

Rossby Wave Theory: An Observational Waves Study

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ABSTRACT

500mb height fields for both hemispheres and global averaged zonal wind speed were analyzed from September 1st to November 11th 2011 for the purpose of verifying Rossby wave theory. From ISU's weather products page, we collected and analyzed the wavenumber, wave speed, amplitude, average 500mb zonal flow and the max upper-level wind speed. We conclude that our observations do not correspond well to Rossby wave theory. With better analyzing methods and longer time scale, we would expect to see a better correlation between Rossby wave theory and what is observed.

Introduction

Rossby waves are synoptic-scale atmospheric mid-latitude wave. They play an important role in the pole-ward transports of energy and moisture. Understanding the propagation of these waves is imperative to forecasting weather over the entire globe. Rossby waves behave like other physical waves and can be modeled by simple equations. The amplitude, wave speed, and wavelength (wavenumber) determine the characteristics of the wave itself. By observing these values, we can make an inference based on wave physics how they are related to each other and how they relate to our everyday weather. In the next section, we will discuss further our methods and the data we obtained. Following that section, we will show our results of our observations with statistical interpretations. Finally, we will provide a conclusion to the statistical evidence in regard to Rossby wave theory.

Data and Methodology

Wave motions are best estimated using 500mb hemispheric plots. We used both the Northern and Southern Hemispheric plots found on Iowa State's Weather products page.¹ This page provides the current 500mb hemispheric plot and a loop of the previous 8 days. Also, this page provides the Global Zonal Wind averaged over the whole Earth. Beginning with September 1st and ending November 11th, we saved the each image (taken at 0 UTC every day) for analysis later. For each day, we recorded the wave number, Amplitude, average wave speed, zonal wind speed at 500mb and at 50° latitude, and the maximum wind speed in the 150-300mb layer also at 50° latitude.

a) Wave number

Finding the wavelength of atmospheric waves is somewhat difficult; instead we used the wavenumber (the number of waves in the circumpolar vortex over either pole.) To find the wavenumber, we defined a specific contour and a specific latitude to focus on. We chose the suggested latitude of 50° latitude for both the Northern and Southern Hemisphere. The contour that we chose varied as the year went on and the circumpolar vortex expanded. For example, we started off with the 5580m height contour, and ended up with the 5400m contour. The number of times the contour crossed the latitude divided by 2 was the wavenumber.

¹ <http://www.meteor.iastate.edu/wx/data>

b) Amplitude

The amplitude of the wave is half the distance from its peak to its trough, as shown in equation one.

$$(1) A = \frac{(Z_{max} - Z_{min})}{2}$$

We only wanted to find the average amplitude of all the waves. So, we found the average height of the ridges (Z_{max}) and subtracted from it the average height of the troughs (Z_{min}).

c) Wave speed

For wave speed, the process to evaluate each individual wave's speed would have been difficult. Here again, we estimated an average of all waves' speeds, or estimated just the most dominate wave's speed. To estimate one wave speed on a particular day, we marked a feature on its longitude the previous day (but still on 50° latitude for both the Northern and Southern Hemisphere) and marked the same feature's longitude on two days later. The wave speed in units of degrees per day was computed by equation two.

$$(2) C = \frac{L(day+1) - L(day-1)}{2} \quad \text{where } L_{(day)} \text{ is the Longitude on the given day.}$$

d) Zonal wind

Using the zonal wind global averages obtained at ISU's weather products page, we analyzed two areas of interest. First we estimated the zonal wind at 500mb. Second we estimated the maximum wind speed in the 150mb to 300mb layer. Fifty degrees latitude, we decided, was

best for estimating the zonal wind. Fifty degrees is close to where the jet stream resides and where the synoptic-scale atmospheric waves tend to be the most pronounced, which is why we choose 500mb for our wave analysis. The 150mb - 300mb layer was chosen because of the jet stream. We wanted to evaluate the influence of the upper-level jet stream.

Results and Analysis

a. How Rapidly do Wave Patterns Move?

Wave patterns were observed to propagate across both hemispheres over a 72 day period. Looking purely at the longitudinal speed of these wave patterns, it was observed that waves propagated an average of 7.42 degrees per day in the Northern Hemisphere with the Southern Hemisphere having a slightly higher propagation speed at 8.21 degrees per day. The maximum propagation in a day was observed to be 15 degrees in the Northern Hemisphere and 21 degrees in the Southern Hemisphere. The minimum propagation in a day was observed to be 5 degrees in the Northern Hemisphere and 3 degrees in the Southern Hemisphere.

b. Is there a Relationship Between Zonal Wind Speed and Wave Propagation?

Direction of wave propagation in each hemisphere was generally west to east, with only smaller scale features, (e.g. cutoff lows) occasionally propagating in the opposite direction of this flow. Using previously stated averages for propagation speed, it was calculated that in 48.52 days a wave would travel around the globe in a circular pattern from 50° latitude in the Northern Hemisphere and would travel slightly faster in the Southern Hemisphere, circumvent the globe in 43.85 days. The authors of this study converted both upper-level wind speed fields from the units of meters per second into units of degrees per day in order to have the wave speed and these upper-level wind fields in the same unit. Having both these data sets in the same unit allowed us to better analyze the relationship between zonal winds and wave propagation. According to Rossby wave theory and accompanied equation below (Holton, 2004) we expect that higher mean flow will result in a higher wave speed.

$$(3) \quad c - \bar{u} = -\beta/K^2$$

Neglecting the Coriolis force change over latitude (β) and the total horizontal wave number squared (K^2) it is easily seen that increasing \bar{u} , or the mean zonal wind, will lead to an increase in the wave speed (c). Using the observed 500mb zonal winds as a proxy for the mean wind, we tested this relationship in Figures 1 and 2.

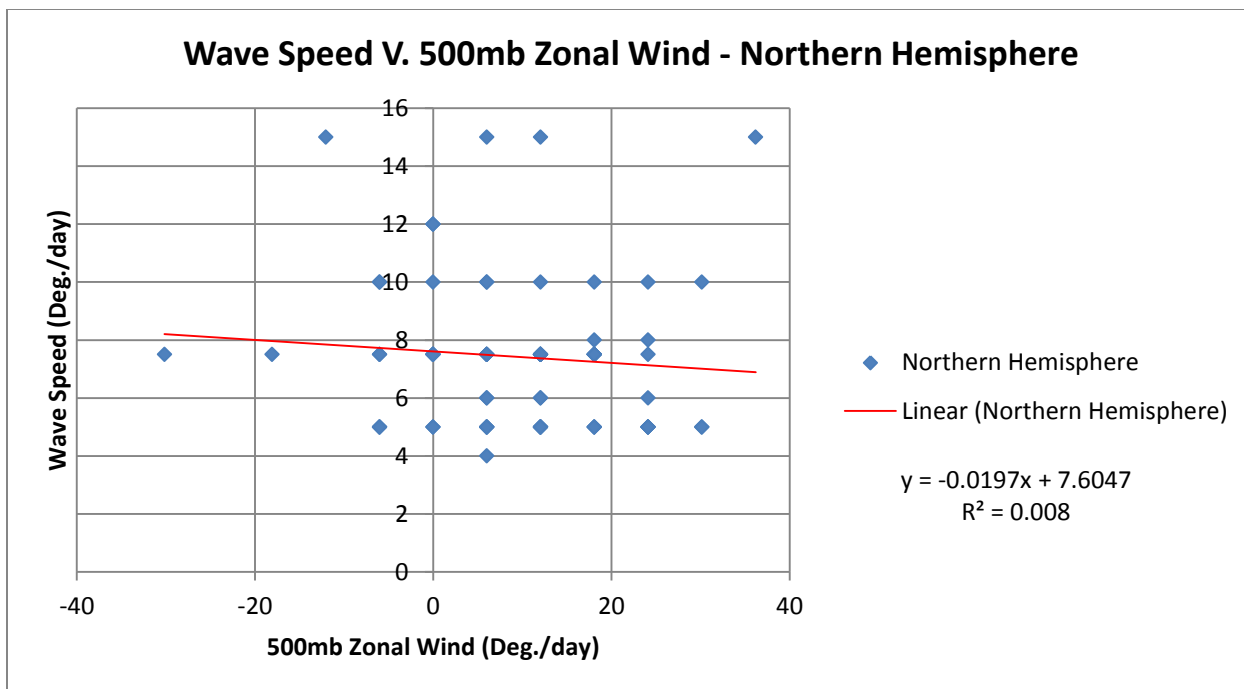


Figure 1

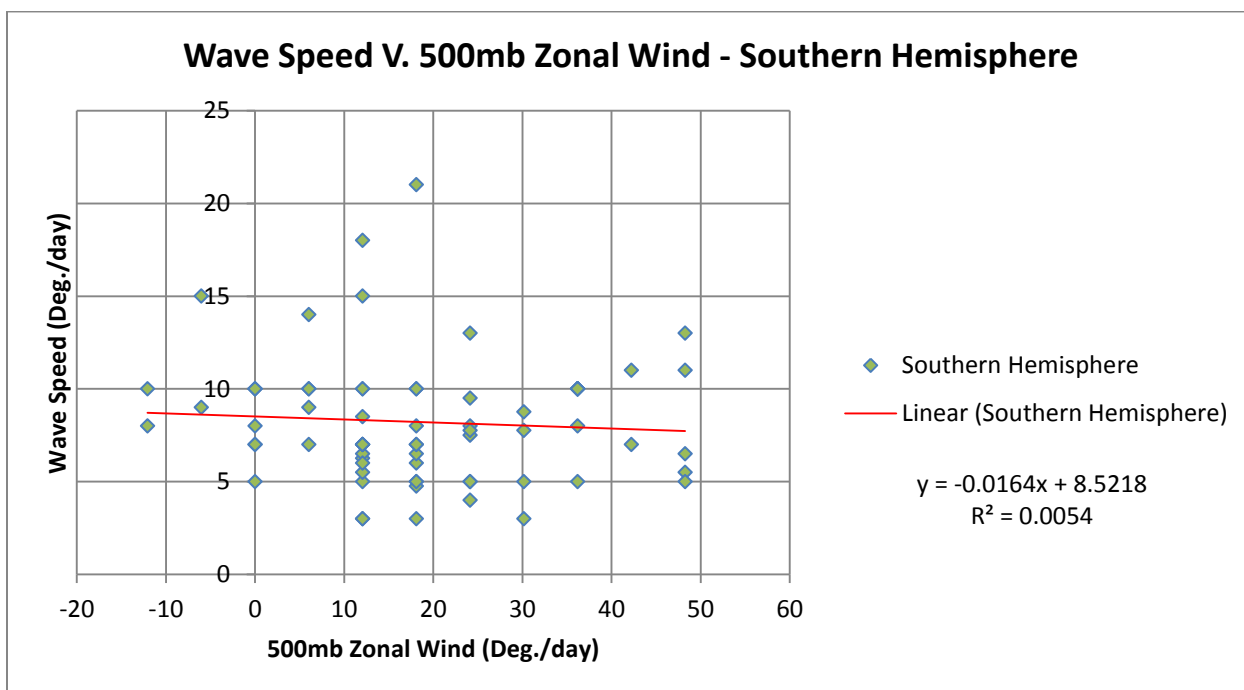


Figure 2

Both figures 1 and 2 disagreed with Rossby wave theory as their linear regressions both showed a weakly negative slope in the observed relationship between wave speed and mean zonal wind. Limitations in the data set for correctly analyzing the propagation of a wave feature may account for the extremely low R^2 values computed for this test.

Wind speed maximum observations were also taken higher aloft, above 50° latitude in the 150–300mb layer to determine if these jet maximums had any influence on the wave speed in either hemisphere. Figure 3 below shows the Northern Hemisphere wave speed relation to these jet maximums.

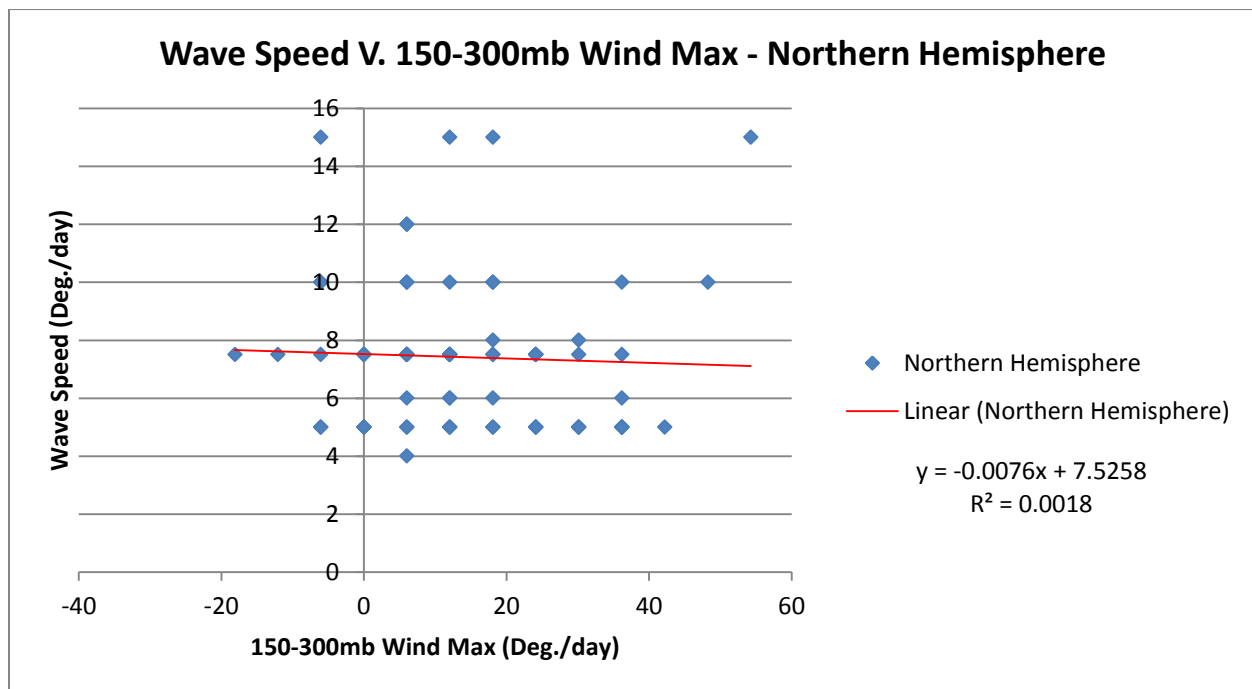


Figure 3

The Northern Hemisphere showed a slight negative relationship to wave speed and increasing 150–300mb wind maximums. However, it is to be noted that this very slight negative slope had a very small R^2 value of 0.0018, and thus, this relationship has a very small linear fit to this data

set. Figure 4, showing this relationship in the Southern Hemisphere, showed quite similar results. Here we also see a slightly negative relationship between increasing jet maximums and wave speeds along with a poor R^2 value of 0.0088. The authors of this study speculate that this low correlation may be due the effects of jets streaks on either side of a trough. While jet streaks ahead of a given wave pattern may work to propagate the wave forward, perhaps when these jet streaks are behind the wave they work to deepen a wave and possibly slow the forward momentum of the feature.

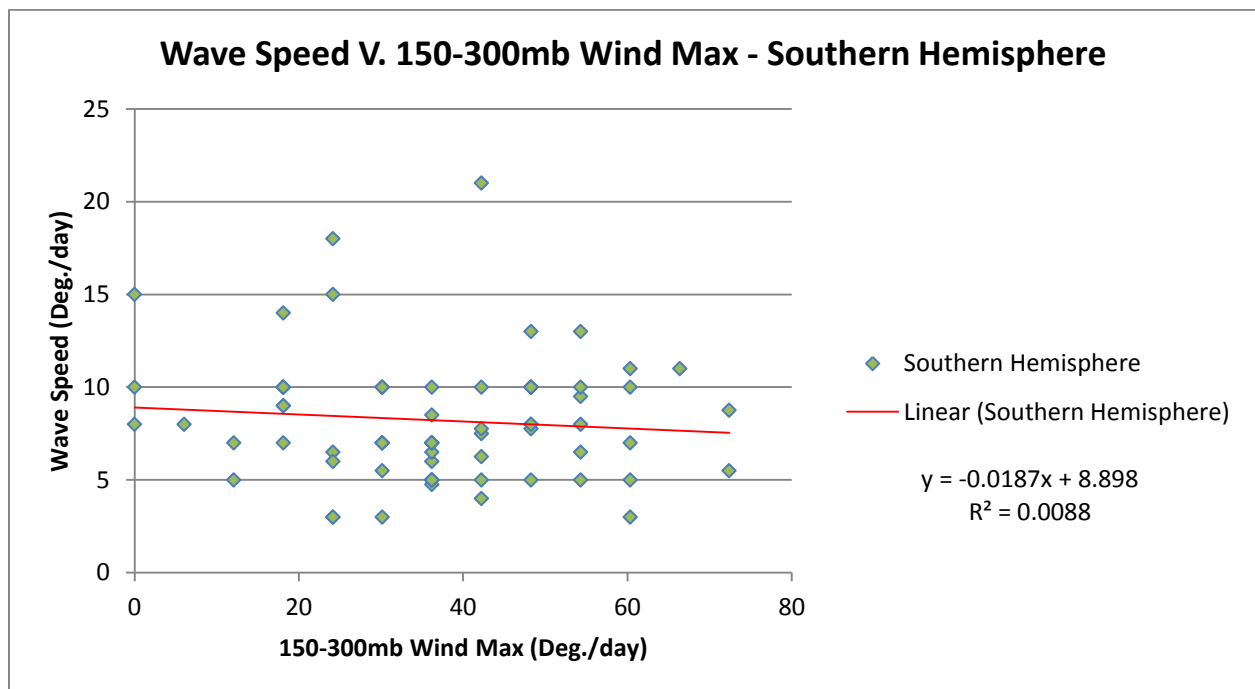


Figure 4

Again, considering the equation, $c - \bar{u} = -\beta/K^2$ we sought to determine if our observations follow general Rossby wave theory: increasing wave number will correspond to lower wave speed values. It is to be noted that using the above equation as a guide, we subtracted

the mean wind from the wave speed to remove the dependence of wave speed on zonal wind.

This aspect of Rossby wave theory was proven to match with our observations in the Southern Hemisphere, however, failed in the Northern Hemisphere. Alas, the R^2 values computed for the Northern Hemisphere (0.0394) and the Southern Hemisphere (0.0137) were quite low. While the correct relationship is shown in Figure 6, the low correlation, and furthermore the disagreement shown in Figure 5, cannot allow us to sufficiently prove or disprove Rossby wave theory with regard to our observations.

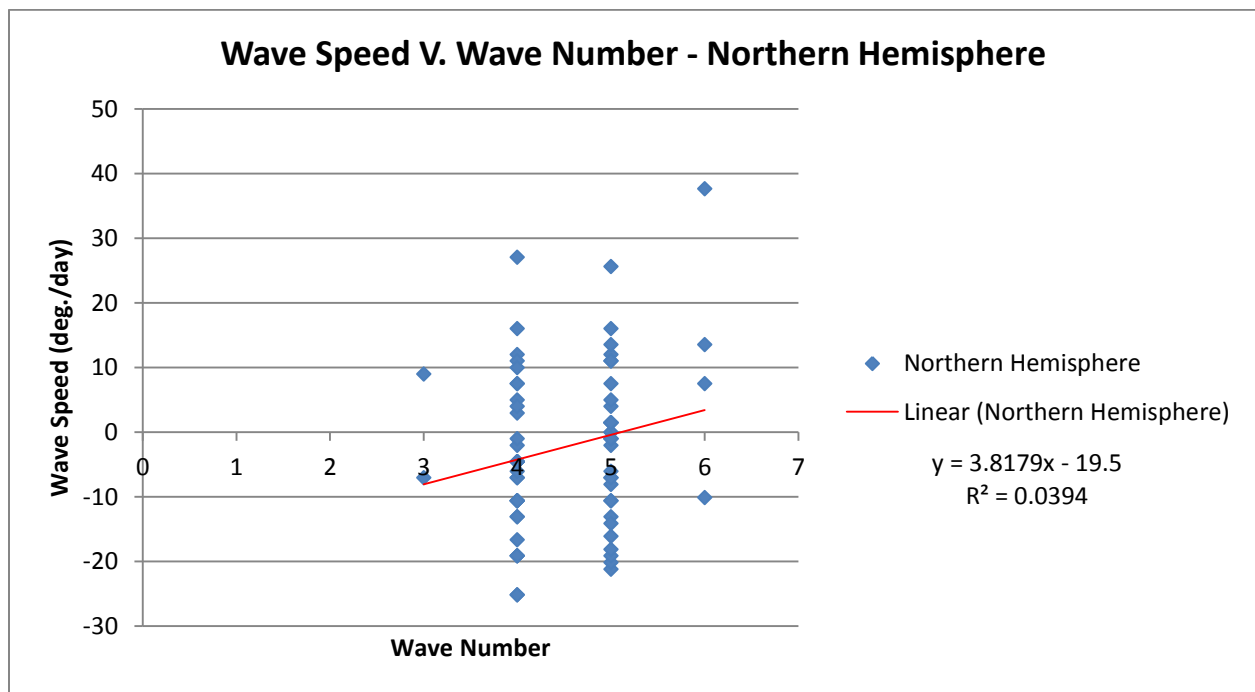


Figure 5

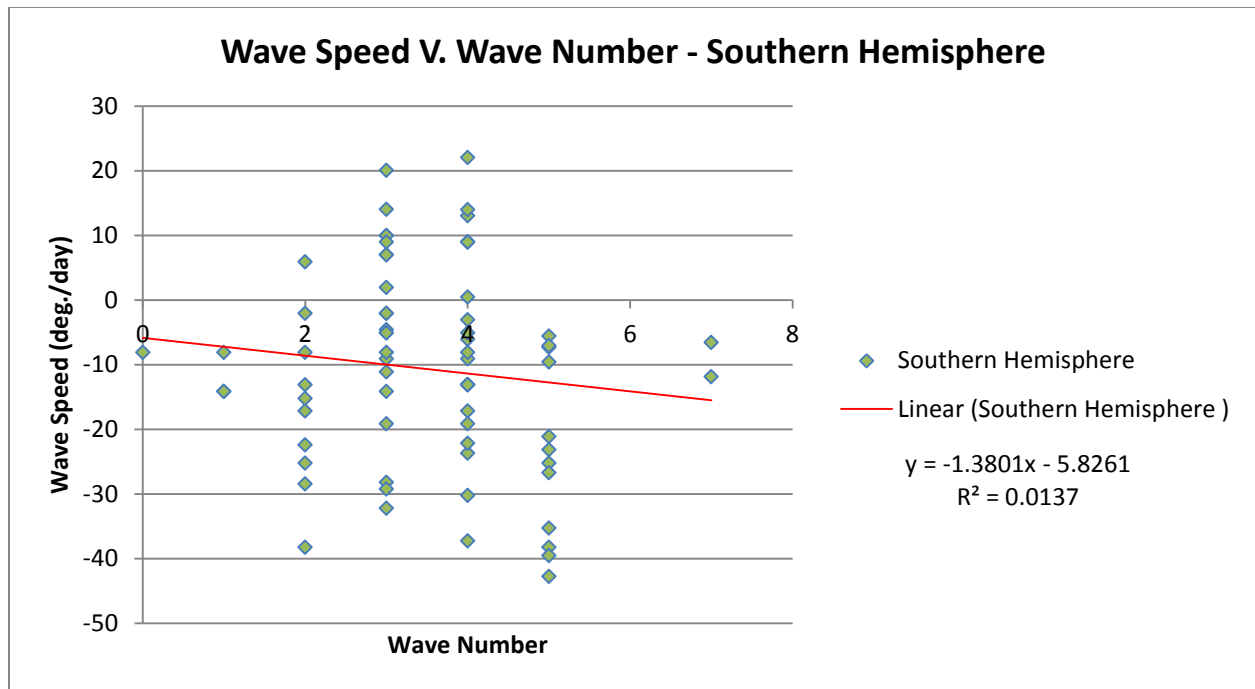


Figure 6

c) *How long does one identifiable pattern last?*

Looking at the wavenumber versus time, we can see how patterns change over time. There is a claim that a higher wavenumber leads to more progressive and active surface weather systems. This suggests that wavenumbers slowly change over time. If this were not the case, forecasting based on wavenumber alone would be too difficult. Our observations seem to confirm this. The wavenumber does not change significantly over time. With the exception of two days out of the entire semester, the wave number never changed more than 3 per day; only a few more days had changes of 2 per day. Also, longer (on the order of a week or two) patterns seem to develop.

The Northern Hemisphere showed less variability in wavenumber than the Southern Hemisphere. The Northern Hemisphere never changed more than two wavenumbers in a day. The Southern Hemisphere had two days where the wavenumber dropped by 3. The Southern Hemisphere also had the most variability between its maximum and minimum wavenumber, from 7 at its peak to 0 at its minimum. The Northern Hemisphere only varied from wavenumber 3 to wavenumber 6.

Both hemispheres can be broken up into multi-week sections with a clear trend. The Northern Hemisphere had a slight upward trend in wavenumber over the semester. It can be broken into two modes. From the beginning of September to October 7th, the Northern Hemisphere oscillated between wavenumber 3 and wavenumber 5. From October 8th to November 11th, it oscillated between wavenumber 4 and wavenumber 6.

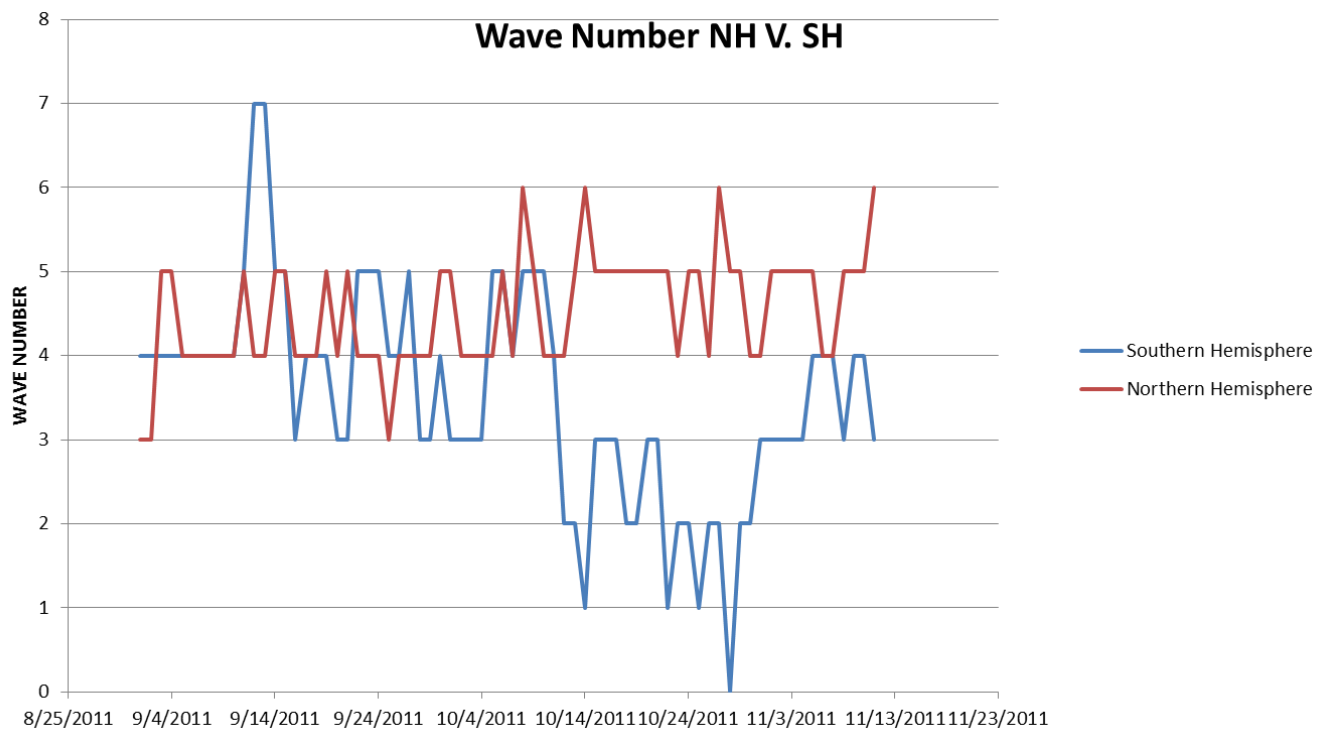


Figure 7

The Southern Hemisphere showed a slight downward trend in wavenumber over the semester. There are three main sections that the Southern Hemisphere can be broken into. The first is from September 1st to October 10th. During this period, the wavenumber oscillates between three and five, with a two day exception where the wave number jumped up to seven. The second is from October 11th to November 3rd, where the wavenumber oscillates from 1 to 3, with one day being a wavenumber 0. The difference between these two periods in the Southern Hemisphere is the largest change out of all of our observations. The third period, from November 3rd to November 11th, is the shortest range of dates, but still is significantly different from the second period. During this period, the wavenumber oscillated between three and four.

The amplitude of the wave shows a non-significant correlation with wavenumber. For both the Northern and Southern Hemisphere, the linear regression line shows a correlation between lower wavenumbers and higher amplitudes (higher wavenumbers and lower amplitudes). Figures 8 and 9 show that the R squared value is very near zero. Our theory matches this observation. If you fix the atmosphere at a “steady state” (here I mean that say the area enclosed by a particular height contour over a pole stays constant, which observation show that it is a good assumption for time scales less than a week), then the more waves a particular contour has, the less Amplitude those waves must have to keep the area enclosed constant. Equation 4 (the equation of a wave) shows that the position variable x is proportional to the Amplitude.

$$(4) X = A \sin(t - k) + \text{constant}$$

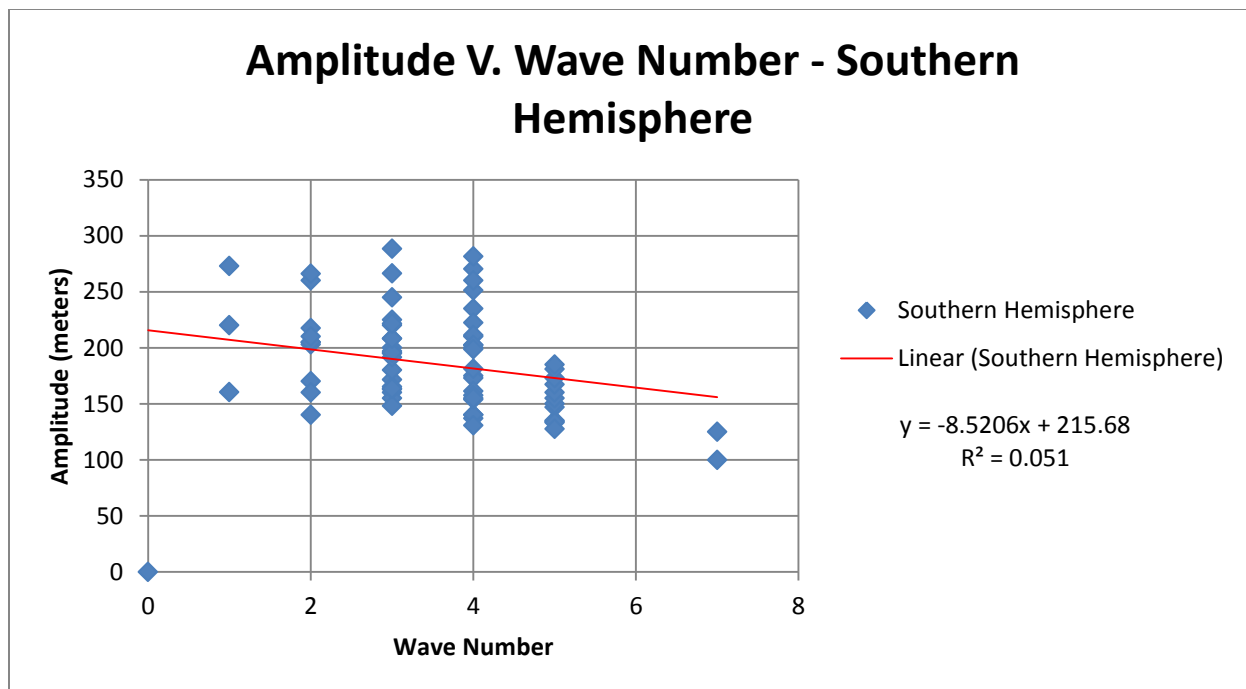


Figure 8

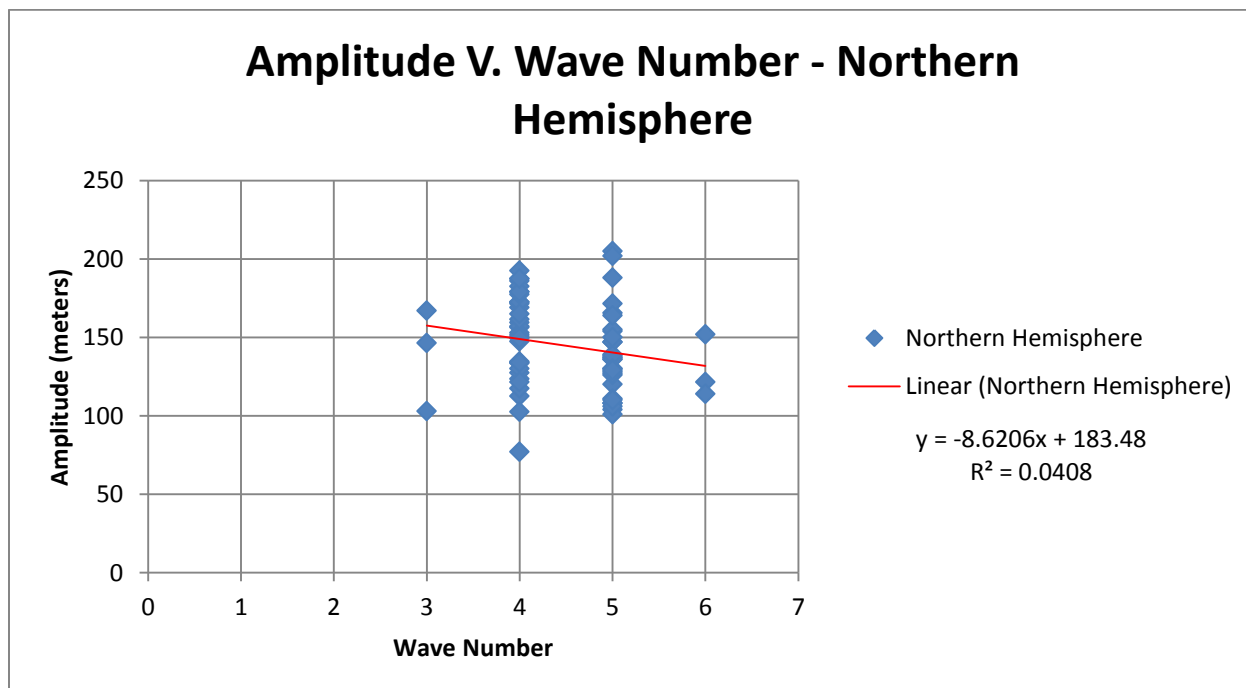


Figure 9

d) *How rapidly do waves increase or decrease in amplitude?*

Waves increase and decrease in amplitude partially based on what is happening throughout the column of air. Quasi-Geostrophic theory tells us that where there is cold air advection in a layer, the thickness of that layer must decrease. Likewise where there is warm air advection in the layer, the thickness of that layer must increase. These two processes work to increase a wave's Amplitude (where there is a surface cyclone). Therefore, the time it takes for a wave to increase in amplitude has significant implications on how surface cyclones develop and intensify.

From observations, waves can change amplitude very significantly in a short time period. Over the course of two days, a wave's amplitude can change up to 60% and even up to 30% in one day. The Southern Hemisphere seems to have more variability than the Northern Hemisphere. The amplitude in the Southern Hemisphere varied from 0 to 275 meters, whereas the Northern Hemisphere varied from 75 to 200 meters. Also, the amplitude was in a constant change. The amplitude rarely changed less than 10% per day and less than 30% every two days. However, there do not seem to be any clear "periods" to break the pattern into, like we did for the wavenumber over time.

e) *How does zonal wind evolve through the period?*

The global zonal winds were averaged over all longitudes in both hemispheres at 500mb and at 50° latitude. The global average wind speed varied more significantly in the Southern Hemisphere than in the Northern. The Southern Hemisphere zonal winds varied from -10 m/s to

40 m/s , whereas the Northern Hemisphere varied from -10 m/s to 30 m/s . Neither the Northern of Southern Hemisphere showed any trend to increasing or decreasing wind speed. On average, the zonal wind speed in the Southern Hemisphere was almost twice that of the Northern Hemisphere, the former being 9.0 m/s and latter 16.0 m/s . The Northern Hemisphere also had more days with a negative zonal wind speed (meaning an average Easterly flow at 500mb). Theory agrees with this observation. The Southern Hemisphere has more open ocean than the Northern Hemisphere. In fact, most of the area near 50 °S is ocean; but near 50°N, it is almost all land. This means there is less friction in near the Southern Hemisphere and therefore a higher wind speed can be reached there.

The maximum upper-level wind speed is defined simply as the maximum wind reading in the 150mb-300mb layer at 50° latitude in both hemispheres. The max wind correlates extremely well with the average zonal winds. In fact, the max wind speed seems to be just a multiple of the zonal wind speed average. As such, it exhibits the same characteristics as zonal wind speed. It varies between 0 m/s and 60 m/s in the Southern Hemisphere and -5 m/s and 45 m/s in the Northern Hemisphere. The average max Northern wind speed is 13 m/s , whereas the Southern is 31 m/s .

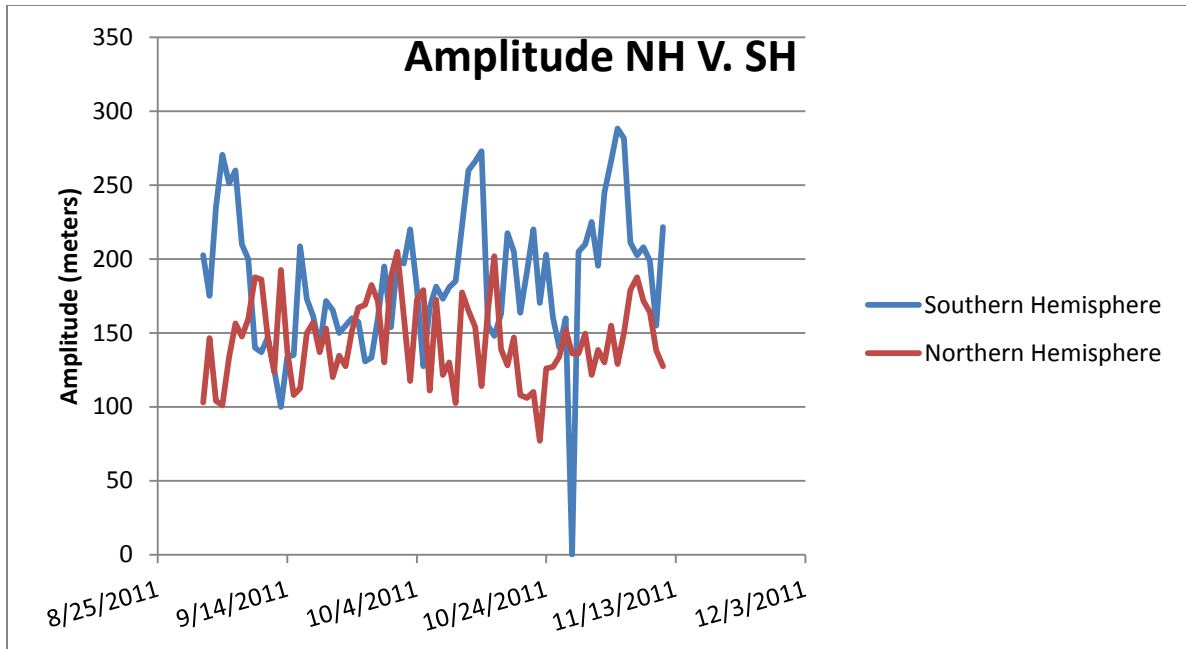


Figure 10

f. Is there a Relationship Between Zonal Wind Speed and Wave Growth/Decay?

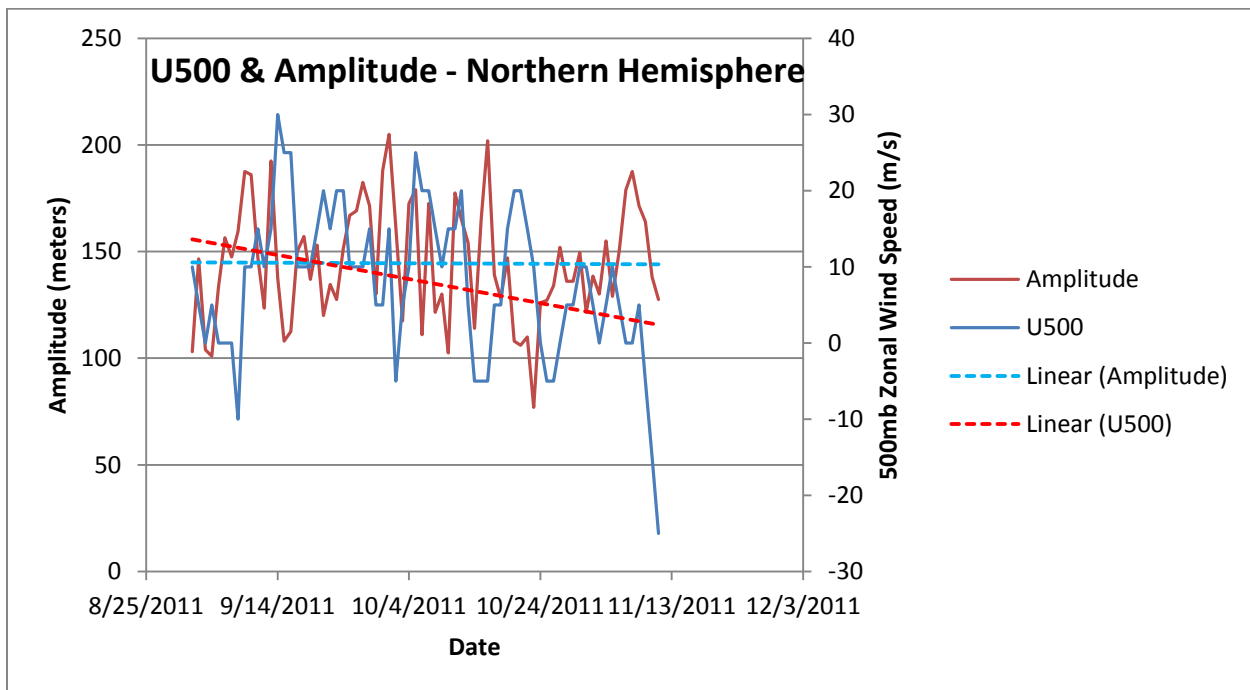


Figure 11

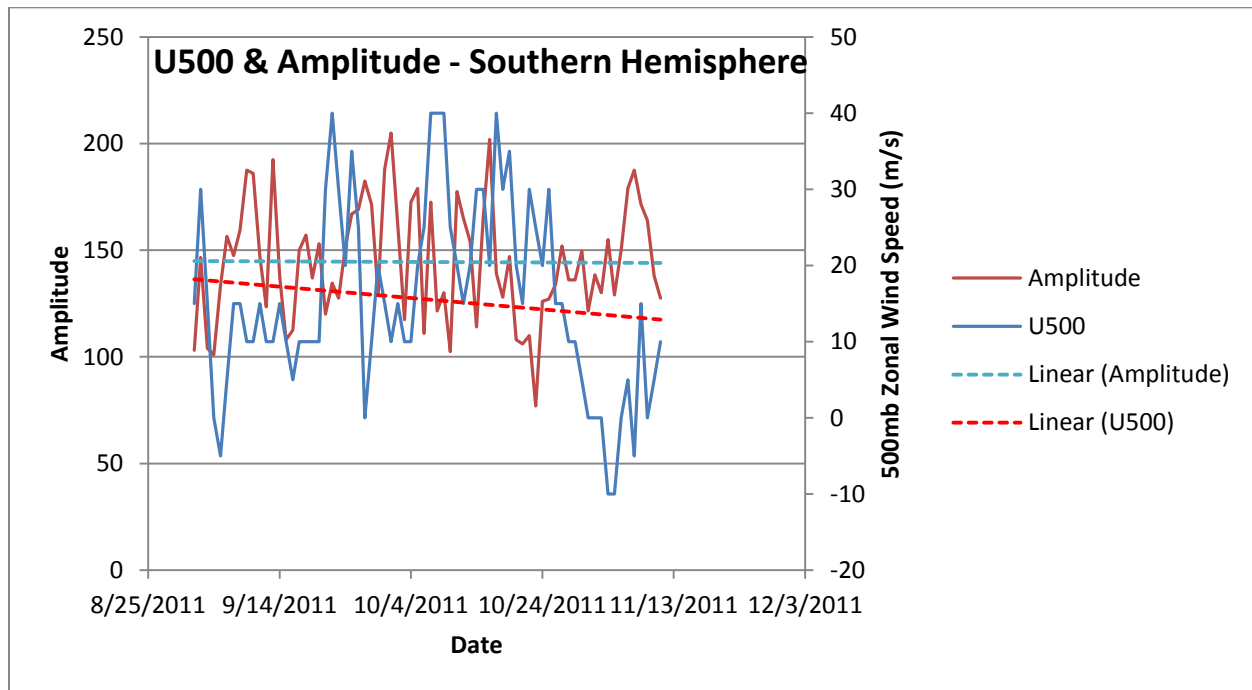


Figure 12

While no drastic relationship between 500mb zonal winds and amplitude can be drawn for either hemisphere, it is sometimes apparent that increases in amplitude correspond to decreases in the 500mb flow and vice versa. In fact, looking at the linear regressions in Figures 11 and 12, we see that over time the trend is for lower 500mb winds in both hemispheres and a slight trend for increasing amplitudes. This increase in amplitude is expected as the Northern Hemisphere heads to a more winter-like pattern with stronger troughs and alike in the Southern Hemisphere as this half of the world nears their summer. The authors of this study speculate that zonal flow patterns (low amplitudes) allow for faster winds as these flow patterns are not influenced by accelerations associated with curved, meridional flow (high amplitudes) that act to slow down the overall flow regime.

Conclusion

While there were instances of our observations agreeing with Rossby wave theory, most statistical analysis showed a weak regression fit (low R squared values). We cannot prove nor disprove Rossby wave theory through this study; however, we can still conclude that atmospheric waves can be shown to behave in a predictable manner, allowing for a reasonable forecasting of these waves for days in advance. 72 days of data analysis may not have been a long enough period to correctly infer Rossby wave theory from the results. Also, the methodology could perhaps be improved to get a more accurate representation of both the upper-level height field and zonal wind approximations. Overall, the authors conclude that the many assumptions in this study led to the poor correlation between our observations and what is expected in regard to Rossby wave theory.