# Atmospheric Waves

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Abstract

It is important for meteorologists to have an understanding of the synoptic scale waves that propagate thorough the atmosphere in order to better forecast global weather patterns. This can be done by comparing Rossby Wave Theory to a time series of observed variables that contribute to the movement and growth of synoptic waves. These synoptic waves mainly occur in the upper levels of the troposphere between 150 and 500 hectopascal (hPa). By studying the characteristics of the waves at these levels, we can obtain a rough idea as to how waves normally behave in the Northern and Southern Hemispheres. Characteristics of the waves included their wave number, amplitude, and motion along with observing the zonal winds at two levels. Some results of this study agreed with Rossby Wave Theory. However, possible errors in data collection and real world phenomena could be the cause of results that dispute the Rossby Wave Theory.

## 1. Introduction

Atmospheric waves are a critical part of synoptic scale meteorological forecasts. Although 500 hectopascal (hPa) flow can be zonal, small perturbations exists that cause troughs and ridges, leading to atmospheric waves. Long waves are usually characterized as covering a scale of 1000 Kilometers (km) while short waves span from 100 km to 1000 km. When atmospheric waves become long wave troughs, they carry large amounts of energy with them. This energy can lead to positive vorticity being advected in front of the trough, leading to upward motion of low level air. This lifting causes the air to expand and cool, frequently condensing water vapor into liquid water resulting in precipitation and can sometimes strong storms. With the additional energy available in long waves, the precipitation amounts tend to be larger. Short waves tend to confine their precipitation to a smaller region and carry less energy.

Zonal wind plays a large role in the forcing that drives atmospheric waves. When zonal flow is zero or negative, waves tend to retrograde across the hemisphere. This occurs more frequently with short waves. Additionally, when there is positive zonal flow, waves propagate from west to east.

Seasons can change the amount of waves and speed of the zonal winds. Generally, zonal winds are weakest in the summer months and strongest during the winter months. This is due to the strength of the temperature gradient in the winter months tending to cause more long waves than short. Additionally, a transition period occurs during the spring and fall. During the transition periods, an increase in wave numbers is observed.

Atmospheric waves can frequently be understood through the Rossby Wave Theory. This theory establishes how the wave number, amplitude, and motion interacts with each other. Wave motion can be characterized by the phase speed in the x - direction ($C_x$):

$$C_x = \frac{\nu}{k} = \bar{u} - \left(\frac{\beta}{k^2 + l^2}\right)$$

The $\bar{u}$ characterizes the zonal wind, β represents the planetary vorticity change with latitude, $k$ is the wave number in the x – direction, and $l$ is the wave number in the y – direction.

The hypothesis tested in the study is that observational zonal wind will diminish in magnitude during the summer months and intensify during the winter months in each hemisphere respectively; faster zonal winds will lead to a faster wave motion; and slower zonal winds will be observed during periods with high wave numbers.

## 2. Data and Methods

*A) Waves*

Daily wave data was taken from the Iowa State Environmental Mesonet website starting from September 2nd, 2013 through November 15th, 2013. At 500 (hPa) heights, wave motion, amplitude, and number were recorded through the observational period. Both the Southern and Northern Hemispheres were analyzed as wave flow was centered using the 50° latitude line. Wave motion, $M$, was calculated by taking the average longitudinal distance a wave travelled over a two day period.

$$(1)\ M = \frac{[lon(day+1) - lon(day-1)]}{2}$$

Wave amplitude, $A$, was calculated by taking the total average of the average N local height maxima, $A_T$, and average N local height minima for the day, $A_R$. Height maxima and minima were located in troughs that extended south of the 50° latitude line.

$$(2)\ A = \frac{[A_T - A_R]}{2}$$

$$(3)\ A_{min} = \frac{(A_R + A_R + \ldots + A_R)}{N}$$

$$(4)\ A_{max} = \frac{(A_T + A_T + \ldots + A_T)}{N}$$

Wave number was calculated to be half the number of times the 5580 m height contour crossed the hemisphere's respective 50° latitudinal line.

*B) Zonal Winds*

Zonal winds were also taken from the Iowa State Environmental Mesonet during the period of evaluation. A cross-section of the average east-west wind in longitude from surface to the top of the atmosphere was observed on a daily basis. Zonal winds at 50° latitude in each hemisphere were evaluated at the 500 hPa levels. Additionally, the layer in between 150 – 300 hPa was used to locate a maximum wind speed because this is the most common location of the jet stream. Locations with positive wind values indicate a west – east wind, while negative values indicated east – west winds.

*C) Accuracy and Limitations*

Several limitations and accuracy issues existed within the data collection process. When evaluating the amount of wave numbers located in each hemisphere, troughs that did not pass over the mandatory 50° latitude line, or could not be easily detected due to the coarseness of the map, were not counted. Additionally, cut-off low pressure systems existing in latitudinal regions that were less than 50 ° were not counted. Therefore, during specific events, the amount waves existing in the system as a whole could be underestimated. When determining wave motions, studying the movement of a single wave can slightly skew the average latitudinal movement for each wave over the 2 day period.

Limitations and inaccuracies also existed in the zonal wind evaluations. Since there was no clear way to locate the 50° latitudinal line, estimates on its location were made. Therefore, the exact location of the jet could be inaccurate. In several cases, a tight gradient (figure 1) existed. This made it challenging to accurately reflect what the wind speed was.

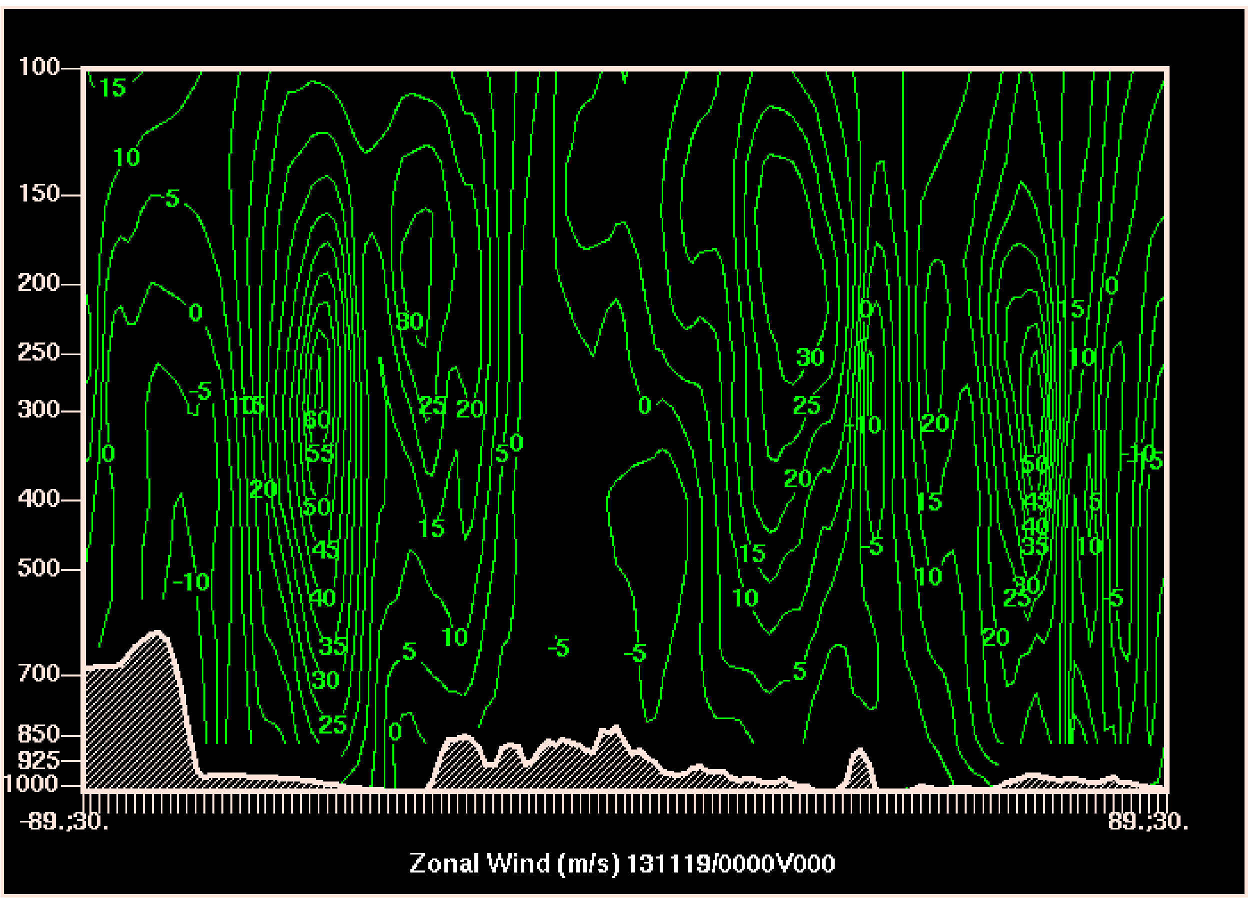


Figure 1: Example of the tight gradients that existed in the zonal wind measurements.
These tight gradients made it challenging to accurately reflect the wind speed.

## 3. Results

*A) Zonal Winds*

Zonal winds are a good indicator for the speed and the direction waves will propagate. Waves will propagate to the west or east with east or west with positive or negative zonal flow respectively.

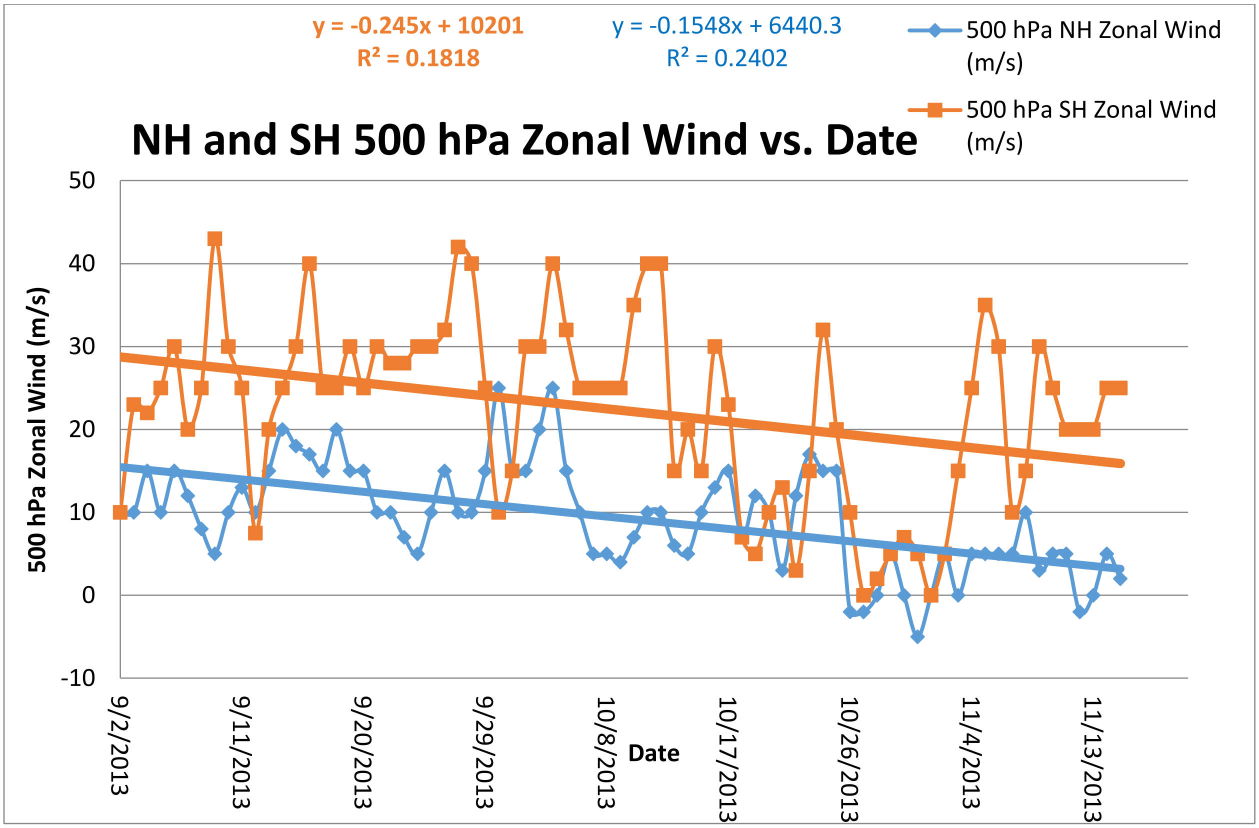


Figure 2: Representation of Northern and Southern Hemisphere zonal wind with time.

Zonal flow declined in both hemispheres partially which opposes our hypothesis. With the changing in seasons, a tighter temperature gradient will exist. This tighter temperature gradient creates a stronger pressure gradient force, which directly results in a stronger zonal wind. This process occurred in the Southern Hemisphere, but not the Northern Hemisphere. Errors made in the processing of the zonal wind data could account for this error.

The zonal wind in the Northern Hemisphere was less than the zonal winds located in the Southern Hemisphere. The average zonal wind observed in the Northern Hemisphere was 11.29 m/s. This is significantly slower than the 27.02 m/s observed in the Southern Hemisphere. One, potential explanation for this could be the large amount of topography seen in the Northern Hemisphere. The increased friction in the topographical features slow the zonal winds down.

The range of the zonal winds in the Southern Hemisphere were from 0 m/s to 43 m/s. Zonal winds in the Northern Hemisphere ranged from -5 m/s to 25 m/s. This illustrates the large range that can be observed in the Southern Hemisphere as opposed to the Northern Hemisphere. Also, the different $R^2$ values illustrate this large range. The most plausible explanation for this large swing in wind speeds again comes from the increase in friction seen in the Northern Hemisphere. The topographical effects slow down the zonal winds in the Northern Hemisphere.

The Northern Hemisphere zonal wind has an inverse relationship with the amplitude of the waves through time (represented in figure 3.) This trend is clear when analyzing the long term trend. Conversely, it is more challenging to see the short term trend. For example, on November 12-13, the wave amplitude increased significantly while the zonal wind speed diminished sharply. Yet, from October 10-12th, both the wave amplitude and zonal winds increased. Potential causes of this could be the magnitude of the observed increase. The increase in amplitude during the October case was minimal while the November case was significant. Additionally, there are times when the zonal wind speed increases sharply and the amplitude only decreases slightly. A good representation of this case is October 15th- 17th. During this time, the wave amplitude decreased by only 20 m while the zonal winds increased by 10 m/s. Although there is only a slight correlation, this does verify the Rossby Wave Theory. The Rossby Wave Theory states that a decrease in the zonal wind magnitude leads to a slower wave motion. This decrease in wave motion is correlated to smaller wave numbers which produces smaller amplitude. The opposite feedback occurs with there is an increase in the zonal wind magnitude.

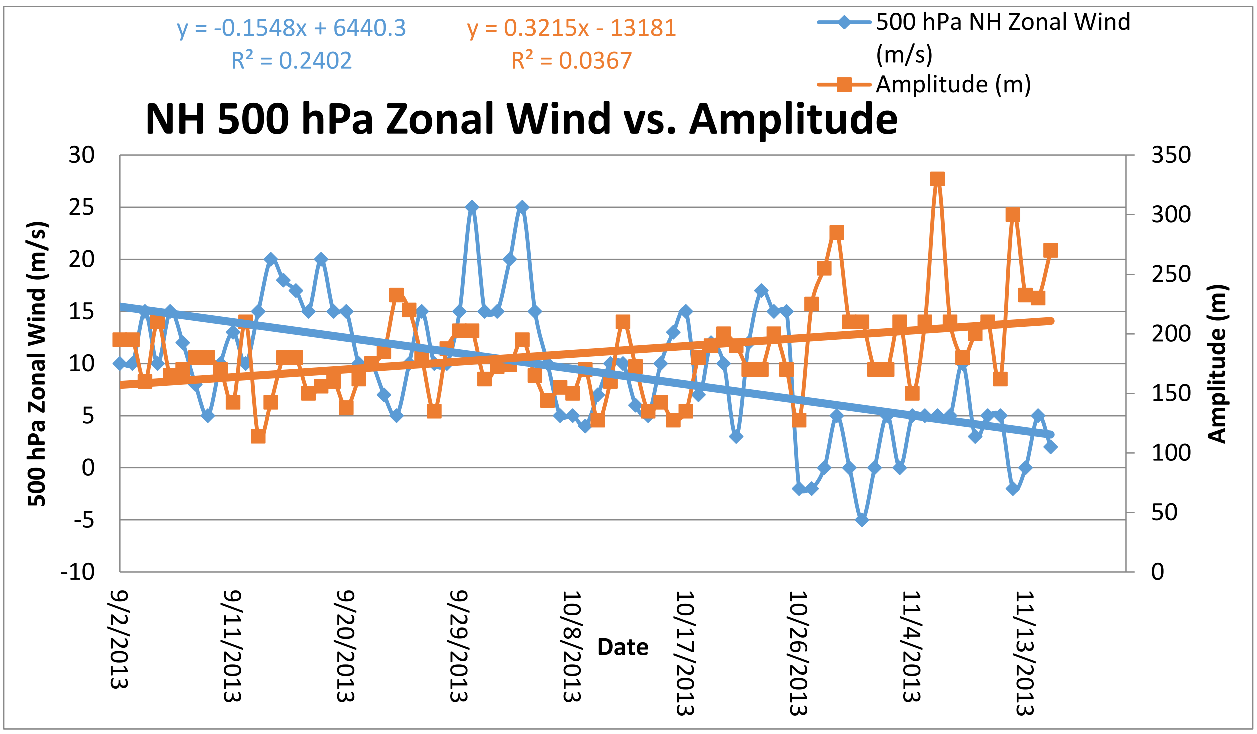


Figure 3: Northern Hemisphere zonal wind compared to wave amplitude as time progresses.

The same observation cannot be made in the Southern Hemisphere. The general trend of the wave amplitude decreases with time as the zonal wind decreases. However, the decreasing trend seen in the amplitude is almost zero and several short term cases verify the Rossby Wave Theory. Specifically, September 29th - 30th experienced a significant decline in the zonal wind speed while a substantial spike in the wave amplitude was observed. The inverse occurred a few days later when there was a local maximum in the zonal wind and a local minimum was observed in the amplitude. Finally, the Southern Hemisphere's slopes were lower in magnitude when compared to the Northern Hemisphere. A possible explanation for this could be due to the slower change in atmospheric conditions due to surface elements. The large continent of

Antarctica along with the higher sensible heat of water causes a dampening of seasonal changes. Thus, there is a smaller change as the seasons change in the Southern Hemisphere.

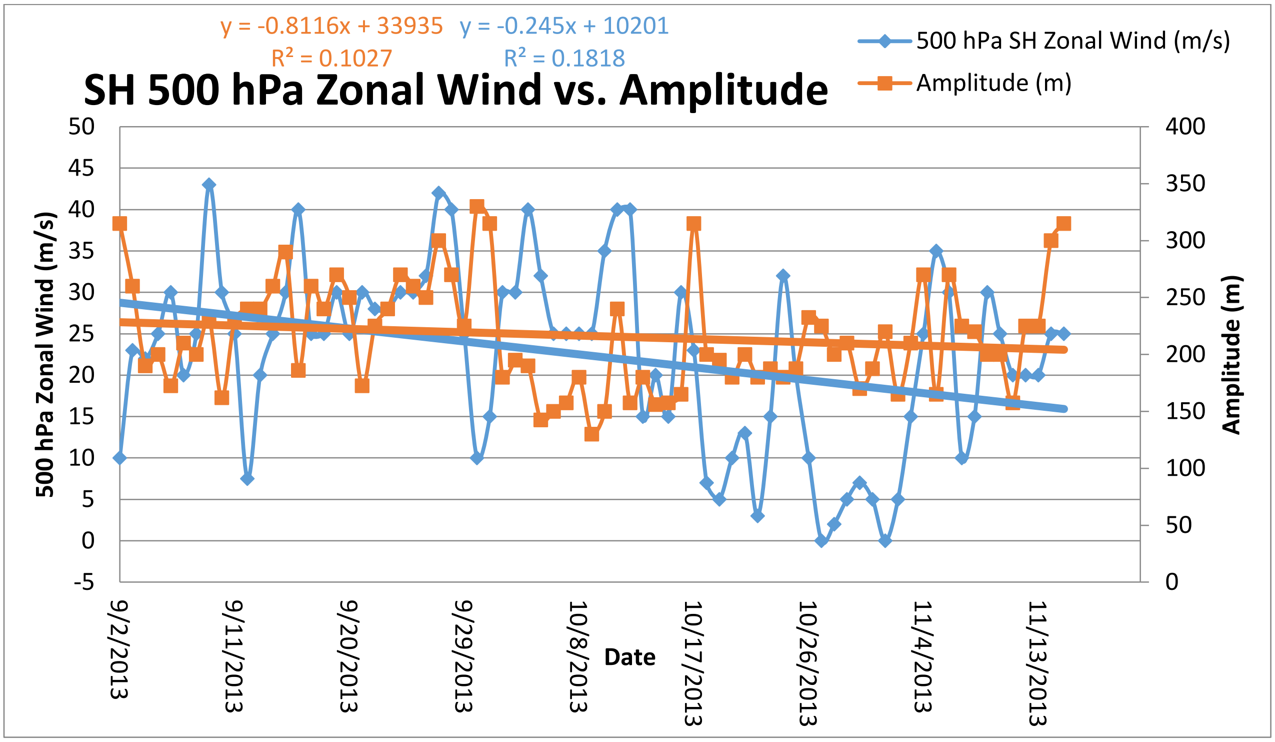

Figure 4: Southern Hemisphere zonal wind compared to wave amplitude as time progresses.

*B) Wave Amplitude*

Wave amplitude generally increases with time in the Northern Hemisphere (Figure 5) and decreases in the Southern Hemisphere (Figure 6). This agrees with theory as the wave amplitudes increase while the wave numbers decrease through time.

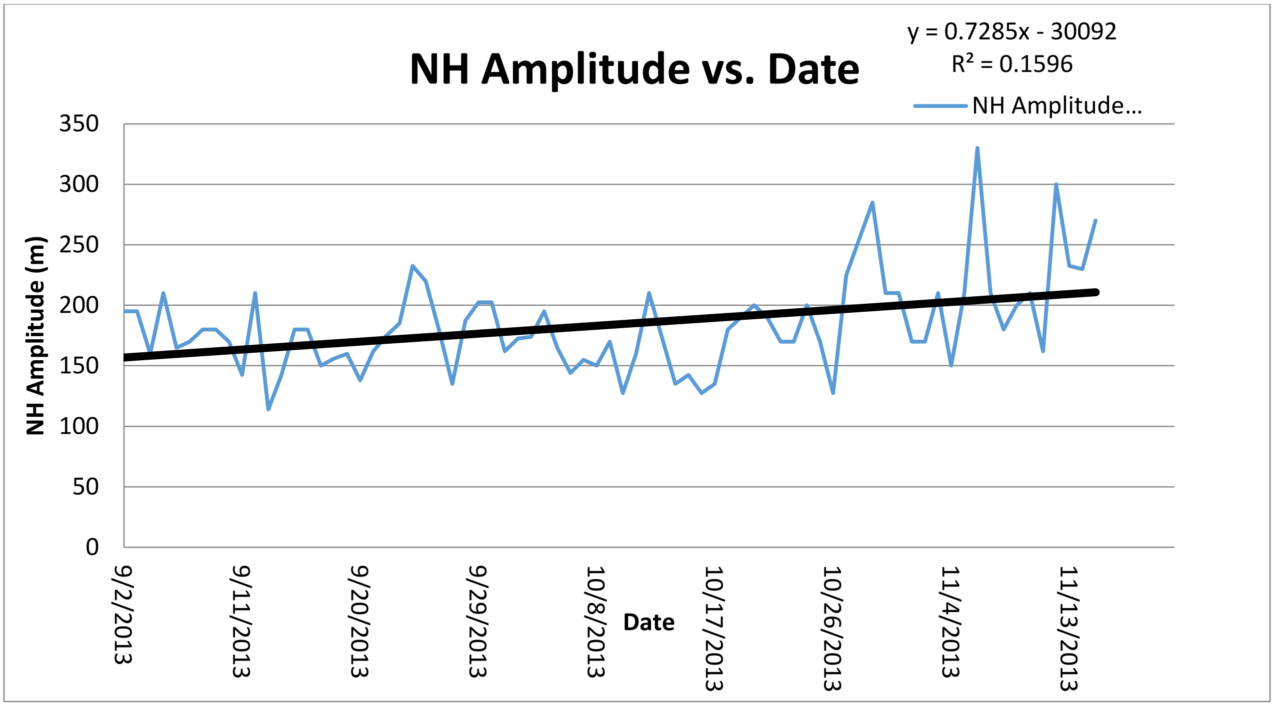

Figure 5: Northern Hemisphere Amplitude through the observed period

The Northern Hemisphere encountered a larger range in the amplitudes than the Southern Hemisphere. The maximum amplitude recorded during the testing period was 330 meters in both hemispheres. However, the minimum amplitude in the Northern Hemisphere was 114 meters while the Southern Hemisphere's minimum was 130 meters. This range is fairly consistent in the Southern Hemisphere throughout the domain, but it increases later in the period in the Northern Hemisphere.

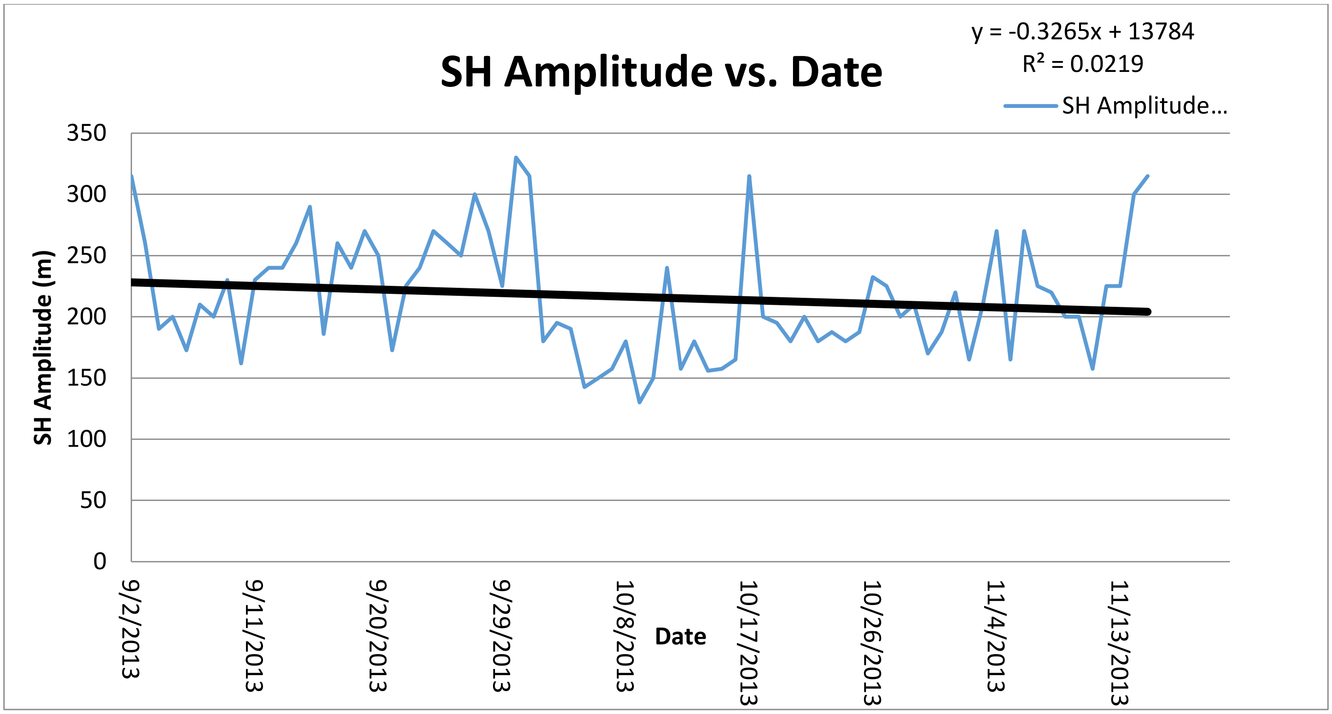


Figure 6: Southern Hemisphere amplitude decreases slightly through the observed period

Each hemisphere encounters periods of growth and decay and both trends can be evaluated when overlaying the amplitudes of both hemispheres (Figure 7). Generally, growth and decay periods are around 2-3 days independently with fluctuations embedded in between. On October 16$^{th}$ - 17$^{th}$, the Southern Hemisphere encountered a 90% growth increase of 150 meters. The sharpest increase in the Northern Hemisphere was from November 4$^{th}$ – 6$^{th}$ where the amplitude grew by 187% to 330 meters. Both of these cases were extremes and coincided with low wave number periods. Finally, there is a noticeable trend between the two hemispheres amplitudes. Frequently, the local maximum and minimums line up around the same time for each hemisphere.

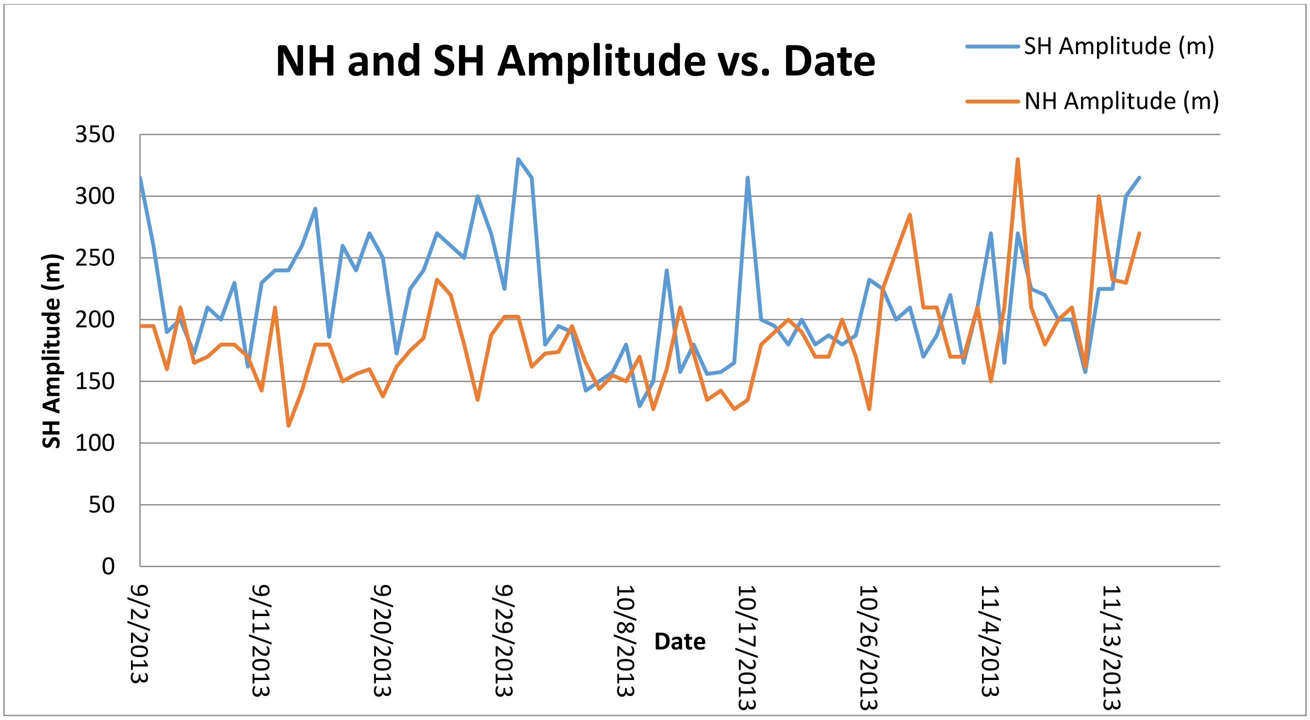


Figure 7: Northern and Southern Amplitude vs. Time

*C) Wave Number*

Wave numbers decreased over the domain in both hemispheres. The rate of declination is faster in the Northern Hemisphere (Figure 8) in comparison to the Southern Hemisphere (Figure 9). Despite this difference, at the end of the domain, there is a sharp increase of wave numbers in the Northern Hemisphere. The opposite occurs in the Southern Hemisphere where there is a sharp decline in wave numbers.

In the Northern Hemisphere, the amount of wave numbers range from one to six at a specific time. Towards the beginning of the domain, fluctuations seem to be quicker. For example, from September 11th – 13th, the wave number drops from four to two, then up to five. The overall change is an increase to five as a wave number, but this is a rapid change over the three days in comparison to later dates. From October 11th – 31st, the wave period changed from three waves to two. This change came at a rate of almost one wave for every five days.

A similar observation can be made in the Southern Hemisphere. Wave numbers fluctuated rapidly throughout the first half of the domain, followed by a dampening effect during the second half off the period. Examples include the rapid change from September 19th – 28th and slow change from October 22nd – 27th. Additionally, each hemisphere experienced a 150% increase in wave numbers over one day. This is an extreme case for each hemisphere.

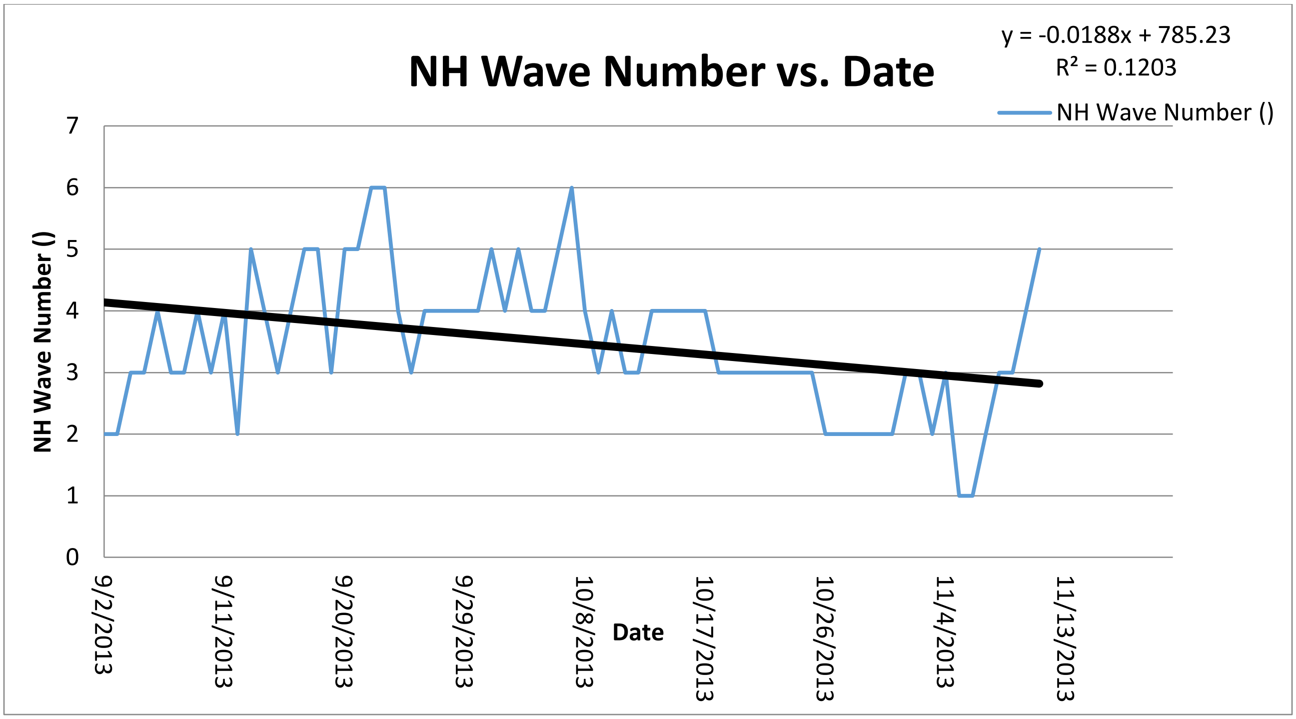


Figure 8: Northern Hemisphere Wave Number vs. Date

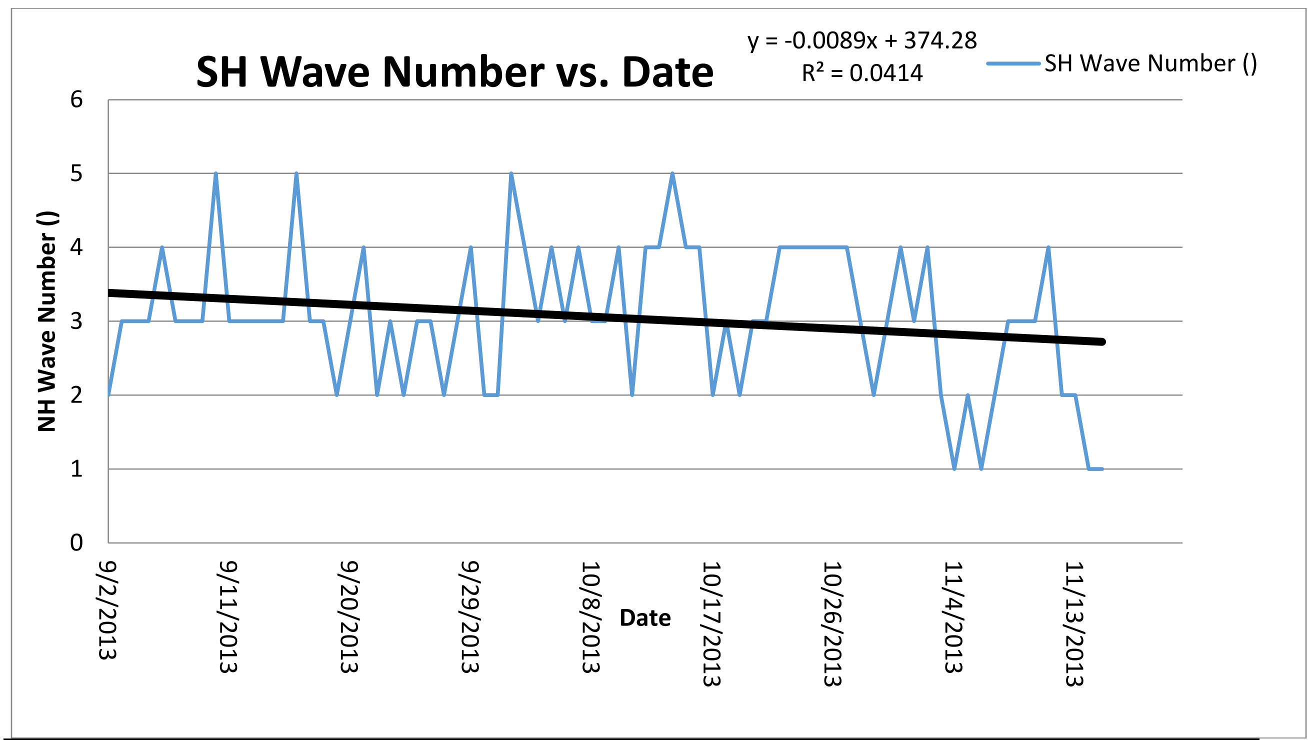


Figure 9: Southern Hemisphere Wave Number vs. Date

Wave amplitude decreased while the wave number increased in both the Northern and Southern Hemispheres. This represents the dependence the amplitude has on the wave number. As wave number increases, the amplitude decreases (more small waves) which have less energy within them to agree with the conservation of energy. Hence, the Rossby Wave Theory is validated through this process. The opposite reaction occurs when you increase the amount of wave numbers.

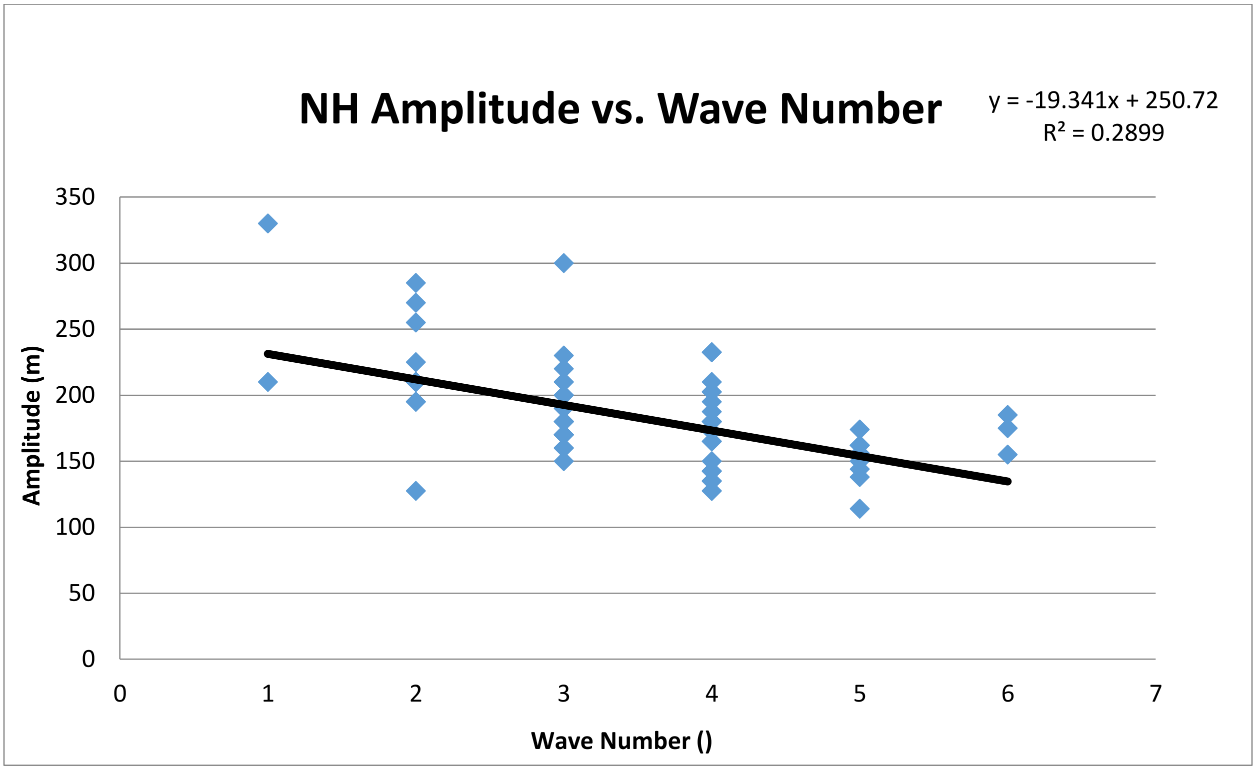


Figure 10: Northern Hemisphere Amplitude vs. Wave Number

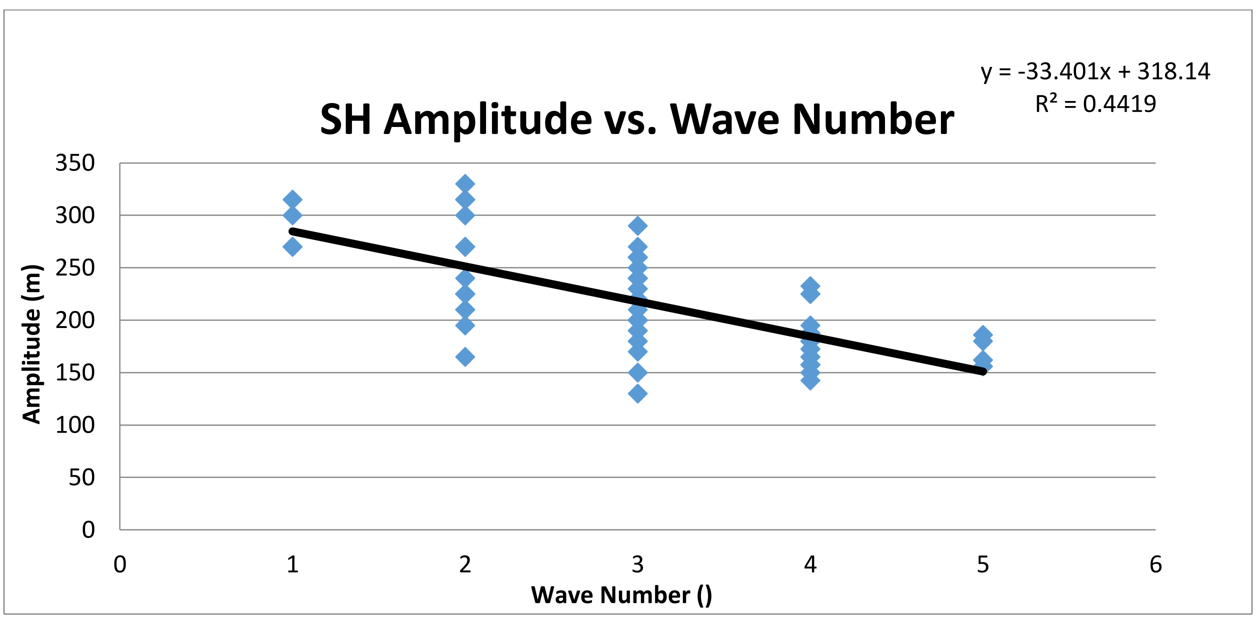


Figure 11: Southern Hemisphere Amplitude vs. Wave Number

*D) Wave Motion*

There is a difference in both hemispheres in the relationship between wave motion and wave number. In the Northern Hemisphere, there is a decrease in the wave motion as the wave number increases (Figure 12). With more waves present, the wave length decreases. This shows that as the wave length decreases, the speed of the wave decreases as well.

In the Southern Hemisphere, however, there is an increase in the wave speed as the number of the waves increases (Figure 13). This disagrees with the conclusion that could be drawn in the Northern Hemisphere. In the Southern Hemisphere, larger wave numbers result in smaller wave lengths, and the smaller wave lengths result in faster wave speed.

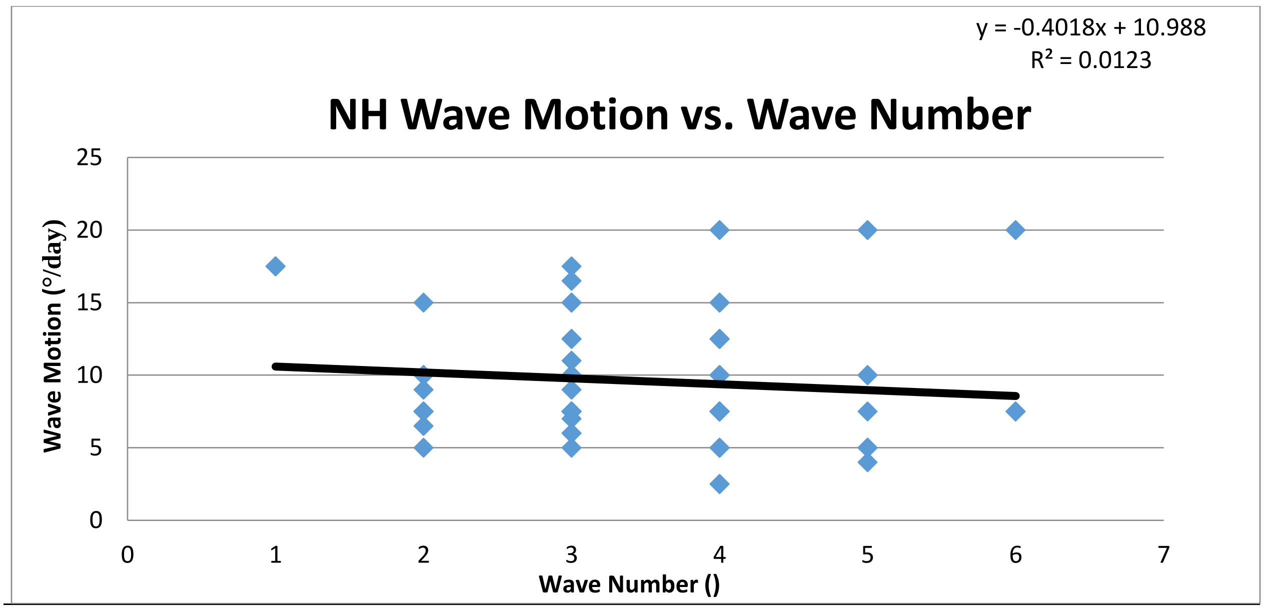


Figure 12: Northern Hemisphere Wave Motion vs. Wave Number

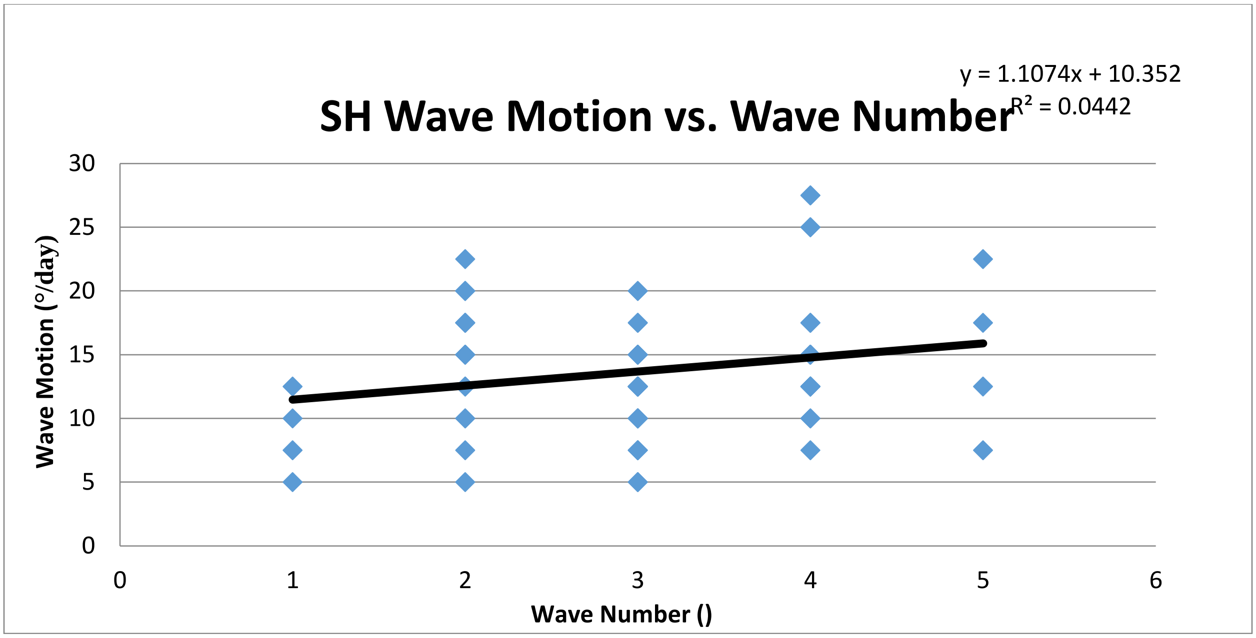

Figure 13: Southern Hemisphere Wave Motion vs. Wave Number

There is also a difference in the relationship between wave motion and 500 hPa zonal winds in the Northern and Southern Hemispheres. In the Northern Hemisphere, there is a decline in the wave motion as the 500 hPa zonal winds increase. This disagrees with the Rossby Wave Theory. With stronger zonal winds to the east, the waves should propagate faster to the east. If there is zonal wind in the west direction or zonal winds less than 3m/s, then there would be a more westward propagation. This was not the case in the Northern Hemisphere.

In the Southern Hemisphere, there is a positive correlation with the two parameters. This agrees with the Rossby Wave Theory. With stronger 500 hPa zonal winds to the west, there is an increase in the propagation of the waves to the west.

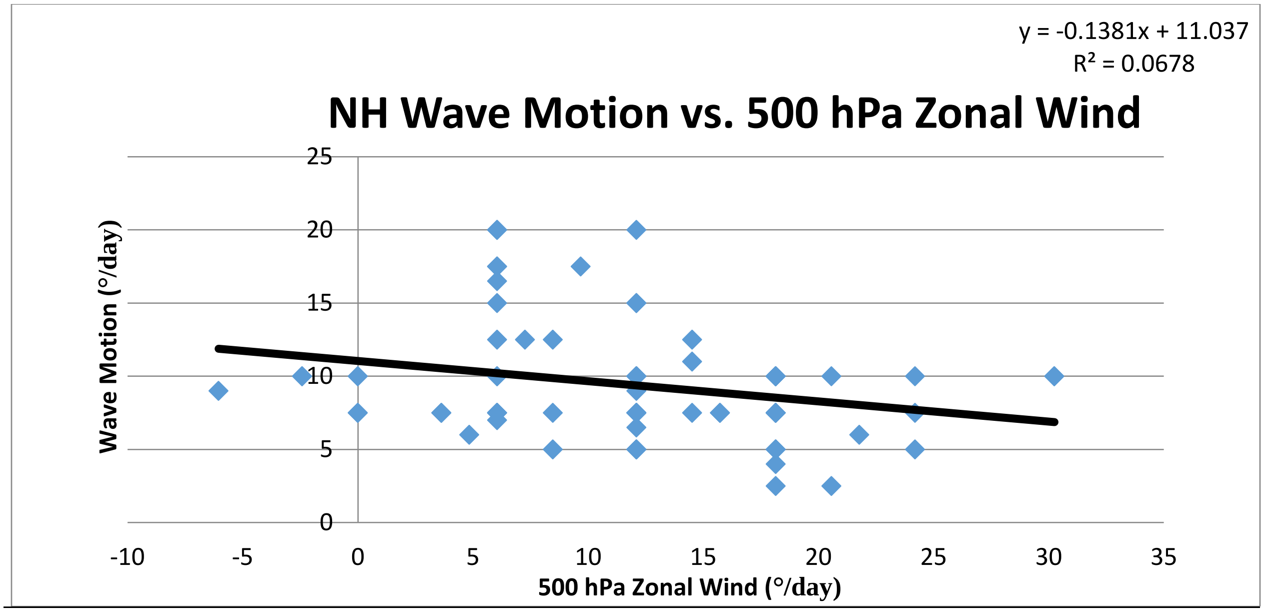


Figure 14: Northern Hemisphere Wave Motion vs. 500 hPa Zonal Wind

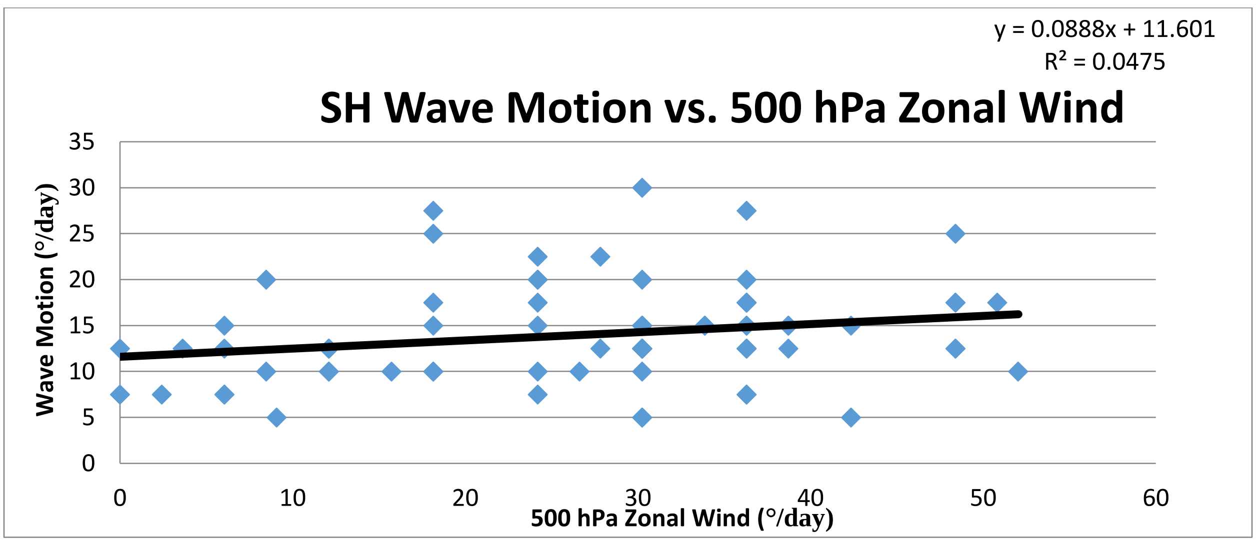


Figure 15: Southern Hemisphere Wave Motion vs. 500 hPa Zonal Wind

There is also a relationship between the wave motion and the 300-150 hPa zonal winds. For the Northern Hemisphere, there is relatively no correlation between the wave motion and the 300-150 hPa zonal winds. This disagrees with the Rossby Wave Theory in that there should be a positive correlation between the two parameters.

For the Southern Hemisphere, there is a positive correlation between the wave motion and the 300-150 hPa zonal wind. This agrees with the Rossby Wave Theory with an increase in the 300-150 hPa zonal winds resulting in an increase in the wave motion.

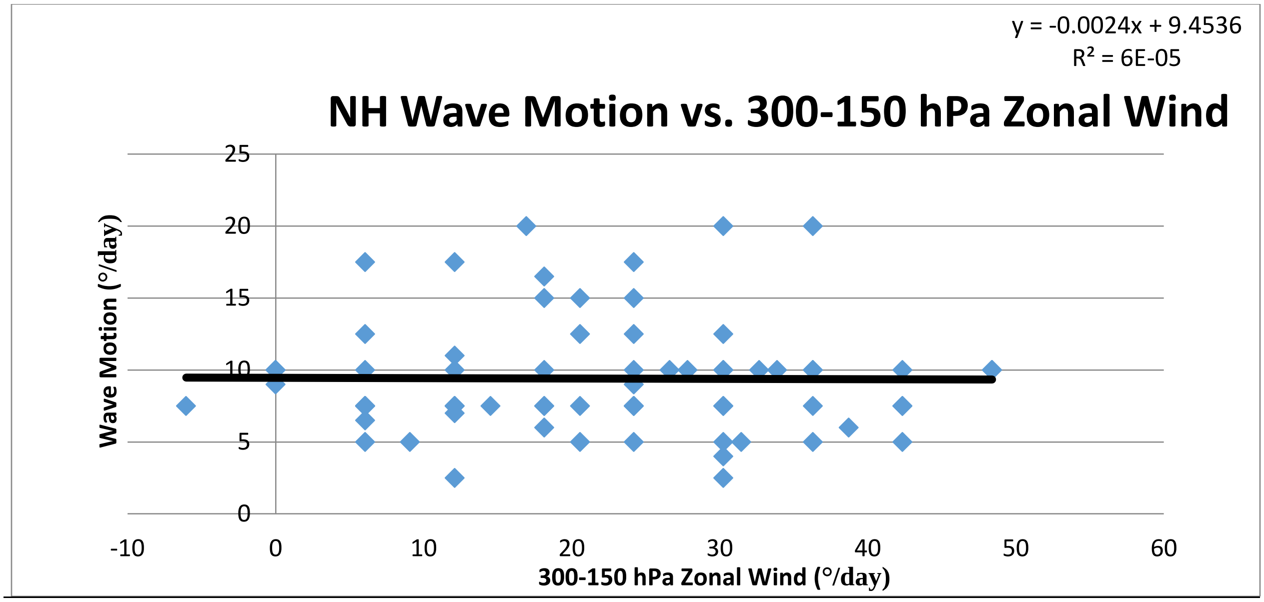


Figure 16: Northern Hemisphere Wave Motion vs. 300-150 hPa Zonal Wind

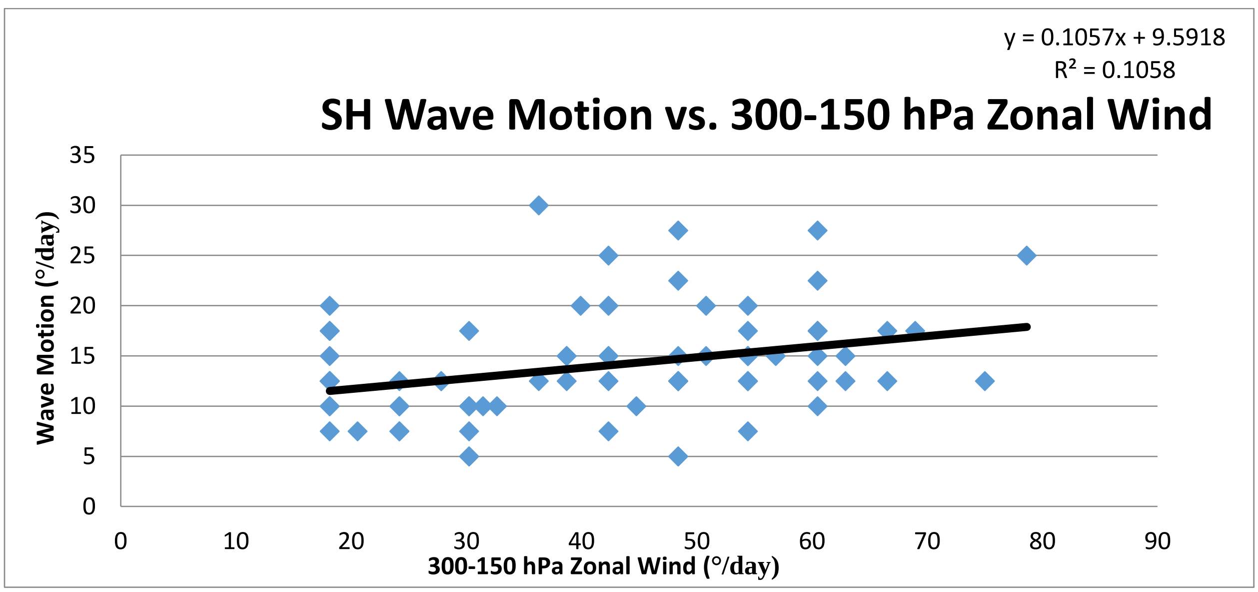


Figure 17: Southern Hemisphere Wave Motion vs. 300-150 hPa Zonal Wind

*E) Thermal Wind*

The relationship between wind and horizontal temperature gradients says that that there will be a change in the geostrophic wind with height when a horizontal temperature gradient is present. Winds at lower pressures will be greater than the winds at higher pressures. The results presented in Figure 18 and Figure 19 support the relationship. Mostly all of the wind speeds in the 300-150 hPa layer are greater than the wind speeds in the 500 hPa layer.

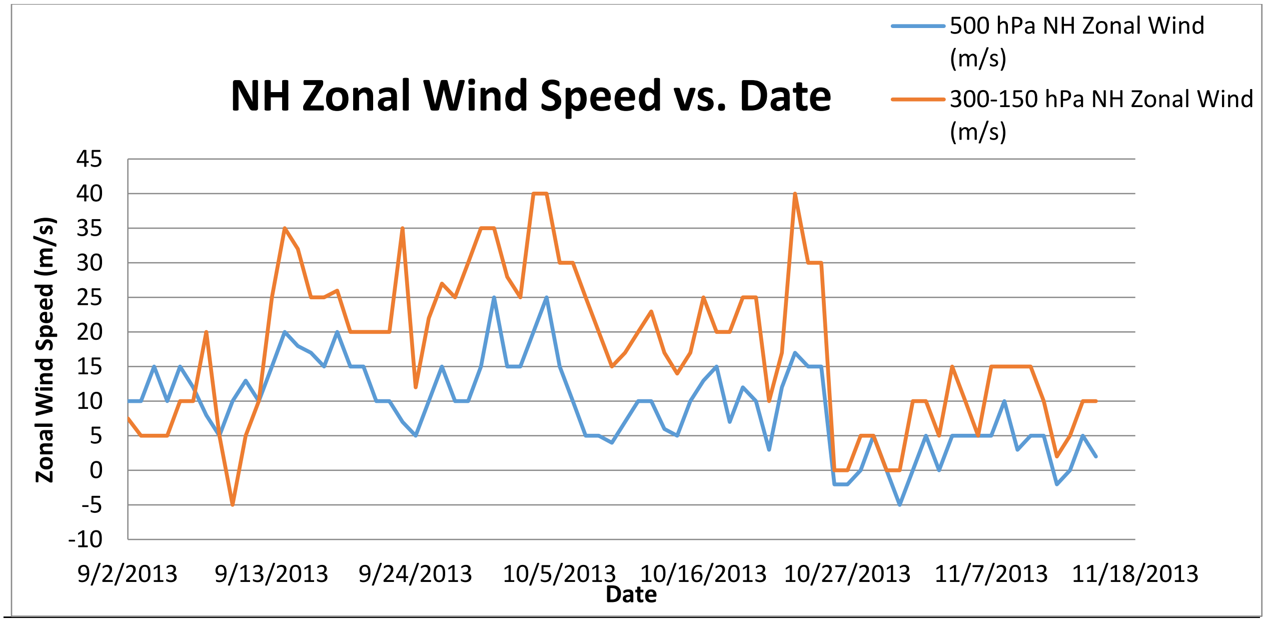


Figure 18: Northern Hemisphere Zonal Wind Speed vs. Date

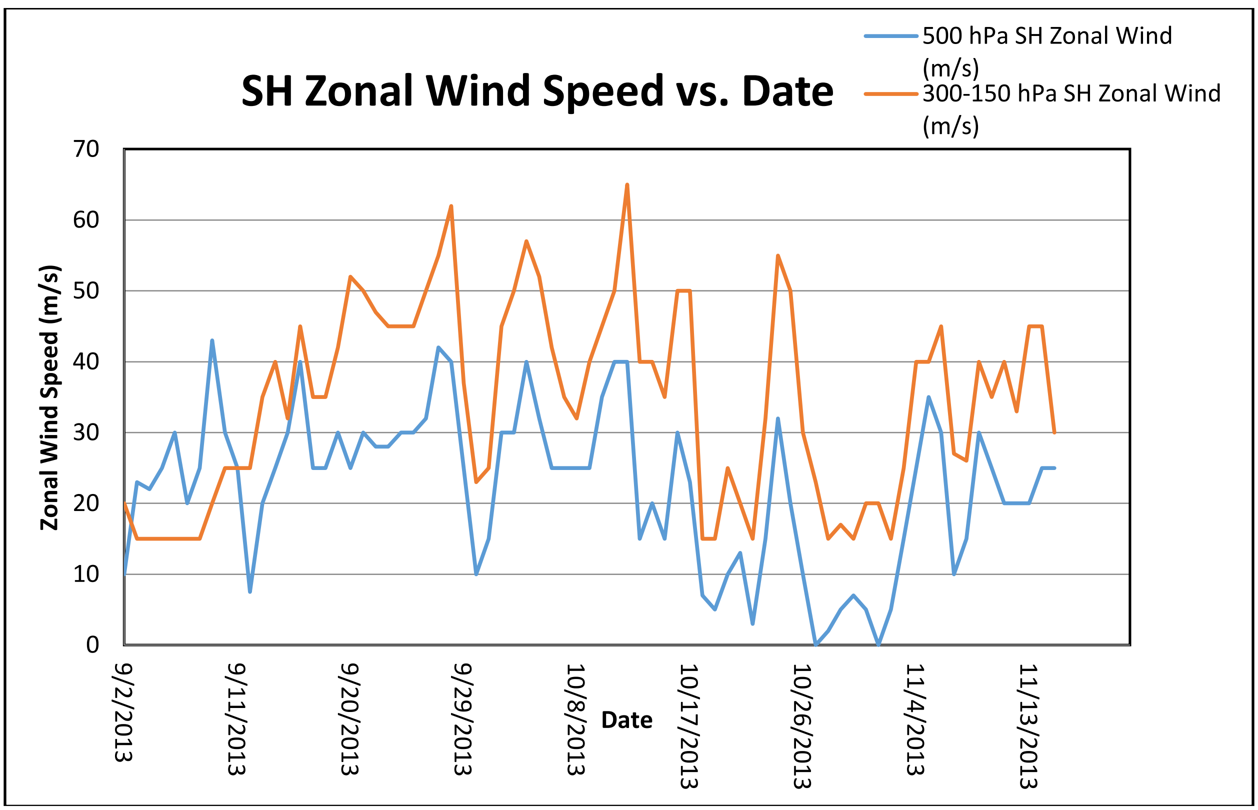


Figure 19: Southern Hemisphere Zonal Wind Speed vs. Date

## 4. Conclusion

After the evaluation of the waves in the Northern and Southern Hemisphere, the results of the study have varied agreements in Rossby Wave Theory. Results that showed agreement in the both hemispheres were amplitude vs. time, wave number vs. amplitude, a very slight correlation for 500 hPa zonal winds vs. amplitude, and a positive change in zonal wind between the 500 hPa and 300-150 hPa levels. All disagreements in Rossby Wave Theory occurred in the Northern Hemisphere, such as wave motion vs. wave number and wave motion vs. zonal winds. No disagreements to the theory occurred in the Southern Hemisphere. The disagreements in the Northern Hemisphere were most likely caused by the subjective analysis of the wave motion, which can become skewed depending on the average motion of the waves during the specific period. The hypothesis for this study was partially supported as zonal winds did not increase over time in the Northern Hemisphere, but decreased over time in the Southern Hemisphere. The reason for a failed hypothesis could be caused by the subjective analysis of the zonal wind, as the 50° latitude line is not labeled on the maps. Regardless, there is bound to be errors when calculating values from maps that do not display a specific variable. There is no perfect strategy for analyzing waves, even when using the Rossby Wave Theory. But, this study proves the theory is still a good tool to allow meteorologists to forecast wave propagations in the atmosphere more accurately while knowing its limitations.

## References

Holton, James R. An Introduction to Dynamic Meteorology Fourth Edition. Burlington: Elsevier Inc., 2004. Print.