An Analysis of Atmospheric Waves
Meteorology 454
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12/10/2010

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Abstract:

For this waves project we analyzed atmospheric waves for each hemisphere. Using the 500mb charts, we calculated many variables including wave number, amplitude, wave speed, and zonal wind speed. We used the data we collected to identify trends and then relate these trends to Rossby Wave Theory. Many interesting trends were found, but Rossby Wave Theory did not always hold true. However, overall, we have found that this theory is at least a good approximation most of the time, especially if the conditions are barotropic. With this paper, we hope to give some insight into how large-scale atmospheric waves play a role in our daily weather.

Introduction:

The weather affects people daily, and while the average person can decipher a weather map well enough to make it through his or her day without getting rained on, most of the time they do not stop and think about the bigger picture. It's true that synoptic scale disturbances are an integral force behind the weather-making systems we experience every day, but to find out why these disturbances are occurring in the first place and why certain weather patterns can be discerned at different points of the year, one must search the poles and analyze the atmospheric waves surrounding them. In this paper, we attempt to study observational data of atmospheric waves so that we can then relate it to Rossby Wave Theory. This theory assumes a barotropic environment; however, in reality we have a baroclinic environment. Therefore, while there are a few obstacles for Rossby Wave Theory to overcome in this investigation, the theory seems to be evident in many of the trends that are represented in our figures.

Data and Methodology:

From September 3rd, 2010 to November 19th, 2010, we collected data from 500mb height charts centered on each of the poles. We also used data collected from zonal wind charts, which included both hemispheres. This data was obtained from the Iowa State Weather Products page: http://www.meteor.iastate.edu/wx/data/. During the observational period, we recorded many variables associated with the atmospheric waves.

First we determined the wave number for each day and for each hemisphere. To do this, we decided on a target height contour and a target latitude for each hemisphere. Because we wanted to be able to compare the two hemispheres in our analysis, the target latitude for both of them was at 50°. The height contour we used for the Northern Hemisphere was 5580m, and the one we used for the South was 5280m. Then to find the wave number, we simply added all of the times the 50° latitude line crossed over the respective height contour and then divide that number by two. This number represents how many waves are present during that day.

The next variable we recorded was wave amplitude (m). To calculate this number, we first had to determine the maximum height that crosses the 50° latitude line for each wave. Then we averaged all of those maxima to get a single maximum value for a particular day. We did the same thing for the minimum heights. Then to get the amplitude we simply used this formula: A=(Zmax-Zmin)/2. Let it be noted that if the latitude line happened to fall in between two height contours, the height was simply estimated to the nearest 15°.

The next variable we recorded was wave motion (deg/day), or how fast the waves were moving from day to day. To do this, we recorded the longitude where the target height contours crossed over the 50° latitude line for each day. Then we used this formula to calculate its motion: C= (LON(day+1)-LON(day-1))/2. To get a better representation of how fast the whole wave system was traveling, as opposed to the speed of just one wave, we averaged the speeds for all the waves in one hemisphere. Finally, the last two variables we recorded were zonal wind speeds (m/s). We used a zonal wind chart to determine the 500mb zonal wind speeds at 50°N and S. We also used the chart to determine the maximum wind speed in the 300mb-150mb layer.

To properly analyze the collected data, some data-tweaking needed to be performed. For example, zonal average winds at 500mb and upper levels had to be converted from m/s to degrees/day in order to be compared with wave speed. This was achieved by using the following formula dx= acosφ dλ to find the distance in 1 degree at 50° latitude. Then by taking the wind speed and dividing by this value, we determined this value in deg/sec. Then we did the simple conversion to deg/day from there.

To attempt to find certain trends in the data, we then created many graphs that we could then compare with Rossby Wave Theory, while also making certain conclusions as to why certain trends were occurring. We wanted to see if there were significant relationships between zonal wind and wave propagation, how long identifiable patterns in the waves would last, how wave amplitudes increase or decrease, and how zonal wind evolves through the period.

Results and Analysis:

1. *Wave Pattern Movements and their Relationship to Zonal Wind*

The direction of movement for synoptic waves is from west to east in both Northern and Southern Hemispheres. Whether the wave patterns generally move at the same speed in both hemispheres is a little uncertain. Wave speed was recorded for each day in the period from September 3, 2010 to November 19, 2010 for both hemispheres in this study. The average wave speeds in each hemisphere were calculated and are available in the table below.

Table 1

Average Wave Speed (Northern Hemisphere)	Average Wave Speed (Southern Hemisphere)
9.2 deg/day	12.7 deg/day

The results are somewhat to be expected, recalling the simple phase speed relationship for Rossby waves $C_x = \overline{U} - \beta/(K^2 + L^2)$. It is observed that the phase speed for the waves is a function of the average zonal wind speed. On average winds are stronger in the Southern Hemisphere due to their being less land mass, large land masses can cause the flow to amplify and slow down the wind. Since the zonal wind is often greater in the Southern Hemisphere in than the Northern Hemisphere it makes sense that the average wave speed in the Southern Hemisphere would also be greater and our finding agrees with the simple phase speed relationship for the Rossby wave.

Since phase speed is proportional to the mean zonal wind as stated earlier it would make sense that on days where the zonal wind is stronger at 500mb and 50° North or South that the waves would also propagate faster and to the east in each hemisphere. Analyzing Northern Hemisphere graph of wave speed vs. average zonal wind at 500 mb (Fig. 1), where both speeds are given in degrees per day it is observed via the linear regression line that wave speed generally increases with the average zonal wind at 500mb and 50° north, which again is to be expected. The R-squared value is very low, which is also expected, partly because the phase speed relationship also has a second term which involves Beta and the wave number, and partly

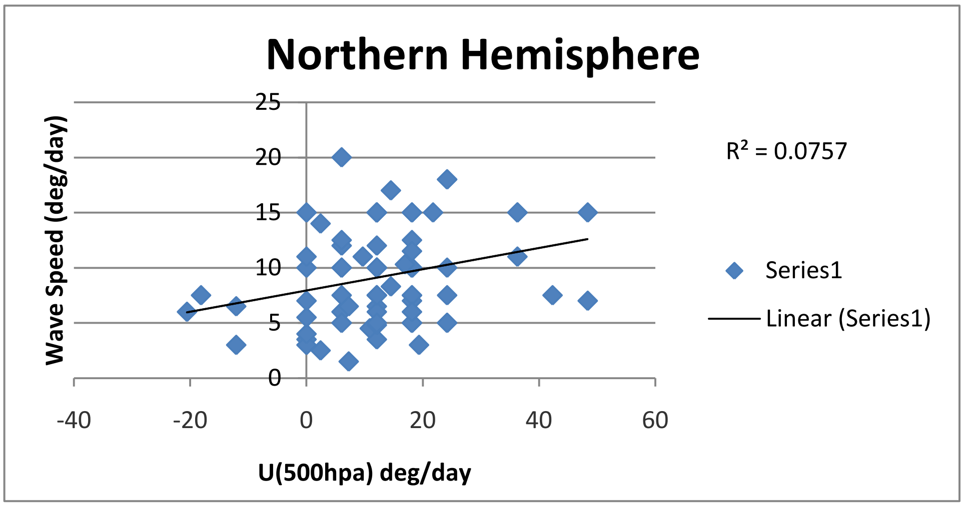

Figure 1 shows wave speed plotted against the average zonal wind at 500mb and 50° North latitude

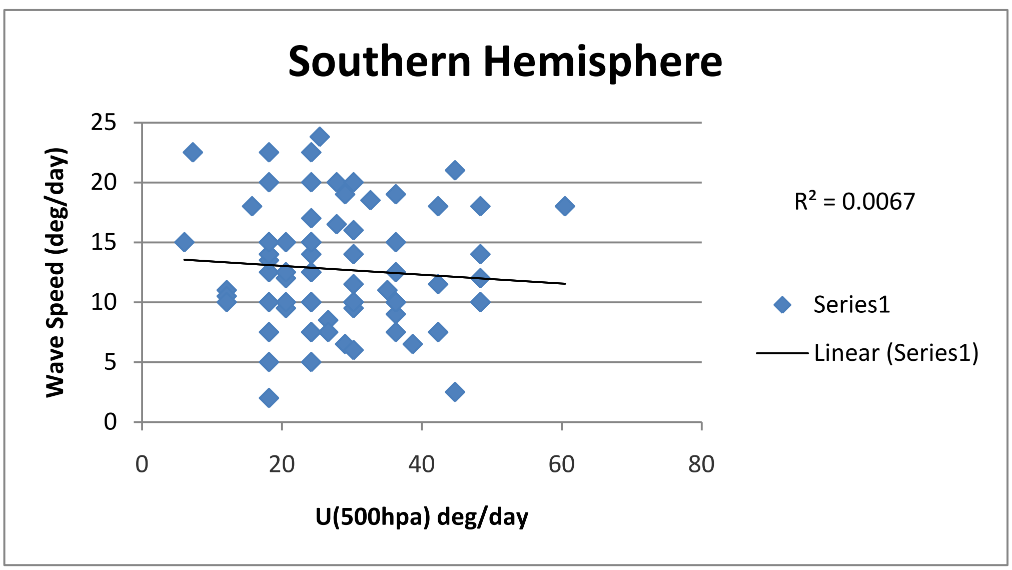

Figure 2 shows wave speed vs. the average zonal wind at 500mb and 50° South latitude because the phase speed relationship is simplified in that it assumes barotropic flow. The same graph was created for the Southern Hemisphere (Fig. 2). It is seen that values for wave speed actually decrease slightly as the average zonal wind increases in this plot. This is counter to what is expected from our phase speed relationship. It should be noted that the R-squared value is extremely small in this case, so the trend is very weak. This slight negative trend could be caused from either of the possible problems with the phase speed relation listed above, or it could possibly just be from human error. Since these speeds are estimated from an image it is possible to be off by a certain degree. Looking at the graphs it should also be noted that the wave speed is generally less than the 500mb zonal average wind in both hemispheres, this result can be attributed to the second term in the simple barotropic model (also referred to as the phase speed relationship). This term is referred to as the dispersion relationship and acts to slow the propagation of eastward moving waves, or even cause waves to retrograde to the west.

The relationship between the 500mb average zonal wind speed and wave speed was split as to whether it agreed with the simple barotropic model for Rossby waves given earlier. Will the relationship between zonally averaged wind in the upper troposphere and the speed of the waves agree with Rossby's theory? A positive relationship between the two variables is seen in Figure 3 for the Northern Hemisphere, with wave speed generally increasing as the zonally averaged wind increases. We even get a more substantial R-squared coefficient, so the linear regression line is a little better fit to our data and the trend is stronger. Looking at a graph of the same variables for the Southern Hemisphere (Fig. 4), there is really little trend evident at all. This isn't surprising after analyzing the southern hemisphere graph for the zonal average wind at 500mb vs. wave speed, where a negative trend was observed. This again does not agree with our simple model, and may be a direct result of the simplifications the model assumes, human error, or possibly something else.

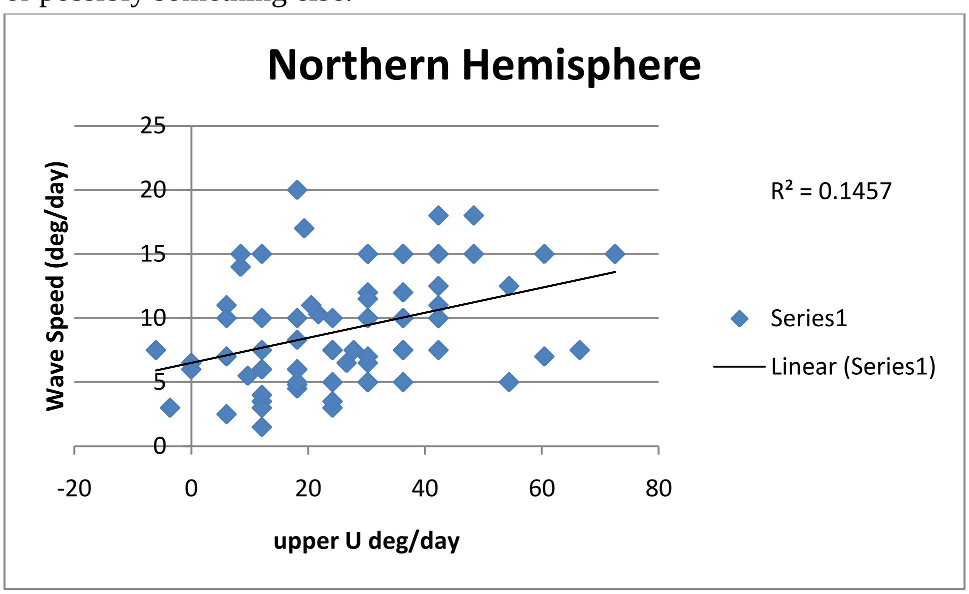

Figure 3 shows wave speed vs. the maximum averaged zonal wind in the 300-150mb layer at 50° North latitude

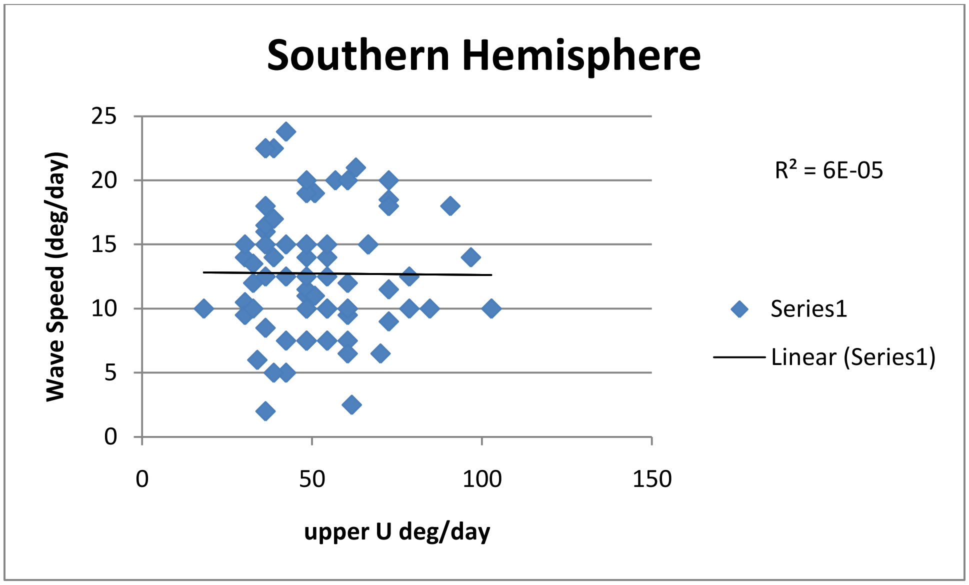

Figure 4 shows wave speed vs. the maximum average zonal wind in the 300-150mb layer at 50° South

Rossby's wave theory as shown in the simple model (phase speed relationship) previously is also dependent on wave number. From the model it is clearly seen that a larger wave number results in the term $-\beta/(K^2 + L^2)$ (known as the dispersion relationship) in the simple model being smaller, while smaller wave numbers make it larger. Since this term is negative, larger wave numbers tend to promote the eastward propagation of waves, while smaller wave numbers tend to inhibit the eastward propagation. This could even lead to retrogression of the wave to the west if the wave number is small enough or the average zonal wind is small enough. In order to analyze the next two graphs the dependence of the wave speed on the zonal wind is removed by subtracting the 500mb average zonal wind from the wave speed or basically $C_x - \overline{U} = -\beta/(K^2 + L^2)$, so as to just observe the correlation between wave speed and wave number.

Wave speed vs. wave number for the Northern Hemisphere is shown in Figure 5 (it should be noted that wave number refers to integer wave number here). A positive correlation between wave number and wave speed is evident here. This is supported by the simple Rossby wave model, because a larger integer wave number results in a larger wave number, which is shown to decrease the dispersion relationship. Looking at a graph of the same variables for the Southern Hemisphere (Fig. 6) it is observed that wave speed is increasing with increasing wave number. Basically shorter wavelengths result in a larger wave number, which results in the dispersion relation being smaller. It should be noted that this result also agrees with quasi-geostrophic theory, which implies that the advection of planetary vorticity is greater (less) than the advection of relative vorticity in longer (shorter) wavelengths , so they tend to propagate more slowly (rapidly) or even retrograde to the west.

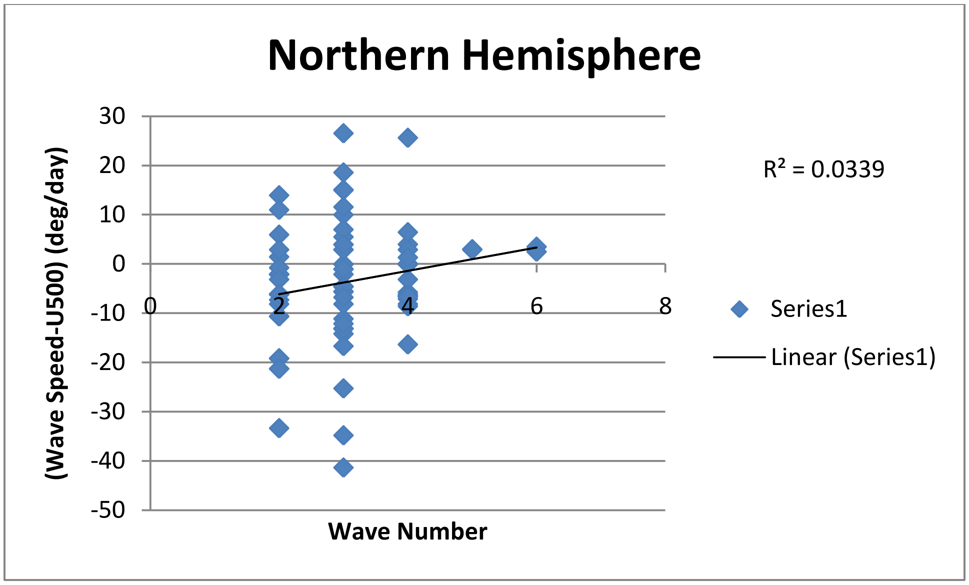

Figure 5 shows (wave speed-U500) vs. integer wave number at 50° North

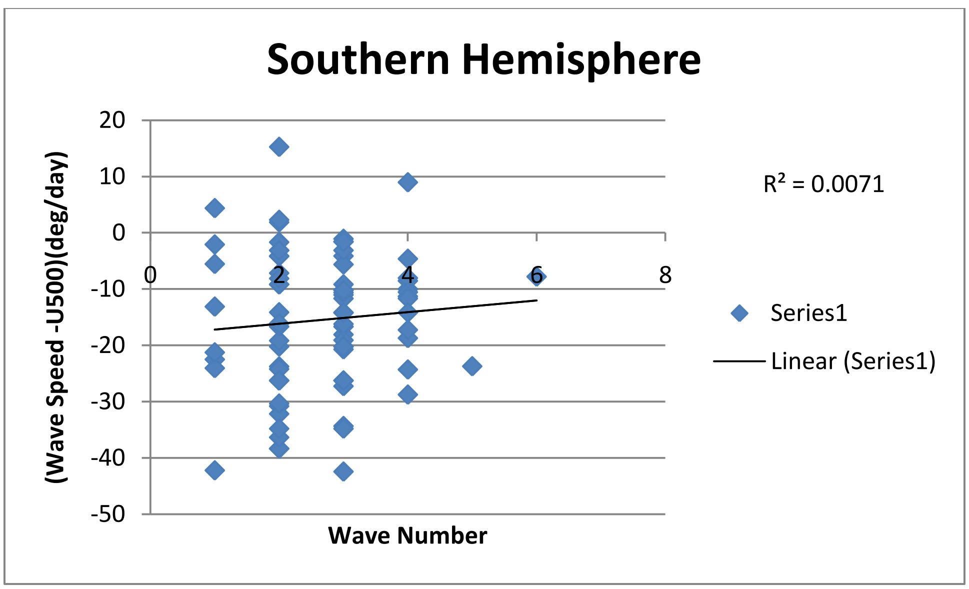

Figure 6 shows (wave speed-U500) vs. integer wave number at 50° South

2. How Long Do Wave Patterns Last?

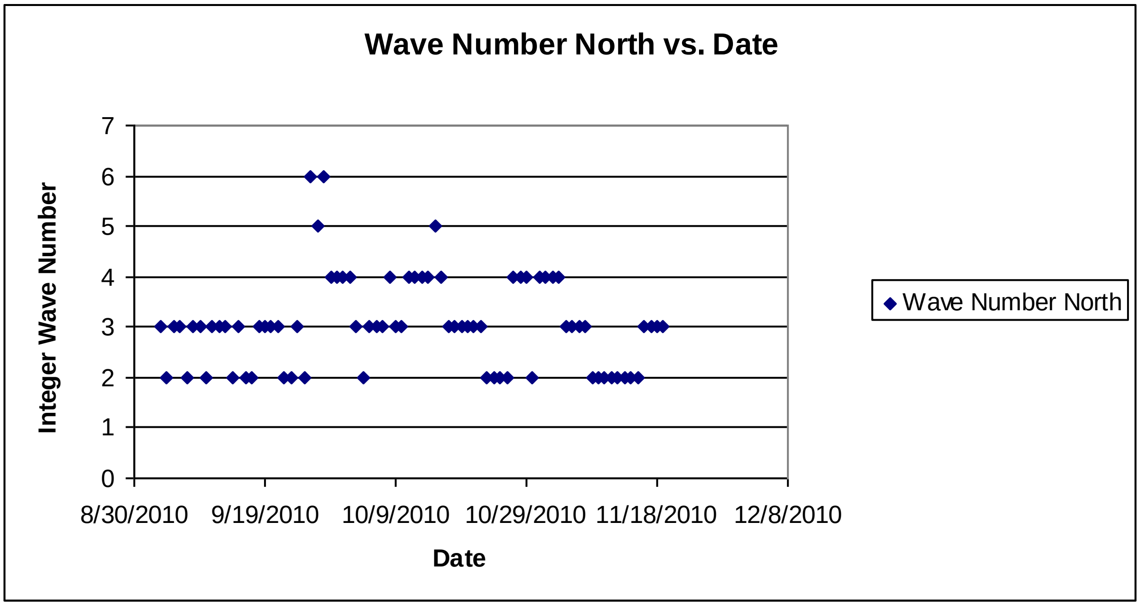

Figure 7 shows the wave number for the Northern hemisphere at 50° vs. the date.

For the Northern Hemisphere (Fig. 7), the wave number only changes by +/-1 for nearly the entire month of September, from the 3rd to the 26th. This twenty-three day period is a bit longer than the average synoptic time scale which is about ten days. There is another period near the end of the data collection from November 4th until the last day of collection November 19th where the wave number changes very little. This period is not quite as long as the earlier one at only fifteen days, but it is still longer than the average synoptic time scale.

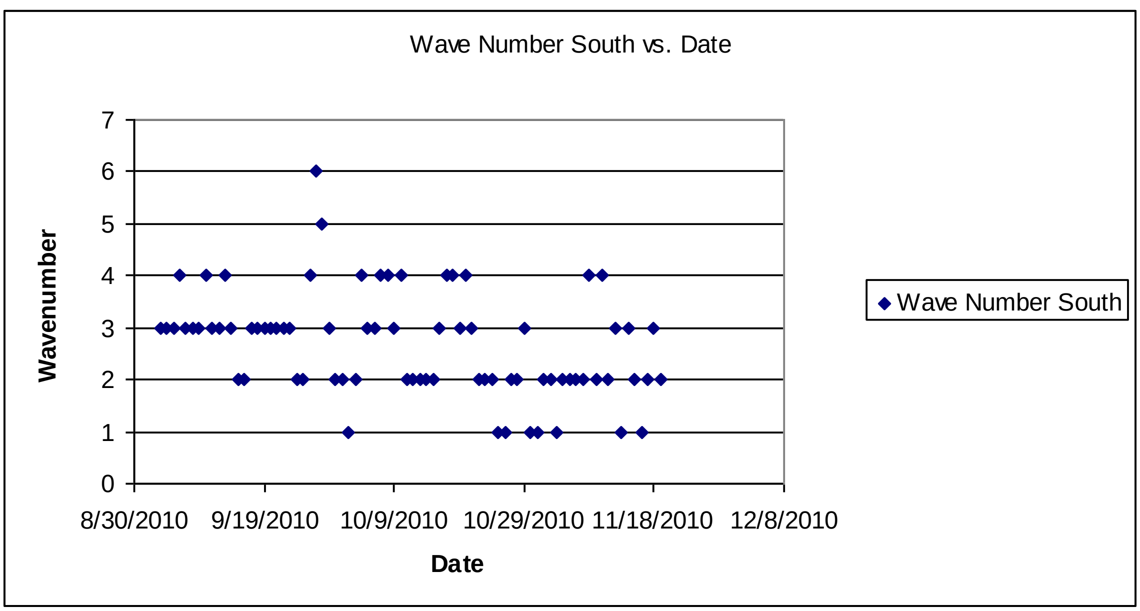

Figure 8 shows the wave number for the Southern hemisphere at 50° vs. the date.

Similarly to the Northern Hemisphere, the Southern Hemisphere (Fig. 8) experiences a lengthy period at the beginning of data collection where the wave number only changes by +/- 1 from September 3rd until September 25th. Unlike the Northern Hemisphere, this is the only time that the wave number persists. The twenty-two day period is about double the average synoptic time scale.

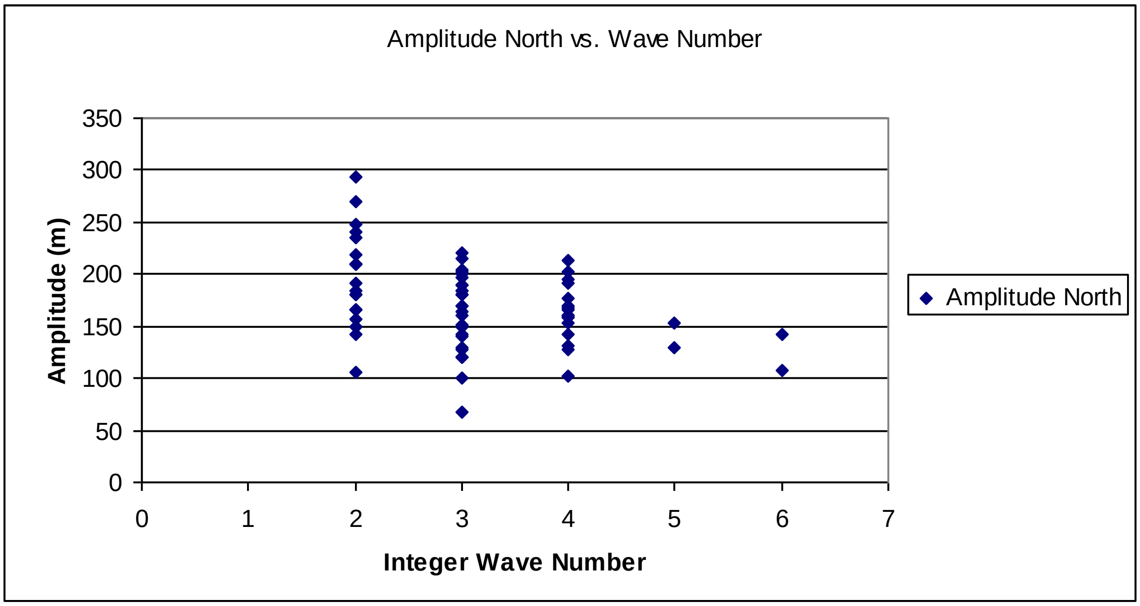

Figure 9 shows the wave number for the Northern hemisphere at 50° vs. wave amplitude.

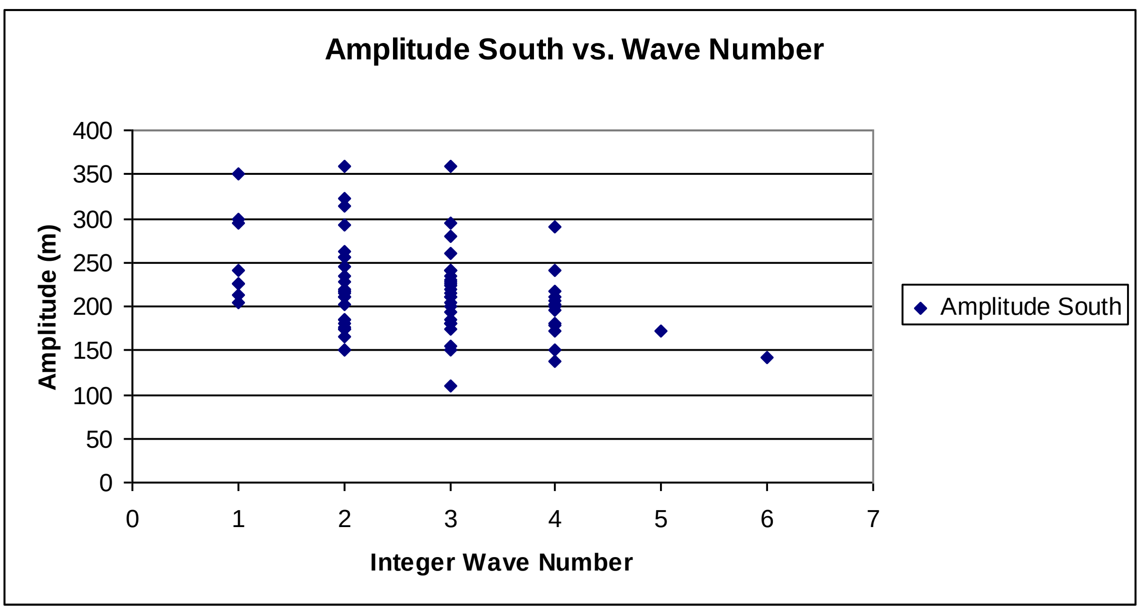

Figure 10 shows the wave number for the Southern hemisphere at 50° vs. wave amplitude.

In Figures 9 and 10 the waves with smaller wave numbers tend to have higher amplitudes which means that waves with longer wavelengths have higher amplitudes ($K = 2\pi/L$). There could be a connection between the wavelength, amplitude, and energy distribution. Higher amplitude wave distribution of energy would create a pattern with a few large ridges/troughs; whereas waves with a higher wave number/shorter wave length would have a greater number of less intense ridges and troughs. This assumption only works based on an approximately equal amount of energy being present overall in both scenarios. The data could also be skewed. Days with larger wave numbers have a better representation of the average amplitude based on the method the data were obtained. If the wave number on a particular day was only one, there would only be two reference points used to create the amplitude, on the other hand, on days with higher wave numbers, for instance four, there would be eight points contributing to the amplitude calculation.

3 How Quickly Does Amplitude Increase or Decrease?

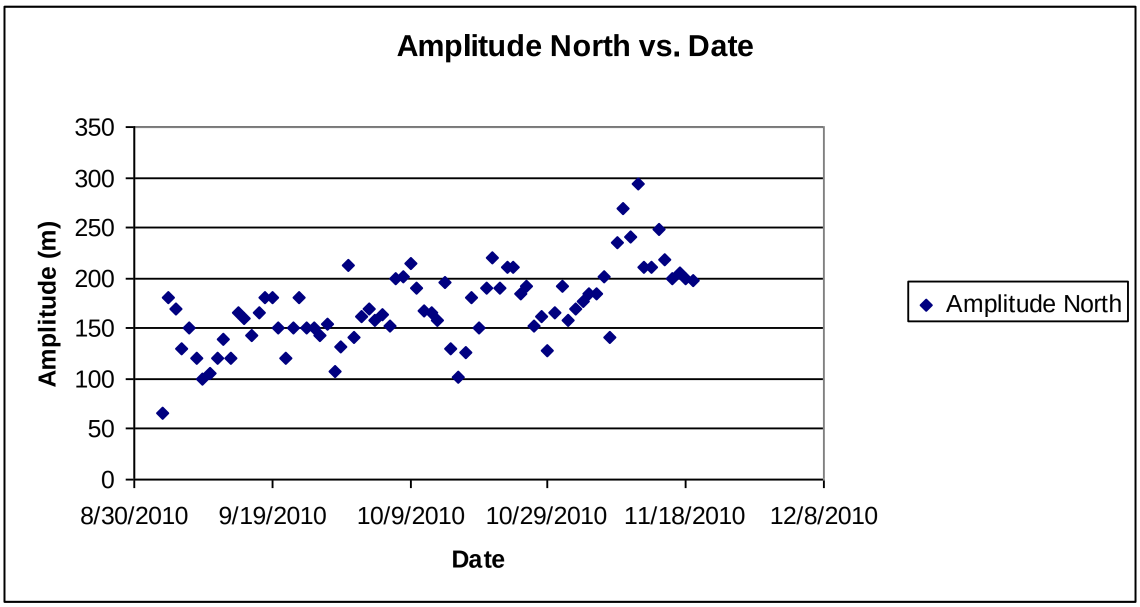

Figure 11 shows the amplitude of the Northern hemisphere waves vs. the date.

The amplitude of the waves in the Northern Hemisphere (Fig. 11) has a general growing trend throughout the entire data collection period. There is clearly a sinusoidal trend occurring, but overall the amplitude is increasing. The percent increase is approximately 230m/140m ~ 64%. There is a relatively steady increase from the beginning of September until the end of October. The percent increase over this time is approximately 180m/140m ~ 29%. Then a very large increase through the first few days in November, and during this time the percent increase of the amplitude is 300m/180m ~ 67%.

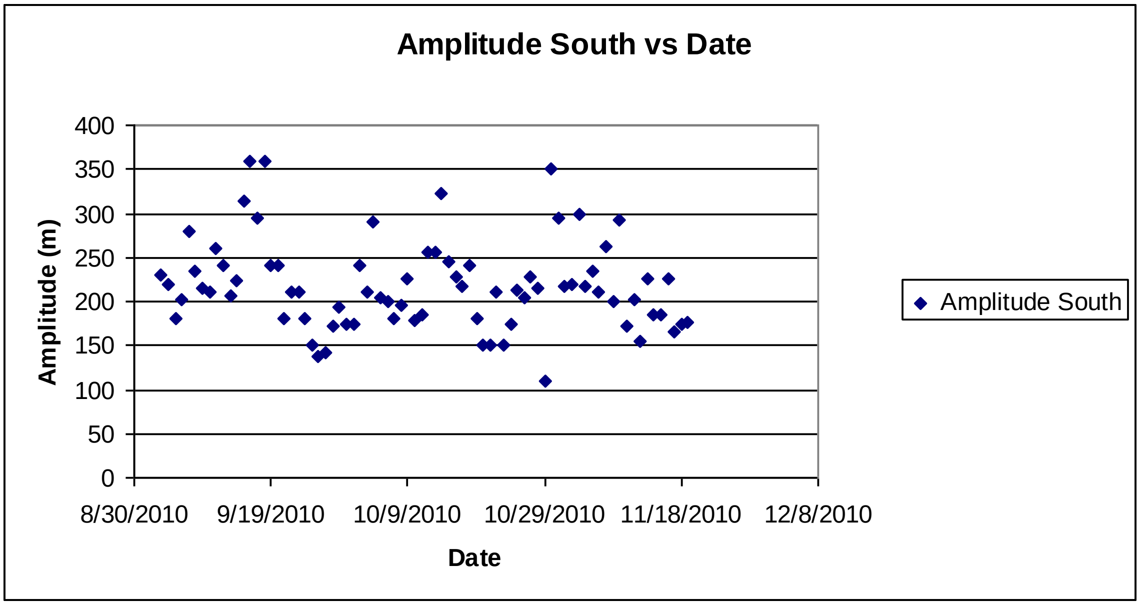

Figure 12 shows the amplitude of the Southern hemisphere waves vs. the date.

In the Southern Hemisphere (Fig. 12), there is an overall trend in the reduction of amplitude. Just like the Northern Hemisphere, there is a wave pattern imbedded in the overall trend. Early to mid September, there is an increase in amplitude approximated by 315m/215m ~ 47%. There is another increase in amplitude from late September through mid October with a percentage increase approximated by 260m/150m ~ 73%, and a final increase from the middle end of October into early November with a percentage increase of about 300m/150m ~ 100%.

4. Zonal Wind Evolution

The zonal wind displayed on the following graphs and discussed in the text was computed by averaging together the wind speeds around the globe at a particular latitude line. These values were determined by using a plot computed here at ISU. The values were constantly taken at 50° north and south for some consistency in the data tables. This degree of latitude also corresponds to the location of the polar jet. The following two graphs show the evolution of the Northern Hemisphere's zonal wind with respect to time.

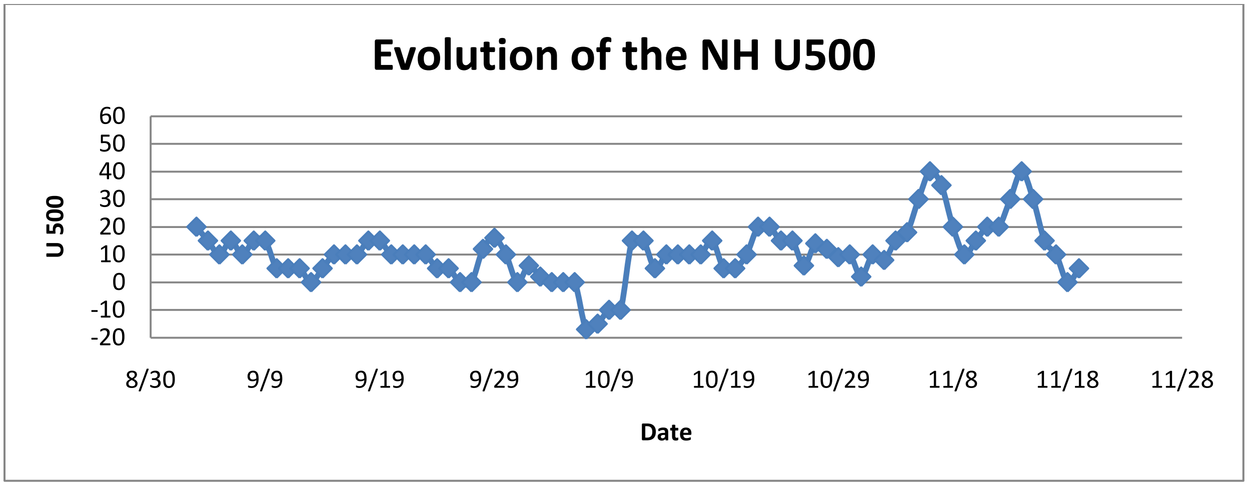

Figure 13 shows the zonal wind speed at 500mb at 50°N vs. the date.

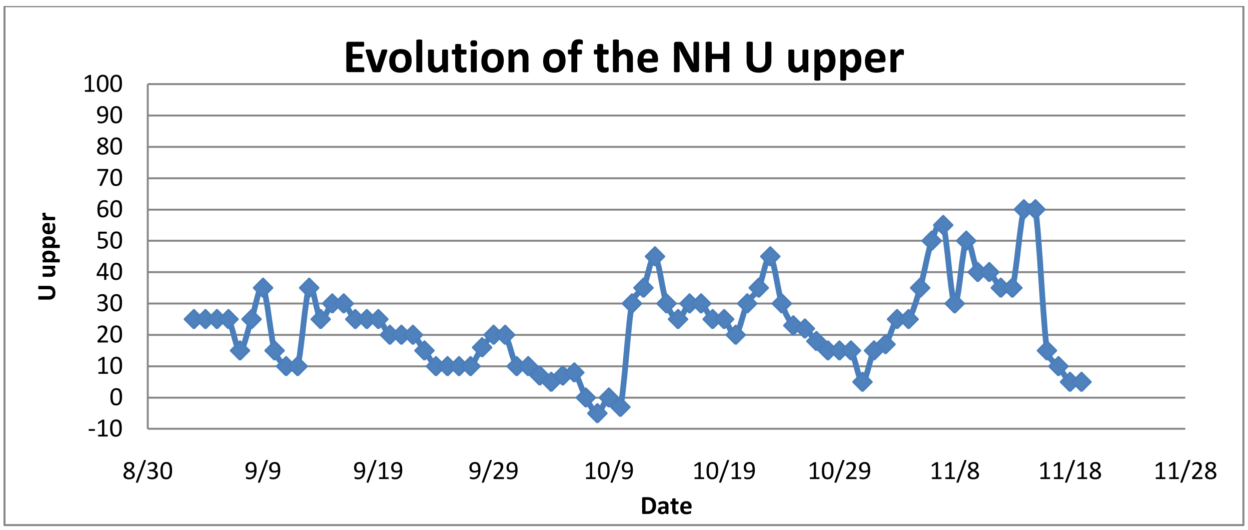

Figure 14 shows the maximum zonal wind speed in the 300mb-150mb layer in the Northern hemisphere.

The First graph (Fig. 13) has the zonal wind at 500mb plotted while the second (Fig. 14) shows the maximum zonal wind from 300mb to 150mb. The magnitude of the upper level plot is almost always larger than that of the 500mb plot. There is quite a bit of variation in each graph but overall they are trending upward. This is most likely due to the increase in the temperature gradient as the northern hemisphere is moving toward winter and receiving much less solar radiation. The next two graphs are of the zonal wind taken at 50° south for both 500mb and the 300mb to 150mb range.

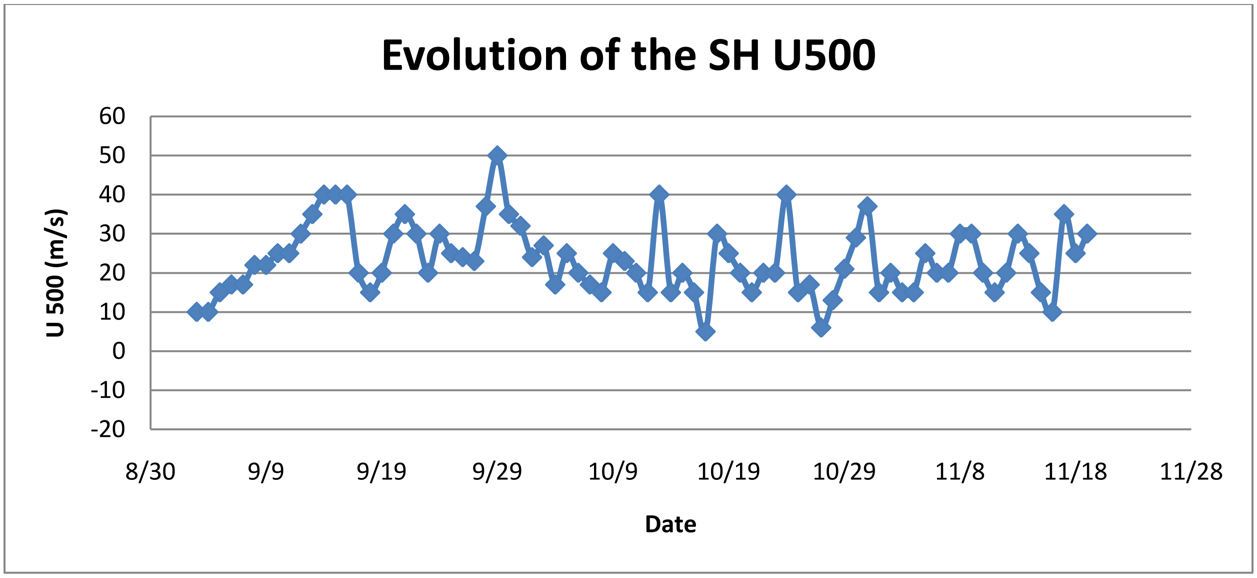

Figure 15 shows the zonal wind speed at 500mb at 50°S vs. the date.

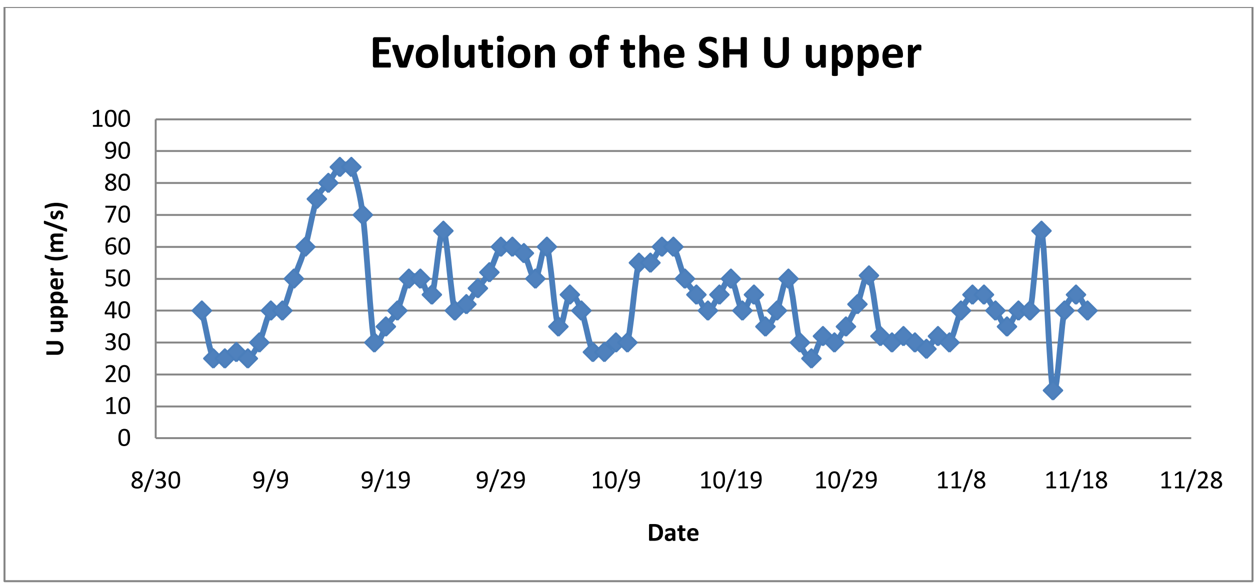

Figure 16 shows the maximum zonal wind speed in the 300mb-150mb layer in the Southern hemisphere.

Here again we see that the upper level graph (Fig. 16) is much larger in magnitude than the 500mb plot (Fig. 15). There is also some variation in the plot but there is an overall decreasing trend in the zonal average wind. This trend is most noticeable in the upper level plot. This trend is most likely due to the fact that the southern hemisphere is now moving into spring and summer so the large scale differential heating gradient is decreasing as the polar regions are now receiving more solar heating. These overall trends of the 4 plots are consistent with the overall dynamics that create these features.

5. Zonal Wind and its Relationship to Wave Growth and Decay

The zonal wind speed shown in the following graphs is the average wind speed at particular pressure level for each degree of latitude. In the following graphs the zonal wind displayed was taken at 500mb and at 50° north and south. The amplitude shown was calculated by maximum height at 500 and subtracting the minimum height also at 500 at 50° north and south. Because both of these data points were taken at 50° north and south they can be compared together. The following figure shows the amplitude and zonal wind evolution with respect to time in the Northern Hemisphere.

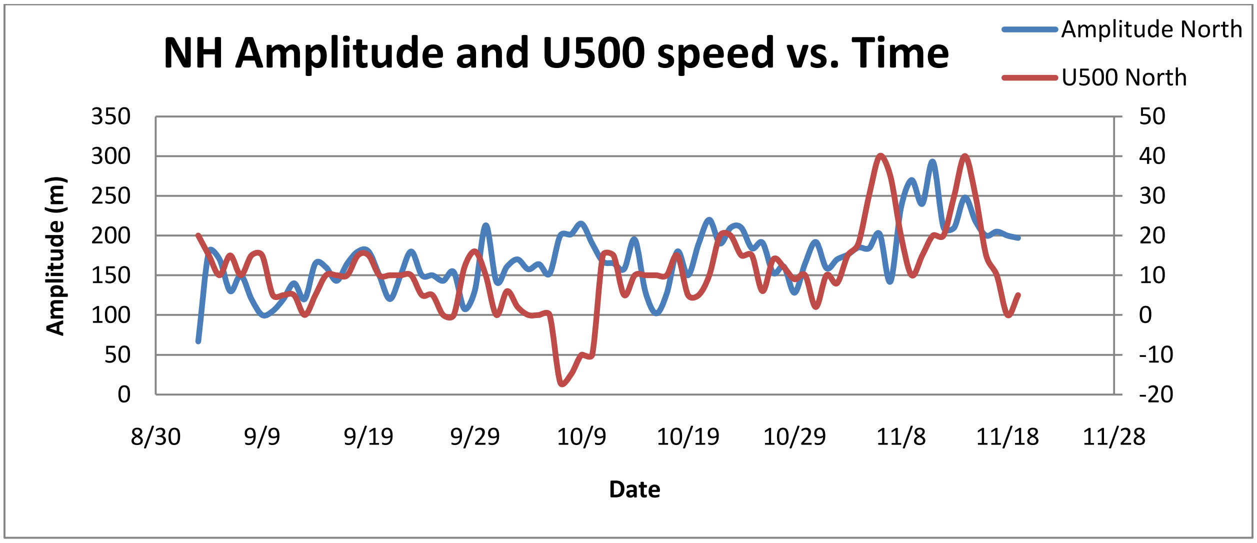

Figure 17 shows the amplitude of Northern hemisphere waves and the zonal wind speed at 50°N vs. the date.

Figure 17 is rather cluttered and has a lot of variation in it. In some instances both amplitude and zonal wind speed increase during the same time period. Other time periods show them trending in two different directions. Due to this great variation in their relationship no real correlation can be made. Over time however they both seem to be increasing. This could be due to the changing seasons in the Northern Hemisphere. The following figure of the Southern hemispheric wave amplitude and zonal winds can be seen below.

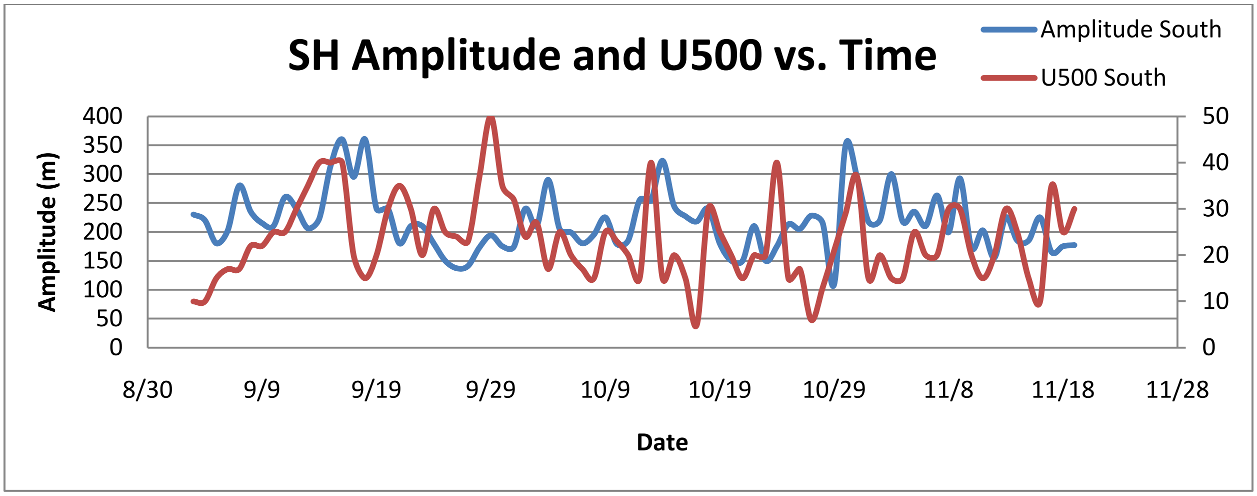

Figure 18 shows the amplitude of Southern hemisphere waves and the zonal wind speed at 50°S vs. the date.

This plot (Fig. 18) also has a lot of noise due to the difficulty in calculating the wave amplitude and the uncertainty in the zonal wind measurements. We can see some trends of the zonal wind increasing as the amplitude decreases. This is most likely caused by the winds becoming more zonal as waves decrease in amplitude. We also see that the zonal wind will increase in magnitude as the amplitude increases. This increase in the height contours would represent an increase in the pressure gradient force thus increasing the geostrophic wind.

Conclusion:

With this analysis, we have found many interesting trends in our data. For example, we have determined that Northern Hemisphere wave amplitude increased as it changed from summer to winter and that it is just the opposite for the Southern Hemisphere. This is due to the fact that more solar radiation is reaching the SH at this time, which keeps the polar jet from diving so far south during the summer months. We also found that zonal winds in the Northern hemisphere increased with time, while they decreased with time for the Southern hemisphere. This is also to be expected because as the NH moves toward winter, that jet stream will be able to reach further down toward the 50° latitude circle.

As for Rossby Wave Theory, we discovered many trends in our data that coincided with it very well, but as predicted, we also found that this theory is not perfect. In some cases, especially for the Southern hemisphere, there seemed to be trends which did not agree with the theory. This could be due to many things, but it is likely that there is some human error involved. Also, as was stated previously, the Rossby Wave Theory assumes barotropic conditions, which could also be the source of some error. Perhaps even the fact that the Southern hemisphere has less land mass, and therefore less friction, had something to do with the Rossby Wave Theory being less accurate in this region as well, but overall, we conclude that this theory is at least a good approximation for explaining real atmospheric waves.

Glossary:

Baroclinic- Conditions under which density varies with pressure and temperature.

Barotropic- Conditions under which density varies only with pressure.

Longwave- Represents a large disturbance in the atmosphere. It is also associated with a large wavelength about a latitude circle.

Shortwave- Represents a small disturbance in the atmosphere. It is also associated with a small wavelength about a latitude circle.

Zonal- A general flow pattern that is from West to East along Earth's lines of latitude.

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