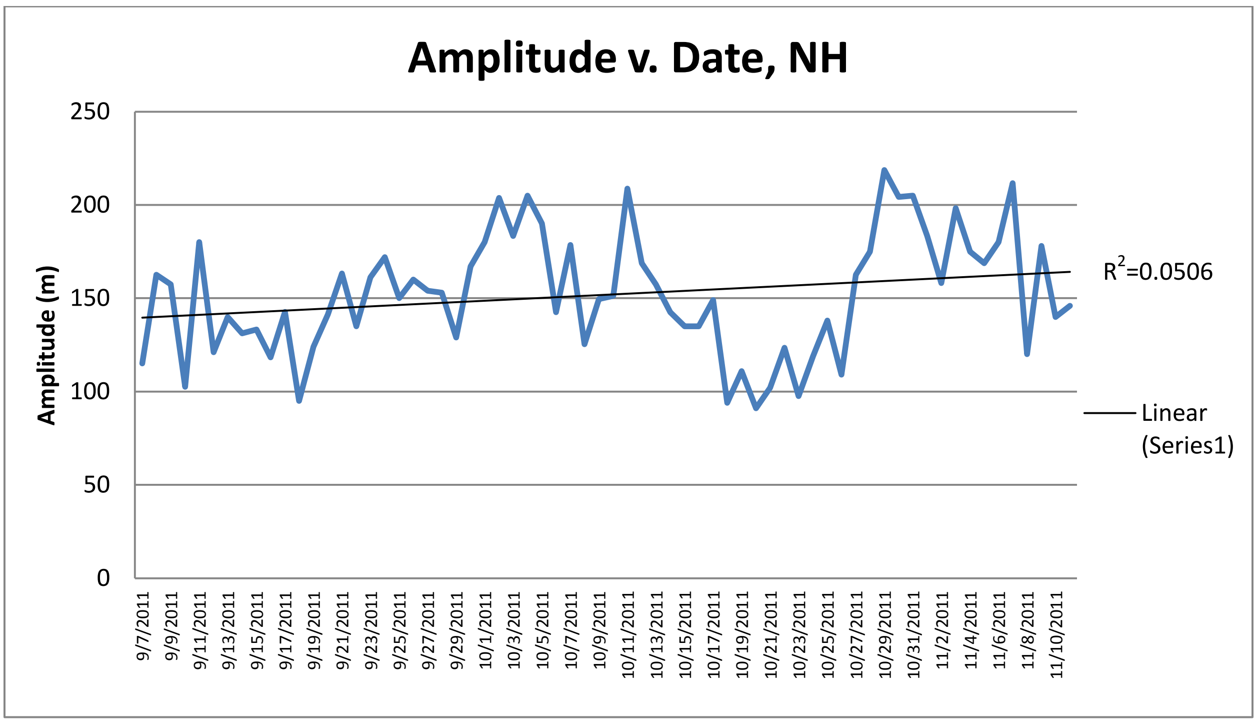


Figure 11: Wave amplitude versus time in the Northern Hemisphere with linear trend lines

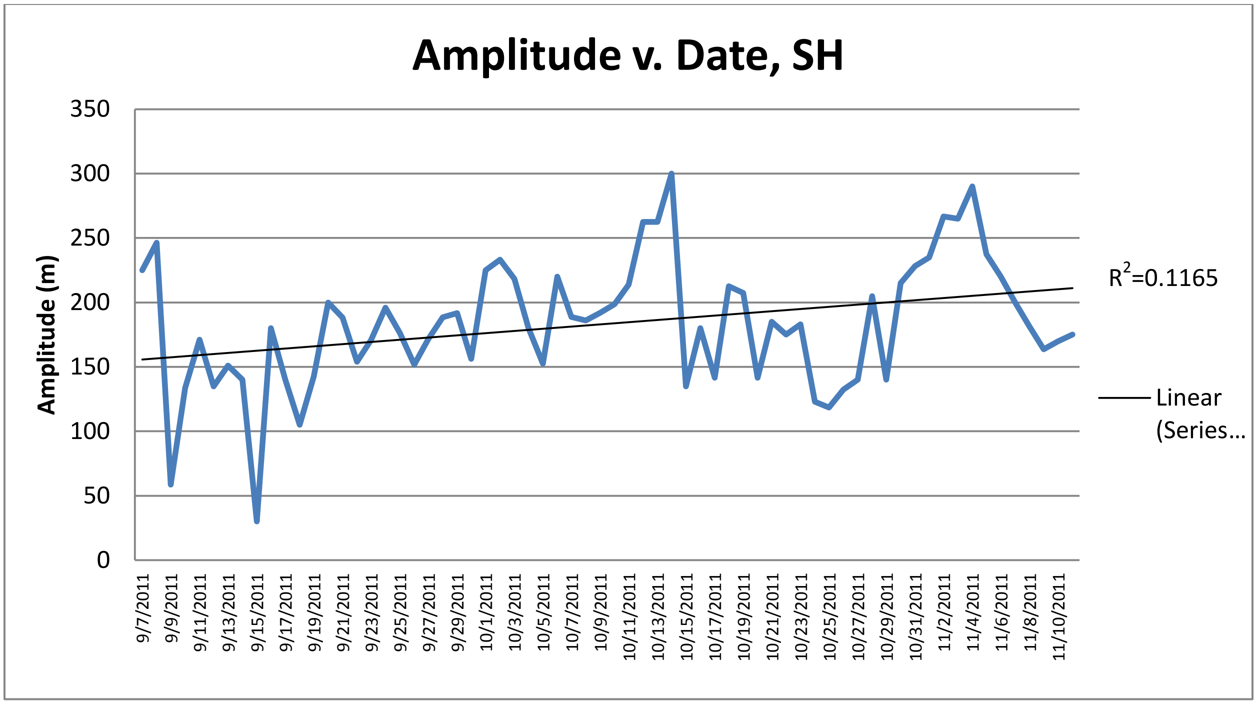
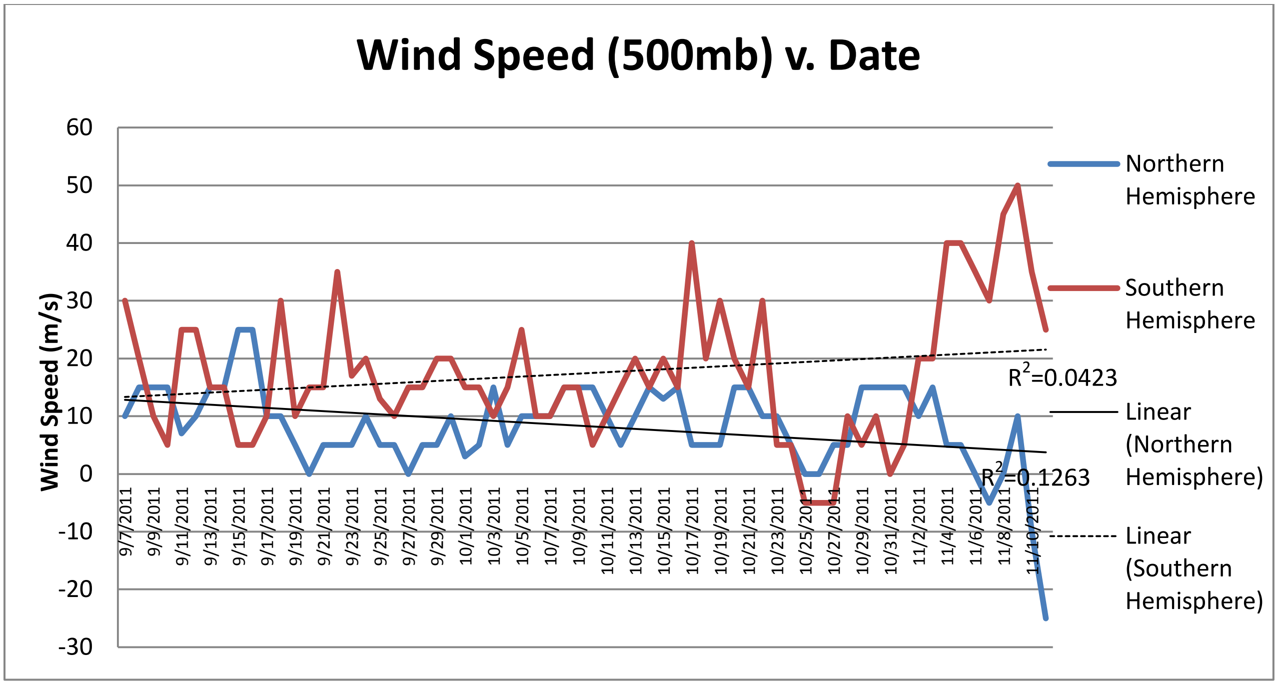
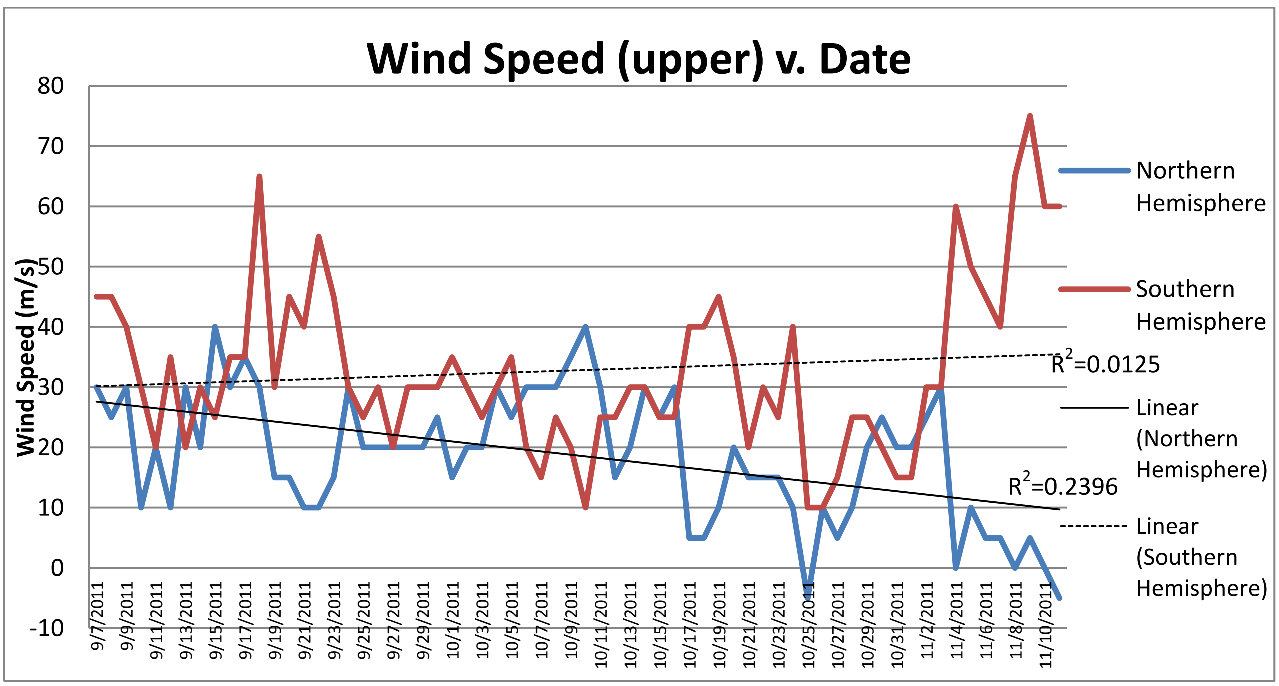


Figure 12: Wave amplitude versus time in the Southern Hemisphere with linear trend lines

e. Zonal wind evolution

Evolution of the zonal wind with time is shown in Figures 13 and 14. Figure 13 shows evolution of the 500hPa wind speed (U500) with time while Figure 14 shows evolution of the upper atmosphere wind speed (Uupper) with time. In the Southern Hemisphere, wind speeds at 500hPa and in the upper atmosphere increased with time. The wind speeds at 500hPa increased more than the speeds at upper levels. In the Northern Hemisphere, wind speeds at both levels of interest decreased, with the upper-level winds decreasing more dramatically than the 500hPa winds. Also, the wind speed in all cases was highly variable. However, in the Northern Hemisphere, a fairly consistent downward trend occurred, while the Southern Hemisphere exhibited fluctuations in upward and downward trends.



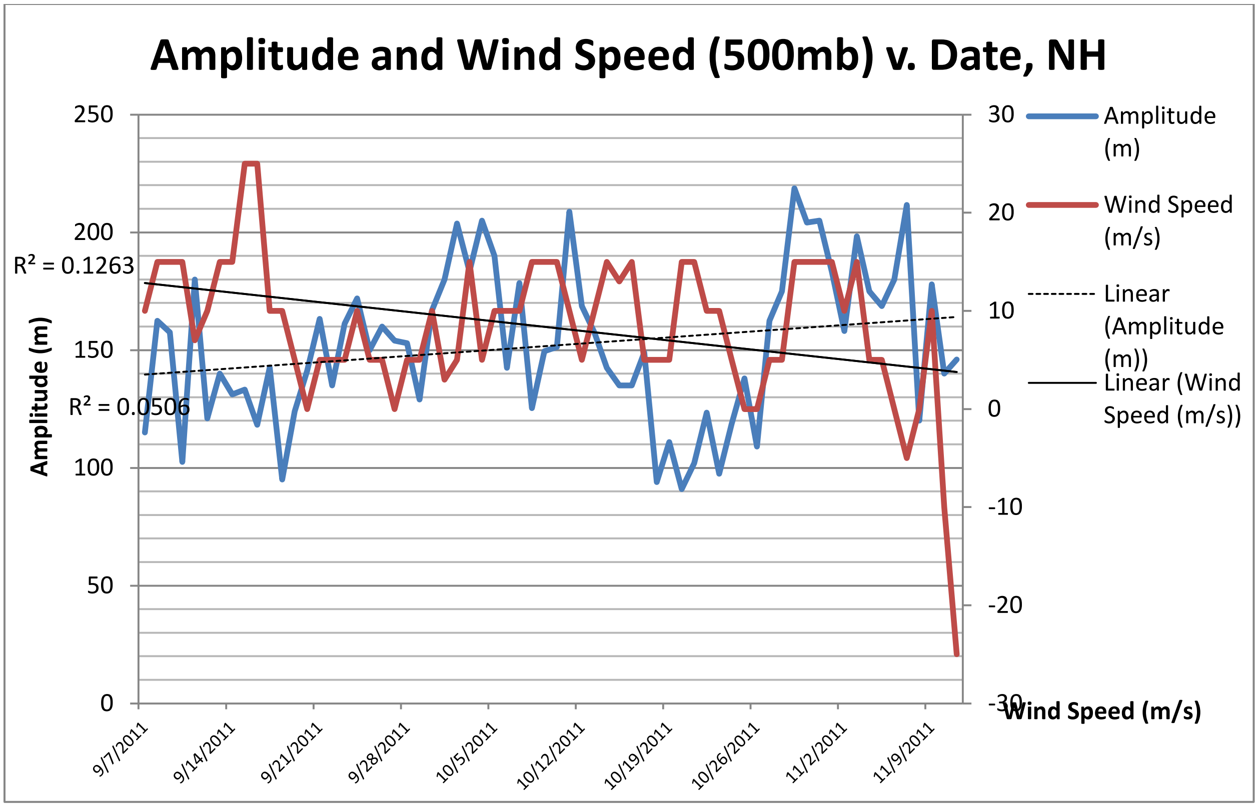


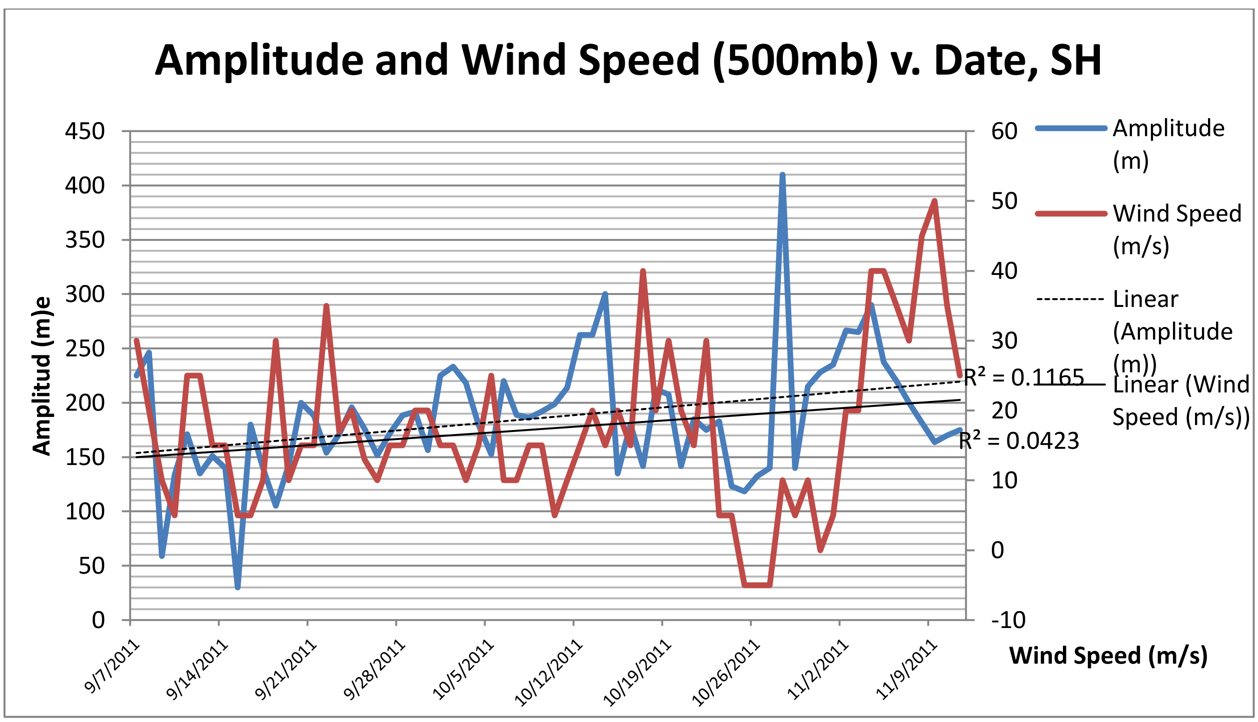
Figures 13 and 14: Wind speed at 500hPa (Figure 13) or in the 300-150hPa (Figure 14) layer, versus time in both hemispheres with linear trend lines

Expected wind speed behavior with time for the Northern Hemisphere is that wind speeds increase with time, due to the change of season from summer to winter and an increase in the temperature gradient between the North Pole and the equator. Expected wind speed behavior in the Southern Hemisphere is the opposite. As the seasons change from winter to summer, the temperature gradient should decrease between the pole and the equator, and wind speeds should decrease. This is the opposite of what is documented in this study.

f. Relationship between zonal wind speed and wave growth and decay with time

The comparison between zonal wind speed and wave amplitude varies between hemispheres. In the Northern Hemisphere, the overall trends oppose each other. Amplitude increases over the time period of this study, while 500hPa wind speed decreases over time. It is also fairly evident in Figure 15 that, in general, wind speed maxima are aligned with amplitude minima. The Southern Hemisphere does not exhibit opposing trends with time. The amplitude and wind speed both increase over the time period. There is not a clear-cut relationship evident in the graph (Figure 16) that wind speed maxima/minima are associated with amplitude maxima/minima.





Figures 15 and 16: Amplitude versus wind speed at 500hPa in the Northern (Figure 15) and Southern (Figure 16) Hemispheres with linear trend lines

5. Discussion

Rossby wave theory describes the evolution of atmospheric long and short waves. The speed of Rossby waves, c_x, is dispersive, which means that c_x is dependent on wave number. This creates a large difference in speed c_x between long waves (small wave number) and short waves (large wave number). According to Rossby wave theory and using Equation 4, without background zonal flow long waves propagate more quickly than short waves against the direction of the zonal flow. When background zonal flow is added to the situation, short waves move faster in the direction of the zonal flow because of their initial, small speed against the zonal flow. Rossby wave theory also states that the longest waves (small wave numbers) typically have smaller amplitudes. Finally, Rossby wave theory implies that energy moves from shorter to longer waves, finally ending up in gravity waves that propagate energy away in either direction.

In general, observations from this study did not agree with Rossby wave theory. The waves in this study exhibited decreasing speed as wave number decreased. In addition, wave number increased as amplitude decreased. Both of these statements do not comply with barotropic Rossby wave theory. Finally, in the Northern Hemisphere the wave speed (C) was actually greater than the zonal wind speed (U500), which means that waves in the Northern Hemisphere were retrograding with time. This is not typically seen in the Northern Hemisphere and may be due to human error in measuring wave speed (C) or simply not a long enough time period in the study.

Disagreement between observations in this study and Rossby wave theory may also be due to the assumptions created when deriving the barotropic Rossby wave theory. Assuming a barotropic environment requires assumptions that pressure is dependent only on density ρ, and that temperature does not vary with location. Due to the existence of fronts in the atmosphere, this is not always an accurate assumption. The conservation of absolute vorticity was also assumed; while this is a helpful assumption, it may not always hold in reality.