Analysis of 500 hPa Height Fields and Zonal Wind in Fall 2009: Is Rossby Wave Theory Observationally Verifiable?

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ABSTRACT

Analysis of data recorded from the 500 hPa height fields and the global average zonal wind charts from August 24, 2009 to November 6, 2009 was used to attempt to prove whether there is a relationship between observable meteorological data and Rossby wave theory. The data were recorded based on a specific prescribed method with the goal of achieving accurate and reproducible results. Based on the analysis there appears to be little discernable relationship between our data and Rossby wave theory. This conclusion was not expected as the behavior of Rossby waves in the atmosphere would be expected to follow closely with the theoretical behavior of Rossby waves. What this study proves is that the behavior of large-scale Rossby waves in the atmosphere would need to be studied in much greater detail in order to be related to Rossby wave theory.

1. Introduction

An accurate understanding of the behavior of large-scale synoptic waves in the atmosphere is necessary to the study of meteorology. Much of our synoptic scale weather is determined by the propagation of large-scale synoptic waves. A greater understanding of the behavior of these waves will provide us with not only an improved ability to forecast weather, but a better knowledge of how energy behaves in our atmosphere. In this paper, we attempt to prove whether the behavior of large-scale synoptic waves can be related to Rossby wave theory using a specific and prescribed pattern of observation that can be easily reproduced. Over a span of 75 days we recorded and analyzed the data archived from 500 hPa charts for the Northern and Southern Hemispheres and global zonal wind averages at two levels for the Northern and Southern Hemispheres. After all data had been recorded we analyzed the data to determine whether any relationship exists between observable data and Rossby wave theory.

2. Data and Methodology

The data for this project were provided from the Iowa State University Weather Products website (http://www.meteor.iastate.edu/wx/data/). This website archived the previous eight days of products, from the current day, into three products which included 500 hPa charts for the Northern Hemisphere, 500 hPa charts for the Southern Hemisphere, and the global zonal wind average chart. The 500 hPa charts for the Northern Hemisphere and Southern Hemisphere were projected onto a map centered at the North and South Poles, respectively, with lines of latitude every 10 degrees from the pole and lines of longitude every 10 degrees from the Prime Meridian. Data from each of these charts were recorded for each day over a span of 75 days from August 24, 2009 to November 6, 2009. All three products were based off the 0000 UTC observations.

The data collected daily from the 500 hPa charts for both the Northern Hemisphere and Southern Hemisphere included the integral wave number (N), the average amplitude (A) of all waves included in the integral wave number count, and the speed of the waves (C). The data collected daily from the global zonal average wind chart included the global zonal average wind at the 50 degree latitude line for both the Northern and Southern Hemispheres (U500) and the maximum global zonal average wind for both the Northern and Southern Hemispheres in the 150-300 hPa layer (Uupper). The data were recorded and saved into a Google Docs spreadsheet that was accessible to all three investigators at all times.

In order to arrive at the most accurate and reproducible results, some specific rules were prescribed for the collection of data. First, the integer wave number, N, was recorded using the 500 hPa charts by identifying a target contour for each hemisphere and then counting how many times the target contour crossed equatorward of the target line of latitude and dividing that number by two. In the case of this study, the target line of latitude was 50 degrees north in the

Northern Hemisphere and 50 degrees south in the Southern Hemisphere. The target contour was 5580 m in the Northern Hemisphere and 5280 m in the Southern Hemisphere. This portion of data collection included one additional rule which was not to count times when the target contour lies on 50 degrees, but does not cross. This would ensure that the number of crossings was an even number and that N was an integer.

(1) $$N = (\#\ of\ Crossings)/2\ .$$

Second, the average amplitude was calculated for all waves included in the integer wave number count that was calculated for each day. For each wave included in the integer wave number count, there is a 500 hPa height maxima and minima. This means that for each day of data there should be N local height maxima and N local height minima. The 500 hPa height charts for each hemisphere were analyzed daily in order to get the local height maxima and minima for each wave. These maxima and minima were obtained by finding the two highest height contours through which the 50 degree line of latitude passed, and interpolating the value between those two height contours. Using these numbers, the sum of all maximums was calculated and the sum of all minimums was calculated.

(2) $$AveMaxima = Average\ of\ N\ local\ height\ maxima;$$

(3) $$AveMinima = Average\ of\ N\ local\ height\ minima.$$

Using these two averages, the average amplitude was calculated daily for both hemispheres.

(4) $$A = (AvgMaxima - AvgMinima)/2.$$

Third, the wave speed was calculated for a wave included in the daily integer waver number count. The wave speed was calculated using the difference in the wave location for one day before the target day and one day after the target day and dividing that number by two. The difference in wave location was calculated by choosing a location where the target contour crossed the target line of latitude and recording that longitude. This calculation results in the average wave speed during the two day period before and after the target date. The average wave speed was then calculated each day in units of degrees longitude per day according to the following equation.

$$C = \frac{\{Longitude\ (Day+1) - Longitude\ (Day-1)\}}{2}. \quad (5)$$

Finally, the global average zonal wind speed charts were used to find the average zonal wind speed at the 500 hPa level (U500) at 50 degrees north and south for the Northern Hemisphere and Southern Hemisphere, respectively, and to find the maximum average zonal wind speed in the 150-300 hPa layer (Uupper) at the same target line of latitude, 50 degrees north and south. These data were recorded for 50 degrees latitude in order to more strongly correlate the wave propagation, as measured at 50 degrees latitude, and the global average zonal wind at 50 degrees latitude. The 500 hPa level was used also because of the analysis of 500 hPa height charts for each hemisphere. The 150-300 hPa layer was used because of the important effects of the upper-level jetstream in the propagation of large-scale flow.

3. Analysis and Results

a. How Rapidly do Wave Patterns Move?

In order to find a relationship between wave speed and upper level wind speed we looked at averages, maximum values, and minimum values of measured wave speed in degrees per day (deg./day), wind speed at 500 hPa in meters per second (m/s), and maximum wind speed in the 150-300 hPa layer in meters per second (m/s). In the Northern Hemisphere we found that waves propagated at an average speed of 11.0 deg./day. The maximum value a wave propagated was 25 degrees per day while the minimum value was 4.5 degrees per day. The Southern Hemisphere waves tended to move more rapidly at an average value of 17.3 deg./day. The maximum value was 32.5 deg./day and the minimum value was 7.0 deg./day. The standard deviation for the northern hemisphere was 4.48 while the Southern Hemisphere was 5.80. This indicates that the Southern Hemisphere waves move both faster and tend to vary more in terms of speed than that of the northern hemisphere waves.

b. Global Average Zonal Wind Speed vs. Wave Propagation

From the analysis in the previous section we see that waves in both the Northern Hemisphere and Southern Hemisphere propagate mainly from west to east. In extreme cases cutoff lows did move from east to west but were not analyzed because wave speed was determined based on an average propagation of all waves across the flow. Based off the averages above it would take 32.7 days for a synoptic wave in the Northern Hemisphere to transverse the 50 degree latitude circle, while it would take 20.8 days in the Southern Hemisphere. We found that the difference in the average wave motion between each hemisphere was 6.34 degrees per day with the Southern Hemisphere being the faster of the two. This is a significant increase in wave speed which we can contribute that to an overall faster wind speed in the upper atmosphere in the Southern Hemisphere compared to that of the Northern Hemisphere. In order to compare wave speed to upper level winds we converted our upper level wind speeds from meters per second (m/s) to degrees per day (deg./day) which is the same unit as measured for wave speed. At 500 hPa the average wind speed in the Northern Hemisphere was 11.68 degrees per day while the Southern Hemisphere was 32.74 degrees per day. Rossby theory says that the faster the general flow, the faster the wave will propagate. This is described by the following equation.

(6) $$c = \bar{u} - \beta/(k^2 + l^2).$$

Where c is the wave speed, $\bar{u}$ is the speed of the general flow, β is the change in the Coriolis Force over latitude, and k and l are simply horizontal wave numbers. If we simplify this equation by making it the following we get a simple equation for wave speed.

(7) $$c = \bar{u} - a.$$

Where $a = \beta/(k^2 + l^2)$. We know that a will always be positive and will be less than ū which means that wave speed must increase with increasing general flow. We will assume that the general flow is approximately at 500 hPa and we find that our observations did not exactly match up with this element of Rossby wave theory. The Northern Hemisphere values tended to decrease with increasing 500 hPa wind speed as shown by Figure 1.

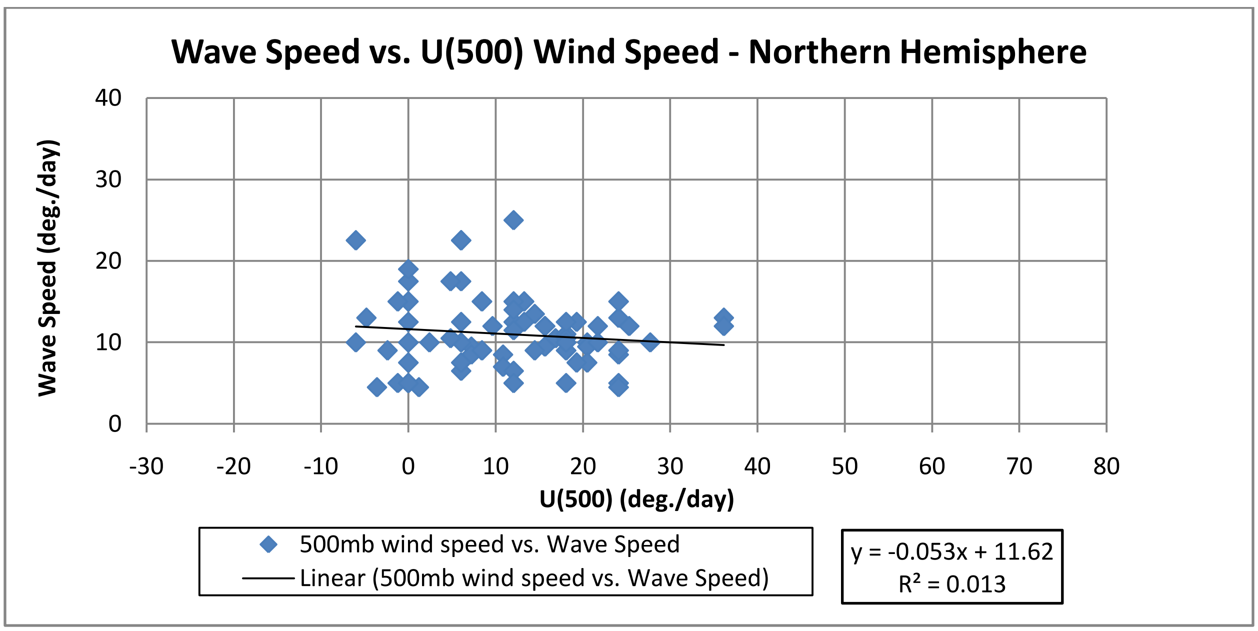

Figure 1

This does not match Rossby wave theory as with increasing winds the wave speed did indeed decrease. During the observation period many cutoff lows did form which may have made collecting average wave speed difficult. The Southern Hemisphere was much more uniform making it easier to get better observations as seen by Figure 2.

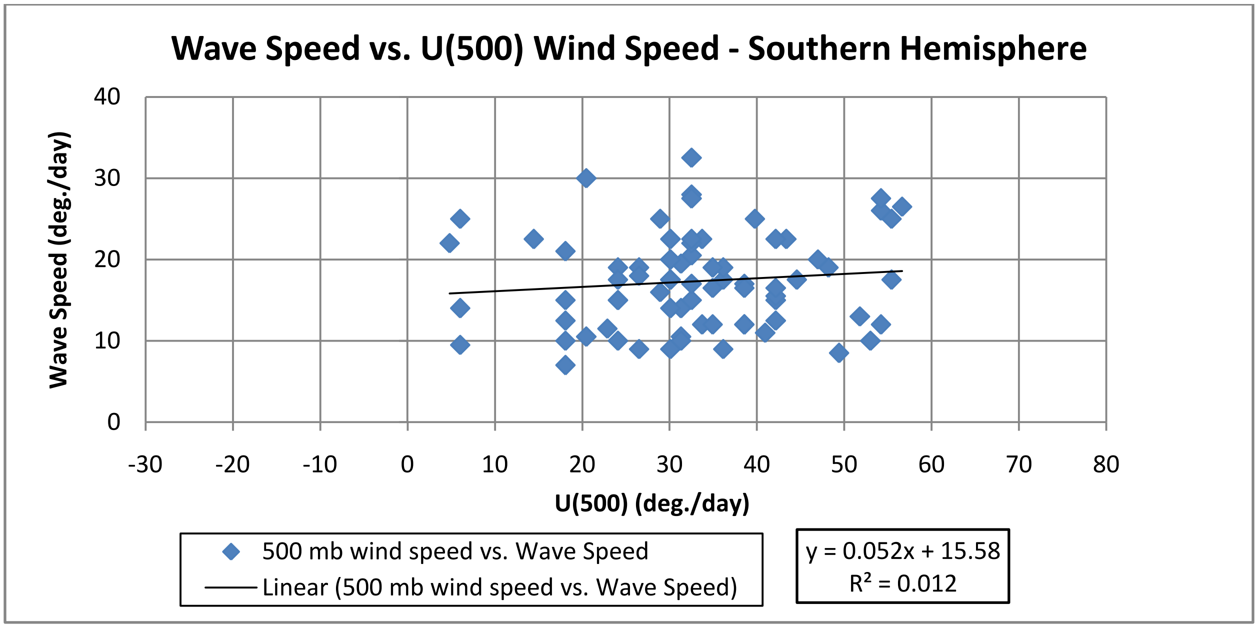

Figure 2

The observations of 500 mb wind speed versus wave speed did agree with Rossby theory with increasing speed of the general flow came increasing wave speed. This increase was not significant as one would have expected with the linear regression slope only being 0.0525 and an R^2 value of only 0.012, but it was positive which is what the basic theory states.

We did take observations of the upper level wind speeds to see if the general flow could be found at a lower pressure level. We took maximum wind speeds between the 150 and 300 hPa layers at 50 degrees north and south. Both hemispheres did not show any clear relationship between the maximum wind speeds in the layer and the wave speed across the latitude circle. Figure 3 shows the scatter plot of wave speed verses that maximum wind speed in the 150 and 300 hPa layer in the Northern Hemisphere. Much like Figure 1 we find a negative regression line indicating that as upper level winds increase in speed the wave speed would slow down which is opposite to theory. Looking at the scatter plot no clear relationship exists as the there is very limited data in areas where the wind speed was greater than 30 degrees per day.

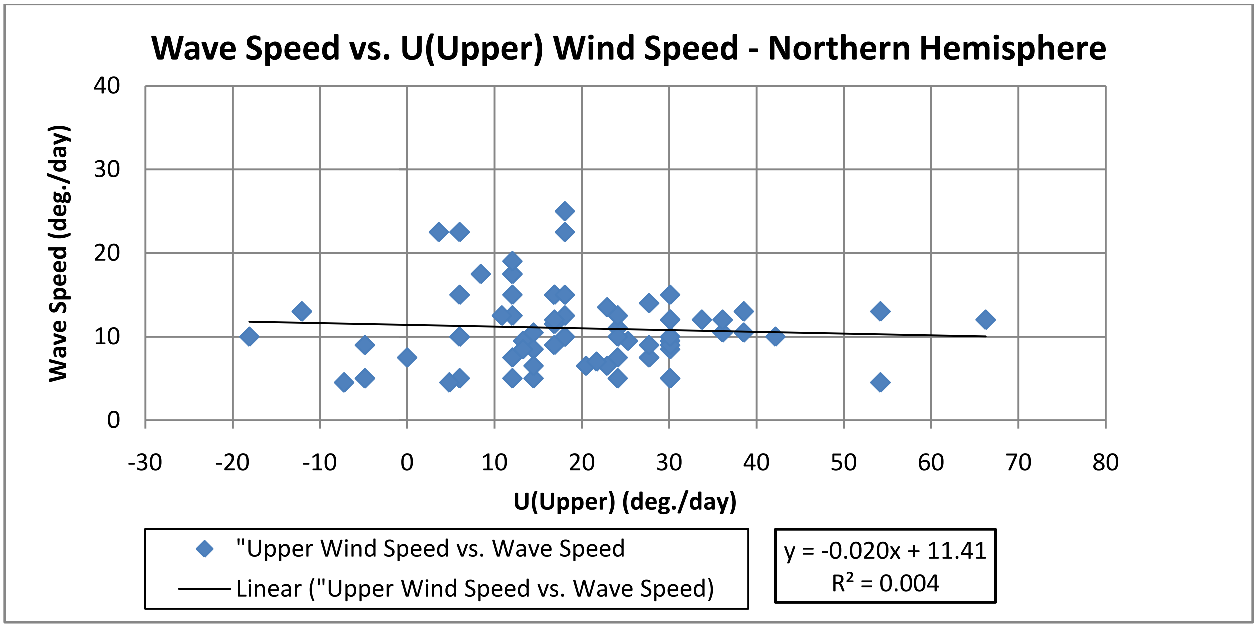

Figure 3

The Southern Hemisphere is the same story with very little relationship existing. The linear regression line indicates a positive slope which would agree with theory however the slope is very small; too small to imply a relationship between upper level winds and wave propagation. Figure 4 shows the scatter plot for this analysis for the Southern Hemisphere.

As you go up higher in the atmosphere less forcing is present because density decreases exponentially with height which is one possible reason for why our general forcing region for calculating ū in our original equation cannot be much above 500 hPa. We also need to keep in mind that we are taking these values at only 50 degrees north and south which may play a large role in why our data does not show a clear relationship.

We also want to explore the relationship between integer wave number and wave speed. Our original equation was $c = \bar{u} - \beta/(k^2 + l^2)$.

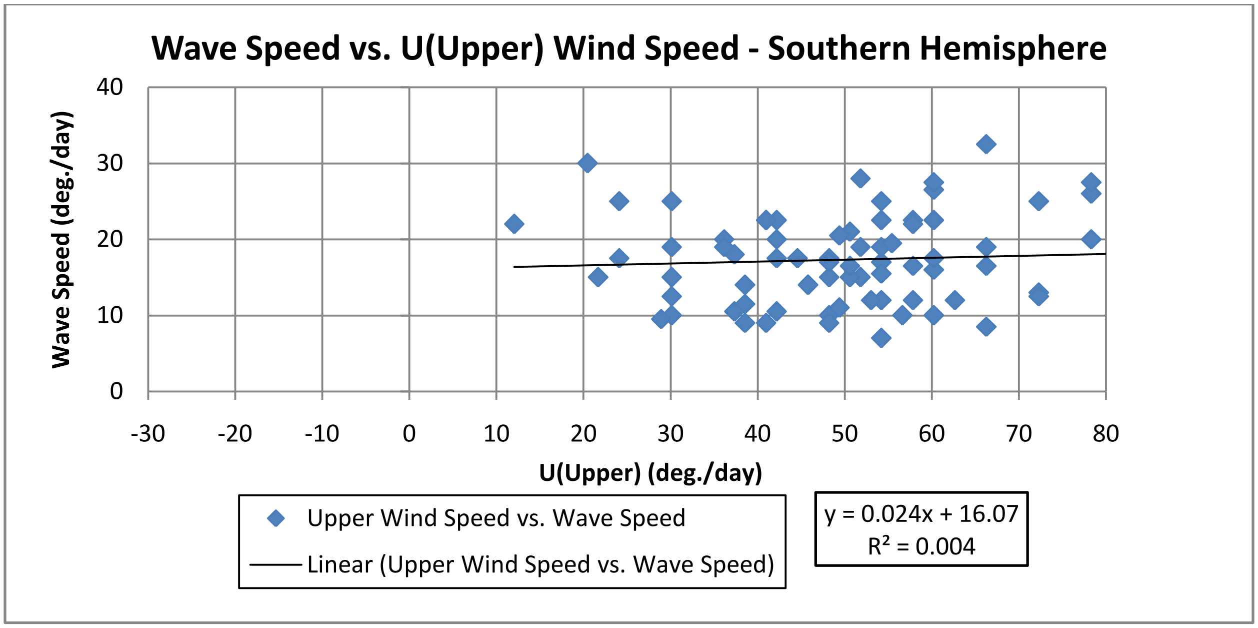

Figure 4

Where $k^2 + l^2$ are our horizontal wave numbers. If we simplify our equation again ignoring the general flow speed and combining the horizontal wave number variables into one we get

(8) $$c = -\beta/(n).$$

Where $n = k^2 + l^2$, or simply an estimation of integer wave number. Thus theory says that with increasing wave number we have increasing propagation in the positive direction. When analyzing this relationship we subtracted our general wind speed at 500 hPa from the wave speed that was measured in each hemisphere in degrees per day. This was done to ignore the effects of the general flow on the wave speed. For the Northern Hemisphere we found a general increase in wave speed with increasing integer wave number as shown by Figure 5.

This relationship is very poor and not statistically significant with an R^2 value of only 0.0016. The slope of the linear regression line is increasing which does agree with theory but overall a statistically significant fit is not present in our sample. As for the Southern Hemisphere a more significant fit was produced, however it disagreed with theory as shown by Figure 6.

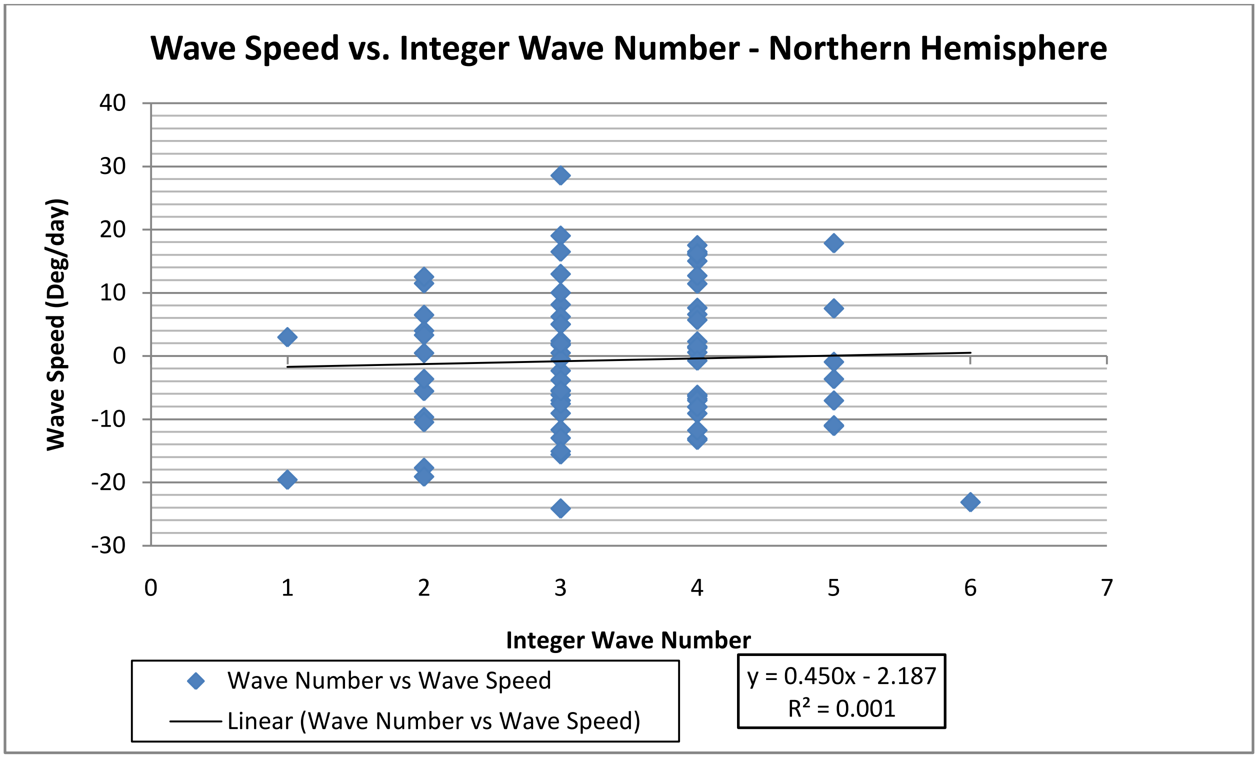

Figure 5

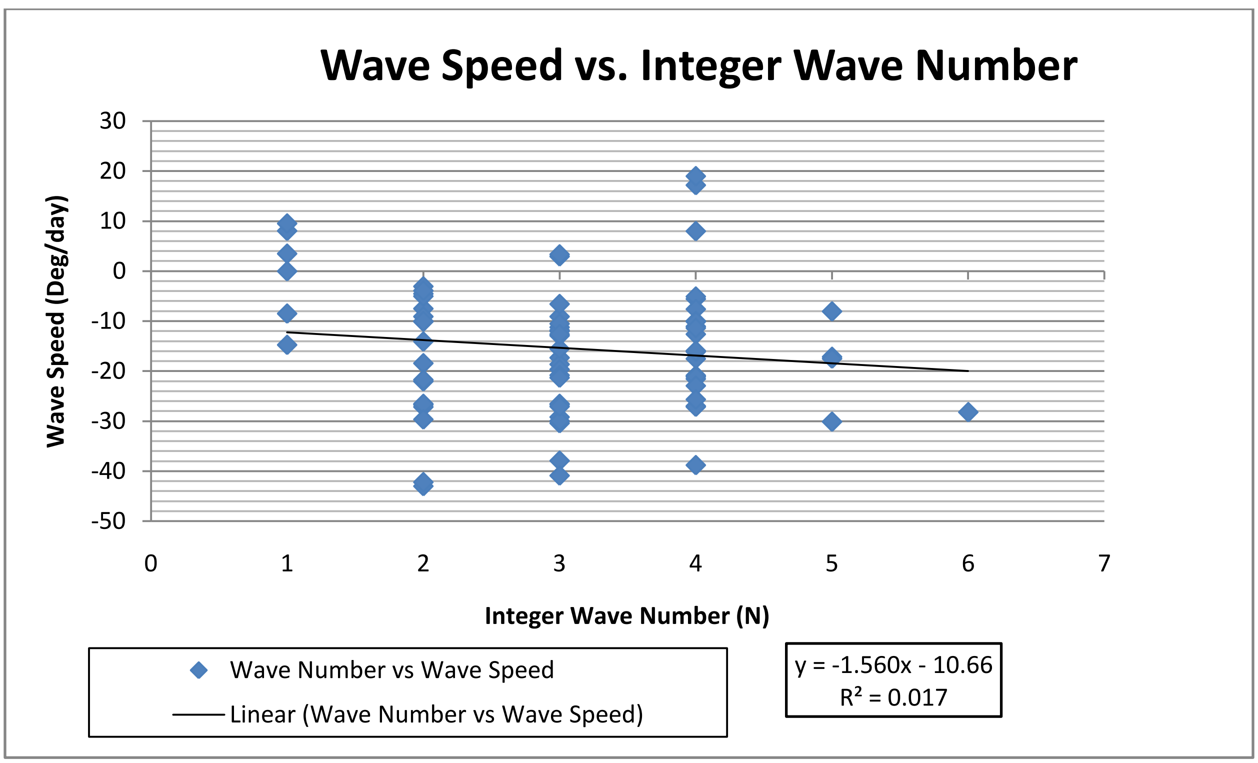

Figure 6

As integer wave number increases wave propagation actually decreases at a fairly significant rate of -1.56 degrees per day as seen by the linear fit. This is opposite of what theory says which again must be attributed to poor measurement.

We conclude that from our sample using wave speed, 500 hPa wind speed, and integer wave numbers no strong relationship was found that helps support Rossby wave theory.

c. How Long Does One Identifiable Pattern Last?

During the period of August 24, 2009 to November 6, 2009, the Northern Hemisphere witnessed a negligible decrease in integral wave number. By using a line of best fit we observed in Figure 7 that the overall change in the integral wave number over the time period was essentially zero. In the Southern Hemisphere, during this same period there was also a negligible decrease in integral wave number as is shown in Figure 8. This makes sense as the average change in integral wave number over several months would be highly dependent on the beginning and ending integral wave number values. A more effective way of determining how long an identifiable pattern lasts would be to separate the time periods in which there are identifiable integer wave patterns and record that length of time.

By analyzing the data during the time period for the Northern Hemisphere, we are left with eight identifiable patterns for integer wave number. We found this by counting the periods of time greater than three days where the wave pattern did not deviate more than one wave number. From 8/28/2009 to 9/2/09 there is a 2-3 wave pattern. From 9/3/2009 to 9/21/2009 there is a 3-4 wave pattern. From 9/23/2009 to 9/26/2009 there is a 3-4 wave pattern. From 9/3/2009 to 10/4/2009 there is a 5-6 wave pattern. From 10/7/2009 to 10/12/2009 there is a 3-4 wave pattern. From 10/16/2009 to 10/20/2009 there is a 3-4 wave pattern. From 10/23/2009 to 10/26/2009 there is a 2-3 wave pattern. From 10/28/2009 to 11/2/2009 there is a 3-4 wave pattern. This gives us a mean duration of identifiable patterns of 6.9 days. This is very much in line with what we can expect for the time-scale of synoptic-scale weather.

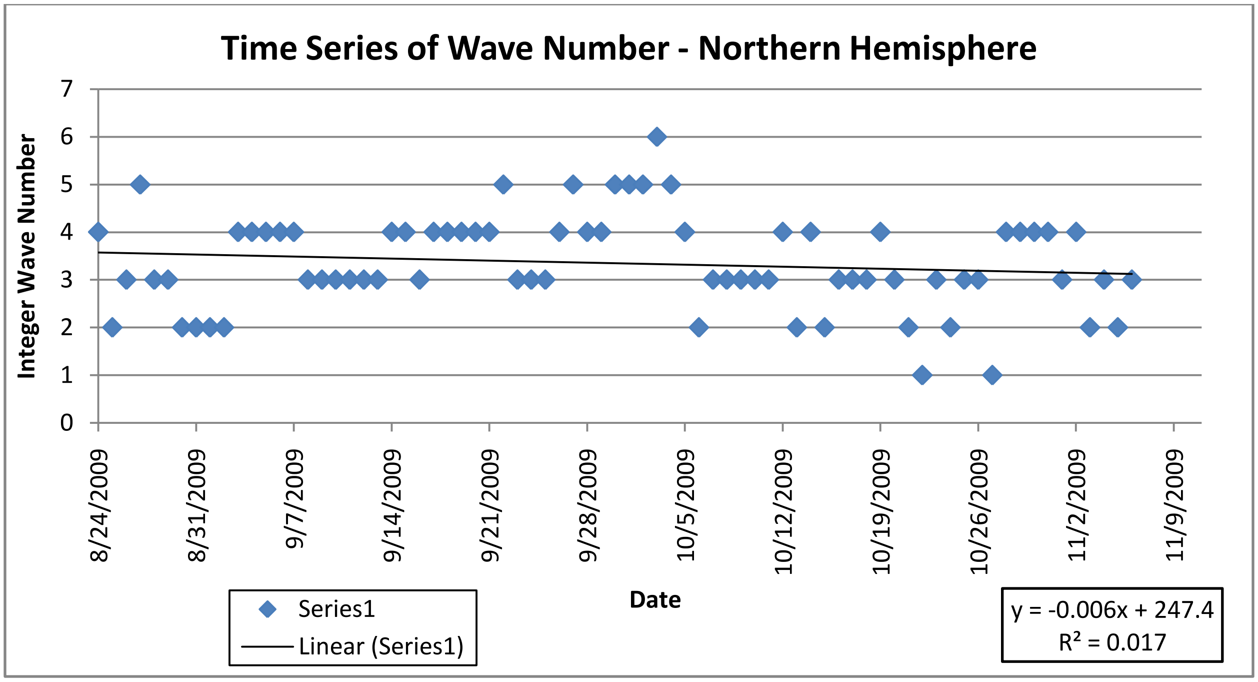

Figure 7

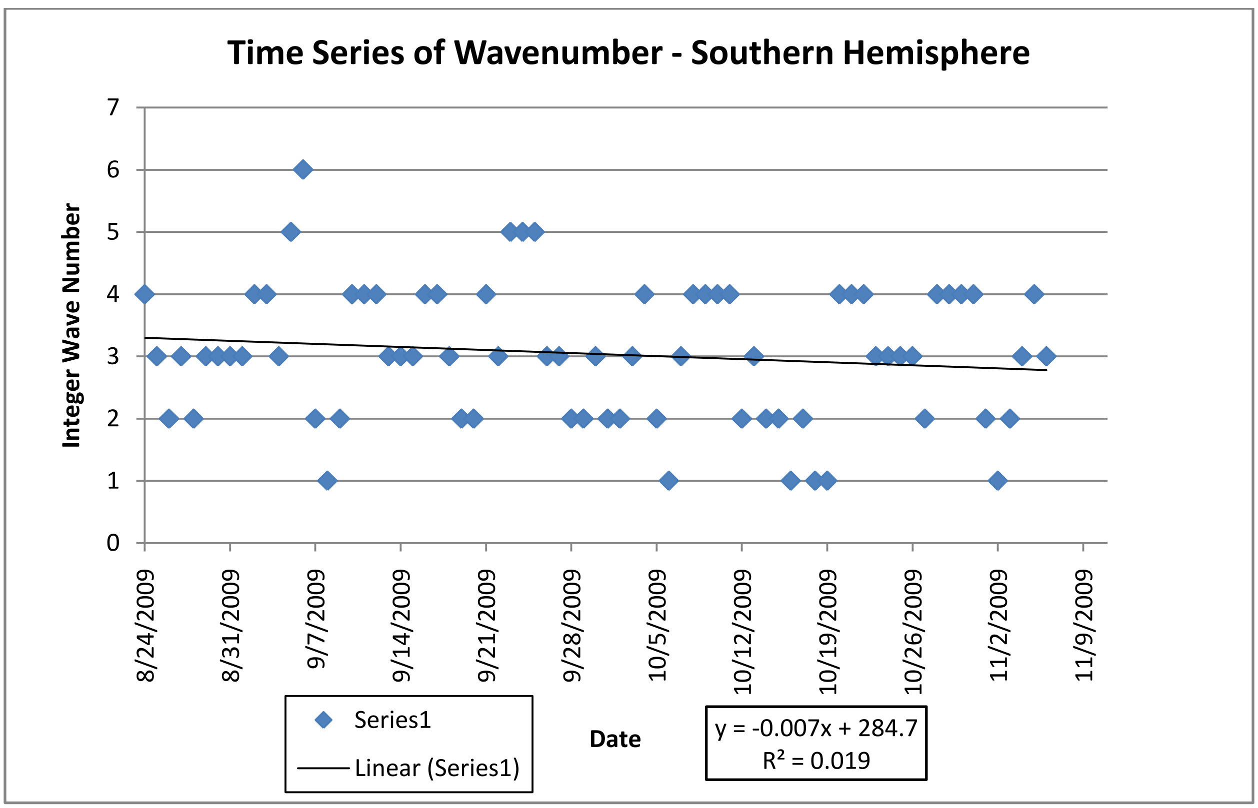

Figure 8

By analyzing the data during the time period for the Southern Hemisphere, we are left with nine identifiable patterns for integer wave number. From 8/25/2009 to 8/28/2009 there is an identifiable 2-3 wave pattern. From 8/29/2009 to 9/4/2009 there is a 3-4 wave pattern. From 9/10/2009 to 9/18/2009 there is a 3-4 wave pattern. From 9/26/2009 to 10/3/2009 there is a 2-3 wave pattern. From 10/7/2009 to 10/11/2009 there is a 3-4 wave pattern. From 10/12/2009 to 10/15/2009 there is a 2-3 wave pattern. From 10/16/2009 to 10/19/2009 there is a 1-2 wave pattern. From 10/20/2009 to 10/26/2009 there is a 3-4 wave pattern. From 10/28/2009 to 10/31/2009 there is a 4 wave pattern. This gives us a mean duration of identifiable patterns of 5.8 days. This also is in line with synoptic time scale.

Analyzing the data for amplitude and plotting it versus wave number gave us the most significant results of our investigation. According to Figures 9 and 10 for the Northern and Southern Hemispheres, respectively, we can say with relatively high confidence that longer waves have larger amplitudes and shorter waves have smaller amplitudes. Analysis of amplitude versus wave number showed this relationship with an R-Squared value of 0.380 for the Northern Hemisphere and an R-Squared value of 0.276 for the Southern Hemisphere. Our explanation for this phenomenon in the atmosphere is that the mean westerly flow throughout the atmosphere does not allow short waves to have a greater amplitude than that of long waves. If short waves had amplitudes greater than that of long waves, the mean flow of the atmosphere would be much more meridional and would significantly alter the dynamics of the mean flow of the atmosphere. The mean westerly flow of the atmosphere is determined by the rotation of the earth and the large scale dynamics of general circulation which, ultimately, are the most important factors and will not be affected by smaller scale flow. The opposite is true as smaller scale is affected by the larger scale dynamics.

d. How Rapidly Do Waves Increase or Decrease in Amplitude?

In plotting a timescale of amplitude, we found that amplitude increased significantly over the course of the time period in the Northern Hemisphere. In the Southern Hemisphere, there was a slight, but not significant increase. In the Northern Hemisphere there were three main periods

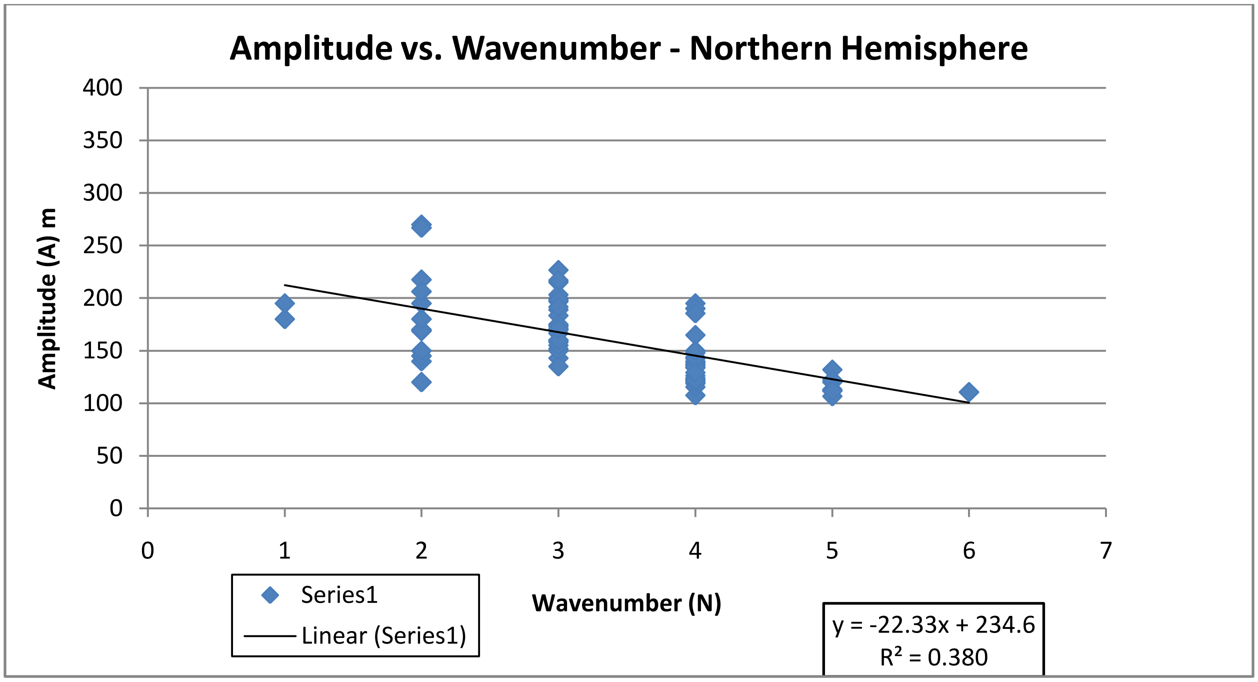

Figure 9

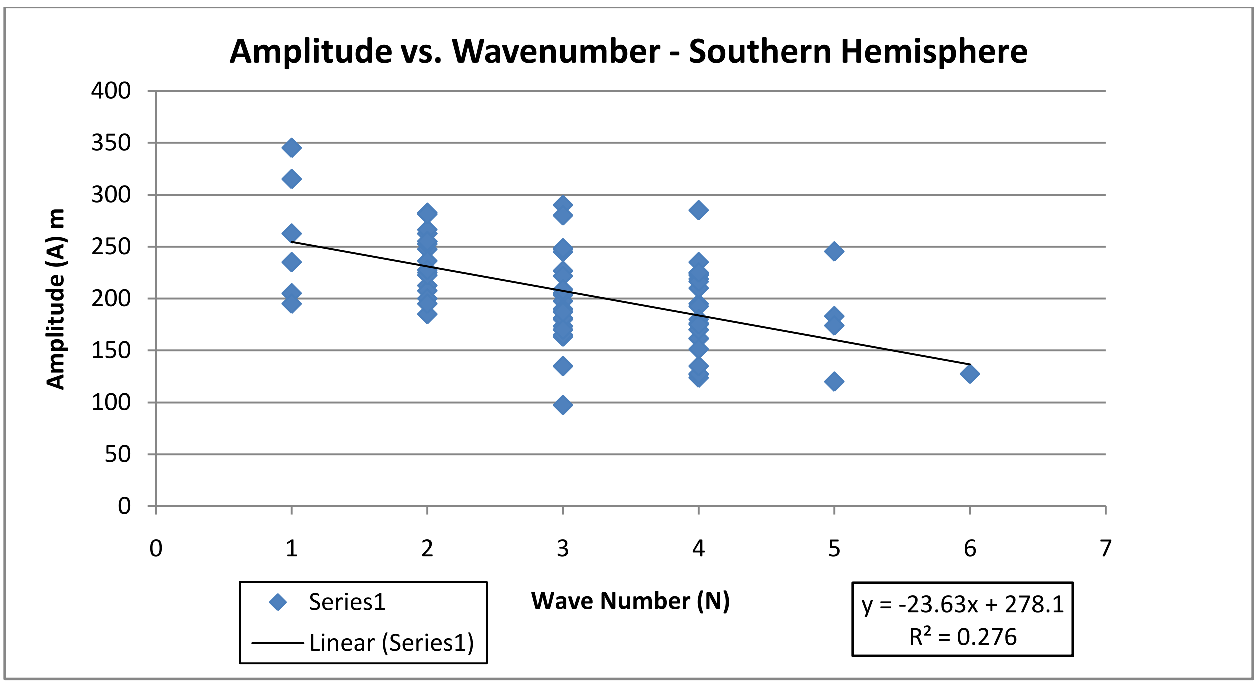

Figure 10

of growth that occurred during the period. These periods of growth were found by calculating the difference in amplitude for each two day period and looking for periods of multi-day growth. From 9/8/2009 to 9/10/2009 the amplitude increased 99.4 m. From 10/4/2009 to 10/6/2009 the amplitude increased 58.0 m. From 11/3/2009 to 11/5/2009 the amplitude increased 81.38 m. These three periods are shown in Figure 11. In the Southern Hemisphere there were four main periods of growth that occurred during the period. From 9/6/2009 to 9/9/2009 the amplitude increased 142.5 m. From 9/15/2009 to 9/19/2009 the amplitude increased 110.0 m. From 10/10/2009 to 10/12/2009 the amplitude increased 71.3 m. From 10/21/2009 to 10/24/2009 the amplitude increased 121.4 m. These periods are shown in Figure 12. In the Northern Hemisphere the overall amplitude increased by 45.3% during the time period. In the Southern Hemisphere the overall amplitude increased by 19.3 % during the time period.

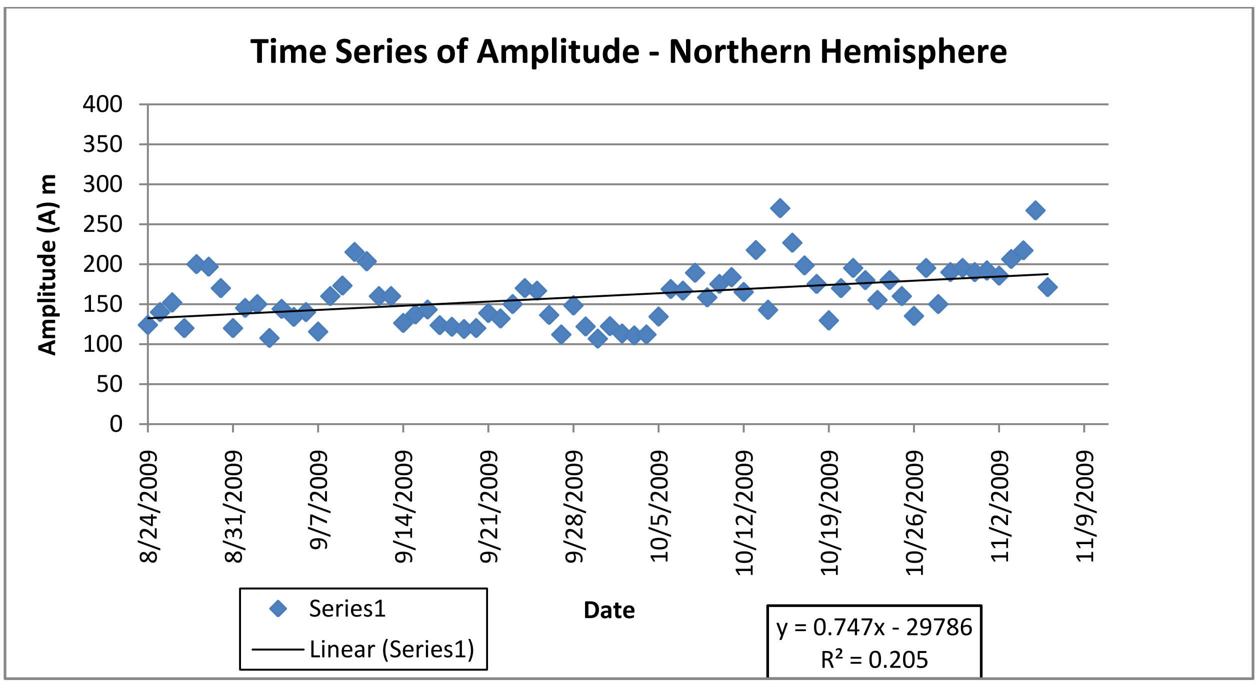

Figure 11

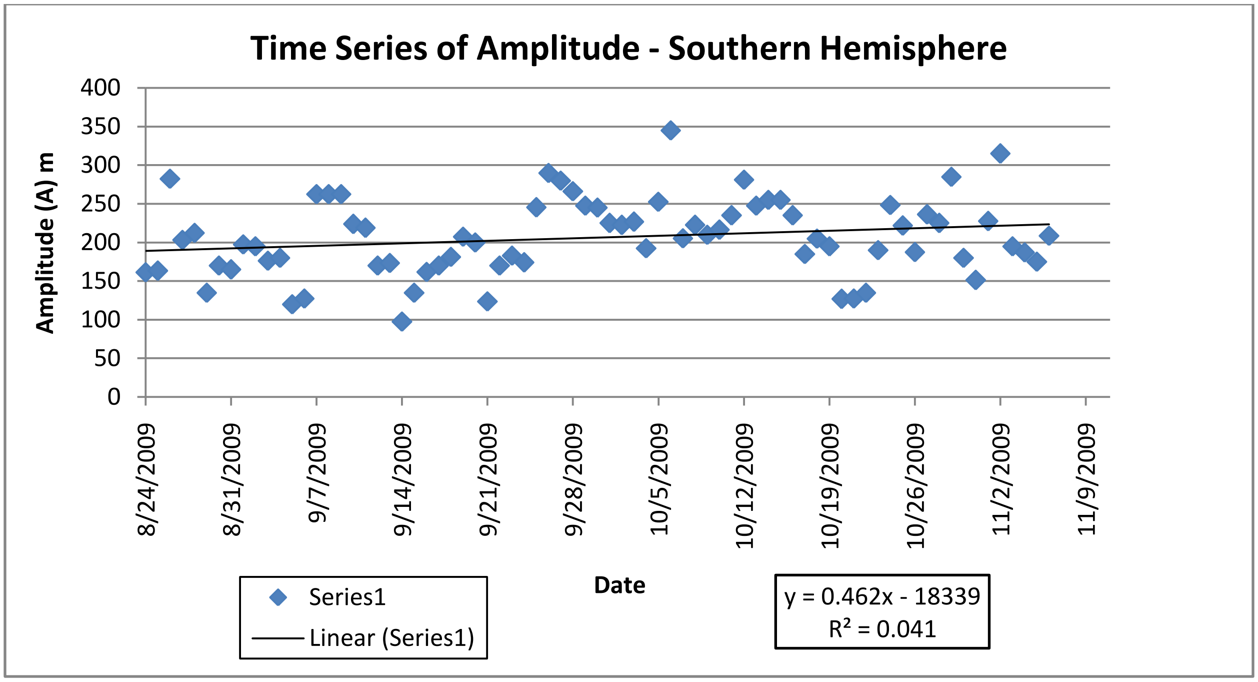

Figure 12

e. How Does Zonal Wind Evolve Through the Period?

Zonal wind speed maximums at both the 500 hPa and the layer between 150 hPa to 300 hPa were graphed for each date in both Northern and Southern Hemispheres. In the Northern Hemisphere, the average zonal wind speed for the 500 hPa level was 9.96 meters per second and 16.45 meters per second between 150 to 300 hPa. In the Southern Hemisphere, the average zonal wind speed for the 500 hPa level was 27.17 meters per second and 41.60 meters per second. Based on these numbers alone we can deduce that the winds in the Southern Hemisphere are overall stronger than the zonal winds in the Southern Hemisphere. This would make sense because the Southern Hemisphere has less land and thus less friction to slow down the winds. The range of the winds in the Southern Hemisphere was larger from between 4 meters per second to 47 meters per second at 500 hPa and 10 meters per second to 70 meters per second at upper levels between 150 to 300 hPa. In the Northern Hemisphere there were multiple times where the winds actually went in the negative direction, or east. Easterly winds didn't occur at all in the Southern Hemisphere. The range in the Northern Hemisphere was -5 (easterly wind) meters per second to 30 meters per second at 500 hPa and -15 (easterly wind) meters per second to 55 meters per second at upper levels. The Easterly winds in the Northern Hemisphere can most likely be attributed to a very stagnate pattern in the earlier portion of our time period where we saw many more cutoffs and propagation of waves back towards the west as a result of these weaker winds or easterly winds.

On Figures 13 and 14, there is a linear line of best fit for both zonal wind speeds at 500 hPa and at upper levels. In the Northern Hemisphere, the winds are ever so slightly increasing through the 75 day period while the winds in the Southern Hemisphere are decreasing at a larger slope. This would make sense as the seasons are changing and the Northern Hemisphere is transitioning from summer to winter and the Northern Hemisphere is going from winter to summer. The fact that the Southern Hemisphere's winds decrease at a larger slope may be due to the fact that there is less friction in the Southern Hemisphere so changes are easier to see.

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

The relationship between zonal wind speed and amplitude is shown for both hemispheres in Figures 13 and 14 and there is also a corresponding best fit line for zonal wind speed and amplitude. In the Northern Hemisphere, it does appear that as the zonal wind increases so does the amplitude in general, likewise, as the zonal wind decreases, the amplitude does as well. A good example of this could be seen in the time period between 9/7 and 9/11 where both rise and fall. Unfortunately, I don't think this would be a statistically significant correlation because there are plenty of times where this correlation doesn't hold. When we look at the best fit lines for both we see that they both increase in general together. However, the amplitude increases at a steeper rate than the zonal wind speed.

In the Southern Hemisphere, there really appears to be no correlation. There are times where

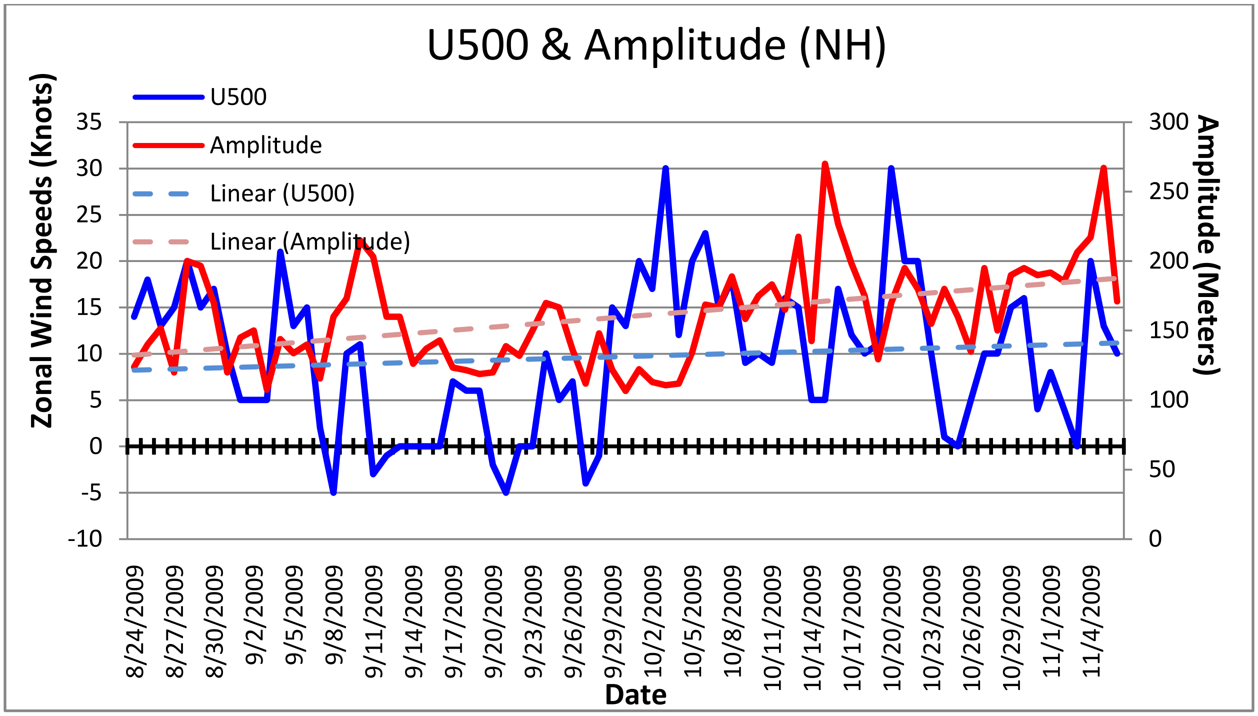

Figure 13

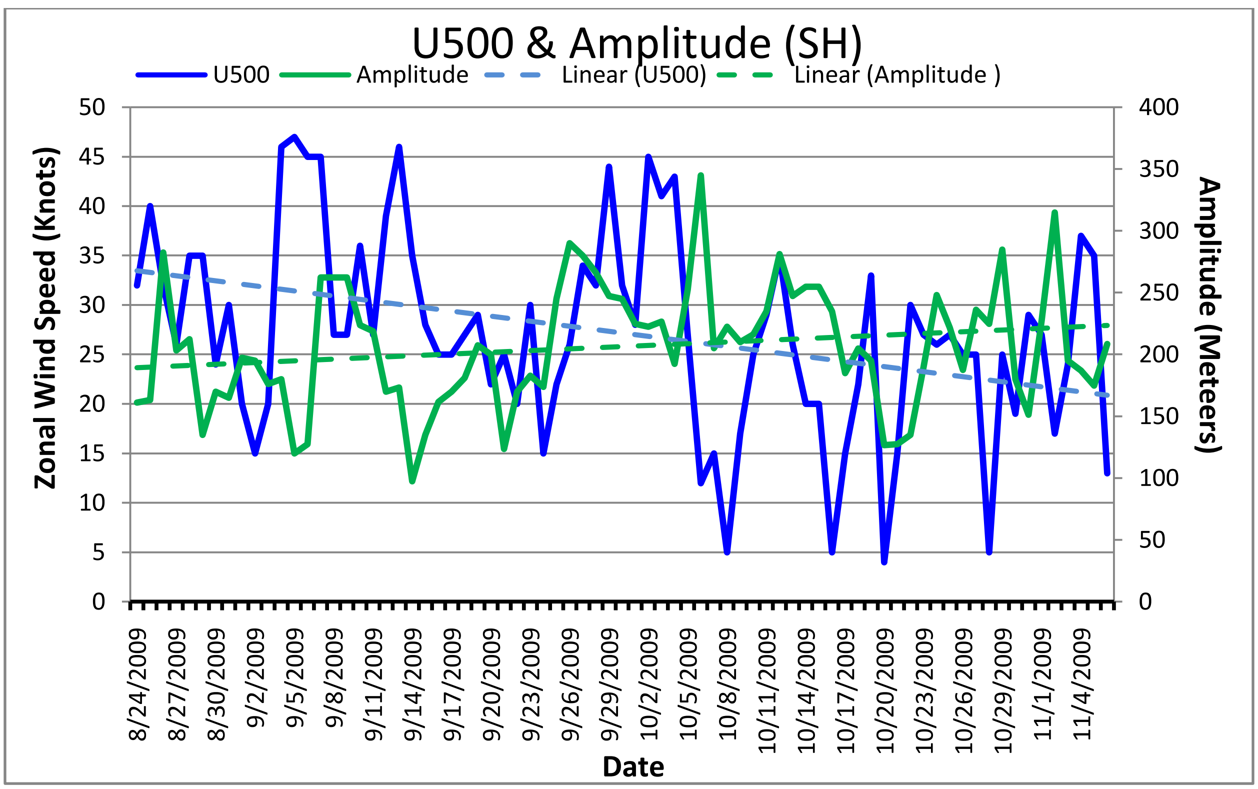

Figure 14

the amplitude and zonal winds do tend to rise and fall somewhat together, but most of the time it doesn't. There is no clear pattern. This can be further backed up by the fact that the lines of best fit do not match. Amplitude increases over the time period while zonal wind speed increases over the time period. It would be thought that since there seemed to be a correlation in the Northern Hemisphere that shows both amplitude and zonal wind decreasing overtime that in the Southern Hemisphere the zonal winds and amplitude should be decreasing overtime. That fact makes it hard to discern any major correlation between zonal wind speed and amplitude.

4. Conclusion

After collecting data over the course of two months we found that our measurements did not confirm or deny the results that of what Rossby found out about waves in the atmosphere. We did conclude based on fair significance that Southern Hemisphere winds tended to be faster than that of Northern Hemisphere at 500 hPa and that as wave number increased amplitude would decrease as well. Many times the general trend was right, but lack of statistical significance could not confirm that this was truly something occurring in the data or if it was just noise. In order to make a decision we need to get more measurements, take more accurate and precise data, and look for more than just linear trends. We made many assumptions, such as waves will track along 50 degrees north and south, that would have added to our error. In order to better test theory one must decide upon a different methodology that will lower assumptions and thus decrease error.

References

Holton, J. R., *An Introduction to Dynamic Meteorology, Fourth Edition.*