INVESTIGATING THE LINK BETWEEN ARCTIC SEA ICE, NORTH PACIFIC GEOPOTENTIAL HEIGHT ANOMALIES, AND PRECIPITATION ACROSS THE UNITED STATES

BY

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THESIS

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ABSTRACT

New evidence is presented to show that decreasing sea ice in the Arctic is causing an increased amplification of the jet stream off the west coast of the United States. We find a statistically significant relationship between sea ice north of Alaska and geopotential height anomalies during the following winter and spring months. We also show that these semi-persistent height anomalies are increasing in frequency in these locations independent of long term ocean cycles, such as ENSO and PDO. These height anomalies cause more persistent precipitation patterns to certain regions of the United States and we discuss these teleconnections as well as their impacts. These results suggest that as the Arctic, specifically the region north of Alaska, continues to decrease in sea ice coverage a more persistent ridge will form in areas adjacent to this location and affect storm track to the continental United States.

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CHAPTER 1

INTRODUCTION

Projecting future changes in upper level wave patterns is an important, yet challenging, research area. Arctic Amplification is the idea that over the past several decades the Arctic has been warming a rate much greater than that in the mid-latitudes. It has been widely speculated that Arctic Amplification is not only resulting in a rapid melting of Arctic sea ice especially during the summer months, but could also be causing a more amplified jet stream (e.g., Francis et al 2009). A more amplified planetary wave pattern tends to result in more regional weather extremes, such as an increase frequency of precipitation anomalies and extreme temperatures (Screen and Simmonds, 2014, Overland et al., 2015). While model results have yielded some evidence that low sea ice summers in the Arctic should contribute to increased planetary wave amplification, the observational evidence remains somewhat inconclusive and highly debated (Screen et al., 2012, Mori et al., 2014, Jaiser et al., 2011, Porter et al., 2011, and references therein).

This study examines the connection between sea ice concentration in the Beaufort and Chukchi Seas north of Alaska and height anomalies in the following winter and early spring using NCEP reanalysis data. A similar study was performed by Mori et al in 2014. They ran model simulations, as well as looking at the European reanalysis, and concluded that changes in the Berents-Kara Sea ice concentration is affecting jet stream amplitude in Eurasian (Also, see: Inoue et al. 2012). That study also found there are downstream implications to localized amplification that our study evaluates for North America. Most of the atmospheric wave amplification in modeling studies has the common theme of occurring within close proximity to summer sea ice loss (e.g., Screen et al., 2012). Bhatt et al (2008) used an atmospheric general circulation model to study low summer sea ice years and its impacts on storm tracks in the Pacific during the following seasons, much like what this research aims to show with reanalysis data.

They found that the ice anomalies caused higher upper level heights in the N. Pacific that was accompanied by decreased precipitation north of the Pacific storm track. Modeling studies have been beneficial in this area because observational evidence is challenging due to the short time scales over which reanalysis and satellite data have both been available and reliable. With that being said, recent research has shown some robust changes in atmospheric circulation using reanalysis data (e.g., Francis and Vavrus 2014). Francis et al (2009) found that there are higher geopotential height anomalies during the winter in close proximity to low summer sea ice locations from the previous year. In a study using the Weather Research & Forecasting (WRF) regional model, Porter et al. (2011) found that low ice years and subsequent higher sea surface temperature can store much more energy during the summer and autumn months in these locations. The surface energy budget changes in sea ice free summers is hypothesized as the reason for changes in atmospheric circulation in the following seasons (Porter et al. 2011; Overland and Wang 2009; Screen et al. 2012).

The primary objective of this study is to find out if these evolving upper level patterns in planetary waves can be subsequently affecting the precipitation patterns regionally across the United States, specifically during late winter and early spring. The primary focus will be on a potentially strengthening of the upper level ridge that has been forming during these months off the west coast of the U.S. Late winter was chosen as the time period because previous studies have concluded that winter wave patterns are affected by summer sea ice concentration (e.g., Francis and Vavrus 2012; Francis et al 2009); we aim to test this hypothesis in the Pacific Ocean. Coumou et al. (2015) showed that the influence of Arctic Amplification on the wave patterns has not just been confined to winter and autumn. It is for this reason we chose to extend our analysis into early spring. To start, the teleconnections of recent trends in height anomalies across the eastern Pacific Ocean with regional precipitation are examined. Next, it is important to determine if a robust climate signal points to connections between localized sea ice concentration and increasing height anomalies. This research will examine the possibility that, even without the effect of long-term ocean cycles, there is still a strengthening ridge south of Alaska that can be correlated with rapid sea ice loss over the previous three decades. Outside of the seasonal forecasting applications this research could have, it will be important to determine if potential long term ridging in the Pacific Ocean during these winter and early spring months could have lasting impacts on regional precipitation patterns.

CHAPTER 2

METHODOLOGY

2.1. Teleconnections on Precipitation

Because the jet stream is never constant in time and space, it can be assumed that subsequent geopotential height anomalies will not be in the same location on time scales as long as a season (Archer and Caldeira, 2008). For this reason, looking at the same location over the course of a traditional three month season for changing height anomalies can sometimes be misleading. This occurs because of the northward shifting jet stream toward the end of winter into the warmer spring months (Archer and Caldeira, 2008) that will cause any potential height anomaly (reflecting an amplified wave pattern) to form in different locations. Barnes et al. have shown as recently as 2013 that blocking frequency has not increased in a fixed location and used the Pacific Ocean, west of the United States, as one of their domains. Our goal is not to pick one grid box and show that blocking patterns have increased or decreased at that location, but rather, to show that several consecutive months have experienced increased ridging over the past couple decades in similar locations. It can be hypothesized that, despite a ridge being centered at slightly different locations from month to month, there will still be climate altering affects to regional precipitation from a semi-persistent ridge and that this can be partially related to sea ice loss in nearby locations. Rather than looking at one grid box for several consecutive months, this research looks first to see where recent height anomalies are taking place each month before choosing our domain of interest for that particular month. Where there are increased height anomalies, it can be hypothesized that these locations have increased atmospheric wave amplification (Francis and Vavrus, 2012).

To test the hypothesis that winter wave patterns are affected by summer sea ice extent for our domain, January through April (JFMA) are examined on a monthly basis to determine where there are changes in the 500 hpa geopotential height fields. To do this, geopotential height fields from the past 12 years are compared to the previous 24 years using the NCEP-DOE AMIP-II Reanalysis (R-2) data set with a monthly time scale (Kanamitsu et al., 2002). R-2 extends from 1979 to present; the entire period incorporates data retrieved from satellites, which is important for regions that have limited observations, like the Pacific Ocean.

Recent research on changes in upper level synoptic scale features show that the last decade and a half has yielded the largest changes in upper level patterns compared to the last several decades. (Screen and Simmonds 2012, Francis and Vavrus 2012 and references therein) This research will examine the possibility that if changes in the synoptic pattern are observed in our domain that localized rapidly decreasing sea ice during the last two decades in parts of the Beaufort and Chukchi seas north of Alaska could partially be to blame.

Figure 1 shows the height anomalies for the past 12 years compared with the previous two and half decades from R-2. Using the maps in Figure 1, we have selected areas of the North Pacific that show increasing geopotential height anomalies in the past 12 years that direct us to potential areas of wave amplification. It should be noted that no results are gathered from this part, but rather, these maps in figure 1 are used as a guide to areas of interest that will be the focus of the statistical analysis. This method is similar to past studies that look at height anomalies within grid boxes in the North Pacific (e.g., Barnes et al. 2014). The differences here are, since the locations of the wave amplification change over the course of a three month time span, the grid boxes of interest are adjusted slightly on a monthly time scale. If it can be shown that the wave pattern is amplifying at these locations, then the teleconnections these anomalies have on downstream precipitation patterns for that month will be valuable information. Figure 1 shows these grid box locations along with the geopotential height anomalies for each of the four months. For the most part, the grid box location does not vary significantly from month to month with location as they are mostly focused west of the continental United States in between the southern coast of Alaska and the northeastern edge of Hawaii.

Using these grid boxes, we then determine how significantly height anomalies within these grid boxes affect the precipitation in 8 climate regions across the continental U.S. (CONUS). Within each grid box, we count the number of times each year during the specified month that a grid point is greater than a set number of standard deviations from the seasonal mean. The seasonal mean is found by taking the monthly mean for each year in the entire box and then averaging those values for the entire period of 1979-2014. The standard deviation threshold is selected based on the size of the box. For example, for most grid boxes, we will count the grid points that are >3 standard deviations away from the seasonal mean during the month for each of the 36 years. Three is used as the standard deviation threshold in most cases because it gives us the most information about the extremes in geopotential height from the probability density function (PDF); meaning we are looking at the right tail of the PDF curve. Once again, the goal is not trying to determine if there are increases in blocking frequency, but to look at how amplified the upper level pattern was during each year for these months. Blocking frequencies depend on meeting specific criteria for several consecutive days (Barnes et al. 2014) and there will be no temporal component to the standard deviation count.

Precipitation patterns in the climate regions across the U.S. are tested for correlation to the geopotential height anomalies at these locations. Similar to previous studies linking low sea ice to effects on storm track, this research is essentially looking at how height anomalies in these locations affect storm track across the CONUS (e.g., Bhatt et al. 2008; Screen 2013; Inoue et al 2012). This is done by testing the statistical significance of the correlation coefficient between monthly precipitation data and the number of times grid points that reach the standard deviation threshold. The goal in the discussion below is to show that height anomalies within these grid boxes can directly affect the precipitation throughout some regions of the U.S., but that it is regionally dependent. The monthly precipitation data is retrieved from NCDC data available online (http://www.ncdc.noaa.gov). The values for each year provide the precipitation anomaly within each of the 8 climate regions with a base period of a 1901-1950. Using anomaly values helps make the results more clear when determining how geopotential height anomalies negatively or positively affect regional precipitation. Therefore, the correlation being tested is the number of grid points that were greater than the standard deviation threshold and the region's precipitation anomaly for that corresponding year. To determine if the correlation is statistically significant, we use the student t test equation.

2.2. Accounting for long-term ocean cycles

After determining the teleconnections geopotential height anomalies have on the precipitation patterns for the United States, we test to see if there is statistical significance to the geopotential height anomalies within the grid box as a function of time. Since the time period is restricted to 36 years for this research, the roles that the Southern Oscillation Index (SOI) and Pacific Decadal Oscillation (PDO) play on these geopotential height anomalies cannot be ignored. McCabe et al. (2003) have shown that SOI and PDO will have strong impacts on geopotential height anomalies due to the two indices' effects on decadal sea surface temperature in the Pacific Ocean, which has been linked to multi-decadal droughts in the United States. Despite relatively high small scale time variability, SOI and PDO have been shown to have multi-decadal cycles between primary negative and positive phases over the past century (McCabe et al. 2003; Kumar et al. 2012). Monthly SOI and PDO values were retrieved from the National Oceanic and Atmospheric Administartion (NOAA) teleconnections page (https://www.ncdc.noaa.gov/teleconnections). During the time period for this analysis, SOI shifts from primarily negative values, indicative of El Niño, to primarily positive La Niña years in the 2000s. This could lead to signals of false increases in the geopotential height anomaly count within the focus area.

There is no conclusive evidence on whether or not SOI will become more positive or negative in a warmer climate. It is important to consider both the statistical significance between the grid box count and time with the effects of these ocean cycles as well as to look at the changes after reducing the role SOI plays on the height fields in these locations. Kumar et al found that in a 500-year climate simulation the no-ENSO run yielded greater variability in PDO than the high amount of variability we already see with the index. Our research also shows that there is a significant correlation between the two indices at these locations. In order to investigate whether strong SOI values can cause a subsequently high PDO, or vice versa, we focus on scaling out the effect SOI has on our height anomalies. Since we find they are mostly inversely proportional to one another at these locations, empirically removing the effects of SOI should also mostly diminish the affect PDO has on the geopotential height in these locations as well. To do this we use the equation:

$$zcount_{adjust} = zcount_{original} - \left(\left(|SOI_x| * \overline{zcount} \right)^{\frac{1}{2}} * \frac{SOI_x}{|SOI_x|} * 10r^3 \right)$$

where $zcount_{original}$ is the number of times the standard deviation threshold is met by a grid point during the month. SOI_x is the SOI index value for the month x, zcount with a bar above it is the average count for all 36 years, and r is the correlation coefficient between SOI index and $zcount_{original}$ for that particular gird box.

Equation 1 reduces the role SOI has on the geopotential height field in these boxes. A positive SOI (La Niña) index acted to significantly increase the seasonal geopotential height count in these grid boxes. It is for this reason the right term in equation 1 was subtracted from $zcount_{original}$. Subtracting the first two terms on the right side of the equation diminishes the effects of SOI on the grid boxes, but in areas that were highly correlated to SOI there was still a statistically significant contribution from SOI on height anomalies. A scale factor based on how correlated the grid box count was to SOI was then added to equation 1 ($10\,r^3$), where r is the correlation coefficient. This empirically reduces the influence of SOI for all grid boxes within all four months to near a correlation coefficient value of zero. This tells us the robust climate signal without the influence of this long term ocean cycle. Inversely, if the entire third term was added to the $zcount_{original}$ then this would act to increase the influence of SOI on the height anomalies, but that does not provide useful results for this study.

Time series for both the $zcount_{orginal}$ and the SOI adjusted grid box count ($zcount_{adjust}$) are analyzed using yearly means and running means of 5 and 8. Running means are both valid and necessary for this analysis because the year to year variability is too great to determine if there is a climate signal or trend based off yearly data. The statistical significance between the count in each grid box and time are then tested to determine if there are robust increases in height anomalies for the grid boxes. Like with regional precipitation, the student t test is used to do this, but the degrees of freedom will be less than before when looking at the running means. For example, a 5 year running mean will have less degrees of freedom for a 36 year time period than the simple yearly mean.

As discussed above, the focus of this research is on linking diminishing sea ice concentration in the Arctic to planetary wave amplification across much of the Northern Hemisphere. Using this concept, we examine if there is statistical significance to sea ice north of Alaska during August and September to height anomalies within our grid boxes during the winter and early spring. The highest connection to late summer sea ice concentration and height anomalies should be during the wintertime based on results from previous work (e.g., Francis et al, 2009). Monthly sea ice concentration was determined using the R-2 data set for consistency. To do this, the average ice concentration of grid points within a 10 latitude by 30 longitude degree grid box for August is added to the values for September for a region north of Alaska in parts of the Arctic Ocean, Beaufort Sea, and the Chukchi Sea.

CHAPTER 3

RESULTS

3.1. Teleconnections on Precipitation

Figure 2 shows the correlation coefficient and statistical significance for the teleconnections between the height anomaly standard deviation count for each grid box and regional precipitation. Figure 2 shows that height anomalies in these locations only have statistically significant impacts for certain regions of the United States. A ridge off of the west coast has long been tied to drier conditions in the western part of the U.S. (e.g., Bhatt et al. 2008). This is true for several grid boxes in this analysis during January through March, but especially in January. The negative correlation coefficients indicate that the driest years will occur when the most significant ridging takes place in these areas. There is also a noticeable downstream effect on precipitation in much of the Midwest and Ohio Valley, but especially, the Upper Midwest. There is a reversal of sign in the correlation coefficient from the West, indicating that strong positive height anomalies at these locations in February and April acts to bring heavy precipitation to these regions. Using basic atmospheric pattern recognition, it makes sense that when a ridge is persistent in these locations storm tracks will be directed away from the West and Southwest and will have a tendency to propagate through the Midwestern part of the U.S. Naturally, downstream effects on precipitation are less than the regions closest to the height anomalies. The remaining climate regions in the United States saw little or sporadic significance.

When trying to determine if these locations are experiencing higher heights because of a warming climate, there should be some consideration as to what might contribute to monthly increases in height anomalies for the grid boxes. Figure 3 shows the correlation coefficients for the time series (both yearly and running means) in the bottom three rows as well as the before mentioned climate indices that may contribute to high height anomalies in these locations during late winter and early spring. The bottom three rows of the Figure 3 heat map deal with statistically significance in the time series of these grid boxes. The 8-year running mean (Yr_8mean) shows that most of these locations are increasing in strength with a confidence level of at least 99% and many with a 99.9% confidence level. As expected, figure 3 shows that SOI (ENSO) has strong connections to the height anomalies, especially in late winter. Our research shows that a time series of seasonal (JFMA) SOI using a 5 or 8-YRM indicates that from 1979 to 2014 there is a steady increase with little variability. PDO has an inversely proportional trend to SOI, which was also expected as we can show that the two indices are in phases that are closely tied to one another. Kumar et al found that long term ENSO coupled climate runs gives PDO far less variability than no-ENSO climate runs and it seems to shift phases in conjunction with ENSO.

3.2. Accounting for long-term ocean cycles

SOI and PDO historically have been shown to go through long term cycles that are longer than our 36 year data period. Equation 1 is important to the analysis so that the climate signals in geopotential height data after diminishing the effects of ocean cycles can be observed. Since SOI shifts from more El Niño years to more La Niño years during the course of the experiment time period, an argument could be made that the increasing heights are due to the shift in ocean cycles experienced during the time period. Figure 4 shows a correlation coefficient heat map similar to Figure 3, but with the adjusted values for geopotential height count. Equation 1 successfully reduced the influence SOI had over the height anomalies. As Figure 4 shows, this reduces all statistically significance SOI has on these grid boxes as well as greatly reduced the effect of PDO. Also, even though PDO still shows some statistical significance, with the effect of SOI removed previous research finds there is a much greater variability in the long-term cycle. This means that despite some small remaining influence on the grid boxes, the 36 year long analysis should be a sufficient amount of time. With that being said, there is sufficient evidence in the yearly and running means that there are at least modest increases in geopotential height anomalies during winter and early spring independent of SOI and PDO affects.

When equation 1 is applied to $zcount_{orginial}$ to adjust the count of standard deviation threshold occurrences, there is an impact on the confidence levels of an increasing time series. This occurs because the phase of SOI acted to increase the height anomaly in the past couple decades. Early in the period, the index worked against increased height anomies in these grid boxes in a predominately El Niño phase. With that being said, there are still robust increases in anomalous height count during the 36 years with varying degrees of confidence. There are still signs of a time series trend in all four months with the weakest trend in January. With that being said, January still has a confidence level of at least 95% for all three grid boxes. Adjusting the values of standard deviation threshold count did not affect the grid box's importance on regional precipitation. Therefore, the adjusted values are important when determining if the trend persistent in late winter and early spring will continue in a warmer sea ice free climate.

Figures 3 and 4 include sea ice concentration correlation with these grid boxes (ICEC). These values show that there is a connection between sea ice concentration north of Alaska in the late summer months with the following winter and spring height anomalies. Like previous attempts to link the sea ice concentrations to height anomalies, the strongest significance to wave patterns occur in late winter and the beginning of meteorological spring. These correlation coefficients have confidence levels of at least 95% for at least one grid box in all four months.

CHAPTER 4

DISCUSSION

This research's primary goal was to look further into the long-standing issue of connecting a warming climate with planetary wave amplification. Attempting to correlate sea ice with localized geopotential height anomalies in the Pacific Ocean isn't a new idea, but the procedure used in this analysis is aimed at quantifying a link with observed sea ice in a particular location that eventually can be tied regional precipitation using reanalysis data. The connection between an increasing ridge and decreasing sea ice could be important for forecasting purposes, especially long term when issuing seasonal forecasts. If there is confidence in a negative SOI values during JFMA after a well below normal sea ice concentration in the previous summer, significant wave amplification resulting in ridging in the North Pacific can be forecasted with some confidence based on our results. This would have hydrological impacts for the United States, but especially, in the western part of the country.

After looking at monthly teleconnections for these anomalies, there is a possibility that some regions could have multi-month periods of changing precipitation leading to increased potential for long-term floods and droughts. Using the same procedure as before, Figure 5 and Figure 6 show the results of these height anomalies applied over the course of a three month span. These values were generated by choosing one grid box for each month and under the assumption each month's height anomalies will develop independent of each other.

Figure 5 shows that JFM height anomalies are strongly connected with late wintertime and early spring precipitation in the West and Southwest. The confidence level of 99.9% for JFM precipitation in the western part of the country means there is higher confidence if ridging continues to develop seasonable than dry conditions will continue for these regions. This is of great concern, especially for California, because the majority of their precipitation usually falls during these months and is vital for water in the region. Snowfall in the Sierra Mountains during these months eventually become one the primary water source for California in late spring and during the summer as the snow melts (Segal, 2013).

Figure 6 shows that during the three month season both JFM and FMA correlate highly with SOI and PDO. Once more, when $zcount_{adjust}$ is used in the two right columns of Figure 6 during these seasons, there is still high confidence in an increasing height anomaly, especially when some of the year to year variability is filtered out with the running means. After adjusting the height anomalies to remove the effect of SOI, the contribution of sea ice to increased ridging remains at a confidence level of 99%. There still remains some uncertainty because the problem is not as simple as saying diminishing summer sea ice leads to regional precipitation extremes. There are still only minor non-significant direct connections between sea ice concentrations with the regional precipitation over the United States in this study. With that being said, the link between sea ice and increased ridging in the Pacific could be an important link to connecting Arctic Amplification with precipitation patterns. The main uncertainty here is an insufficient amount of data. Like previous studies on this subject, the greatest changes in the amplification have taken place in the past decade and a half.

Figure 7a shows the 8 year running mean for summer sea ice in our domain of interest. The summer sea ice concentration for August and September in the region north of Alaska begins to decrease steadily in the 1990s through the end of the period. This could be the reason why there is some uncertainty in the time series for $zcount_{adjusted}$ before the early 2000s, when the positive height anomalies begin to rapidly increase in strength during the past 15 years. This decline in sea ice in the past 15 years could explain why there is less random variability in the time series and a more persistent ridge within our grid boxes shown in figure 7b. Once again, there is uncertainty with that assertion because of the few years sea ice has been drastically declining in this particularly location. Dynamically, it is not a surprise that significantly decreasing the sea ice coverage would have major impacts on sea surface temperature and subsequently on localized geopotential height fields (Porter et al, 2011). If sea ice concentration trends continue to move toward a more ice free area north of Alaska, than our research suggests that there will be a persistent ridge in the North Pacific with some dependence on the phase of the SOI and PDO during JFMA.

Throughout the results and discussion, we have spent most of the time discussing the changes in the western part of the country, but the downstream effects to the east cannot be ignored. While the confidence levels are less for downstream impacts on seasonal precipitation, there are significant results especially for Upper Midwest climate region. February has the highest confidence level that precipitation could be tied to height anomalies in the three grid boxes. February shows the most confidence in its connections to decreasing sea ice as well as high confidence in the 5 and 8 year running means trending upward. Further research is needed, but this could hint at stronger, or more frequent, February Midwestern snowstorms as ridging increases in our grid box locations. There are more influences on precipitation during April for the Upper Midwest. Using a similar method, the ridge increasing in strength off the east coast in figure one can be examined. The results suggest that this ridge is also increasing at a confidence level of 99% and that, coupled with the ridge off the West Coast, is further strengthen the teleconnections to rainfall in the Upper Midwest. This begins to drift away from our primary domain for this research, but it is worth noting that further downstream amplification of the jet stream could create a positive feedback cycle with precipitation in certain regions and could be an area of focus for future research.

Reanalysis data is used as observations in this research to display these results. Since all reanalyses have errors, we repeated the first couple steps of this project using the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) (Dee et al. 2011). These results were not presented because they matched nearly identically to what we saw from R-2. The monthly averages in geopotential height fields for the past 12 years compared to previous 24 from figure 1 only minor non-significant differences. We then tested to see how closely correlated the daily threshold count for each year correlated with R-2 data and found that they had correlation coefficients of at least .97 for one grid box in all four months. There were slight differences due to changes in resolution between the two data sets, but the results were too similar to validate showing both sets of results.

CHAPTER 5

CONCLUSIONS

Significantly decreasing sea ice concentrations north of Alaska in parts of the Arctic Ocean as well as the Chukchi and Beaufort Seas is causing amplification to wave patterns in the North Pacific off of the west coast of the CONUS. Even when the effect of ocean cycles, such as PDO and SOI, are empirically reduced from $zcount_{original}$ a robust climate signal of increasing height anomalies is still being observed. This research provides increased confidence expressed in previous works that Arctic amplification is affecting wave patterns across the Northern Hemisphere (e.g. Francis et al., 2009). Much like the conclusions made by Overland et al. (2015), our results suggests that the Arctic may be acting as an amplifier of jet amplification rather than the cause and that these changes will be regional, seasonable and will vary yearly based on background atmospheric and surface conditions.

The increased ridging off of the West Coast of the United States not only affects the climate regions adjacent to that location, but also has downstream impacts on precipitation. This has major hydrological implications on the ongoing drought in the West Coast. While the Upper Midwest shows signs of increased precipitation, the primary concern with the findings of this research would be for the water deficit in the West. The region has experienced some of the warmest and driest winters the past few years and is stuck in the midst of a significant drought because in large part to the lack of winter precipitation (Segal 2013). In 2012, our data shows that sea ice in late summer was so low that the area north of Alaska was almost entirely ice free. The following winter of 2013 was the driest JFM in at least the last 36 years for the West region. With that being said, this sample size of ice free years is not adequate. At some point in the near future, August and September sea ice concentration for this part of the Arctic will be near zero most years as Arctic amplification continues to warm this part of the World at a much faster rate. Some research suggests that the Arctic could be ice free frequently during the summer occurring sometime in the next 2 to 4 decades (Wang and Overland 2009; Stroeve et al. 2007).

When this happens on a regular basis, it is unclear how much more the wave pattern will be affected. Based on this research there is marginally high confidence that years like the amplification seen in 2013 will become more frequent.

CHAPTER 6

FUTURE RESEARCH

This research focuses on the four month season from January to April over one specific region in the Northern Hemisphere. One way to help validate the results presented in this project would be to repeat this process in other parts of the Northern Hemisphere for more than just the four month time frame. Coumou et al. (2015) showed that jet stream amplification was not just confined to the colder seasons and their results show that even during the summertime there are changes taking place to the upper level patterns. Not just in our domain, but over multiple domains across the Northern Hemisphere, this idea could be tested using the method outlined above. As we mentioned, previous research have found that there are amplitude changes to the jet stream across Eurasia (Mori et al. 2014 and Inoue et al. 2012). This could be a domain where this experiment design can be tested again. If we see similar results correlating sea ice concentration in the Berents-Kara Sea with jet stream amplitude, then this could help validate the conclusions made in this project. Multiple reanalyses can also be used. We chose to look at the European reanalysis to help validate our results. For the most part, we saw that the two reanalyses would give us nearly identical results. It would be valuable to repeat this process with a newer NCEP reanalysis as well as a fourth reanalysis. This would just add to the confidence of our results when looking jet stream amplitude related to sea ice concentration.

Like the work done by Screen and Simmonds (2014), another application of this work would be to test a similar method with temperature as opposed to extreme precipitation. NCDC has temperature data broken down into region, like the precipitation data, and that can easily be used to test the regional dependence of jet amplification on temperature like we did here. It can be hypothesized that jet stream amplification would have a correlation with temperature that is greater than or equal to the significance levels we found with regional precipitation since surface temperature is also highly dependent on the upper level patterns.

CHAPTER 7

FIGURES

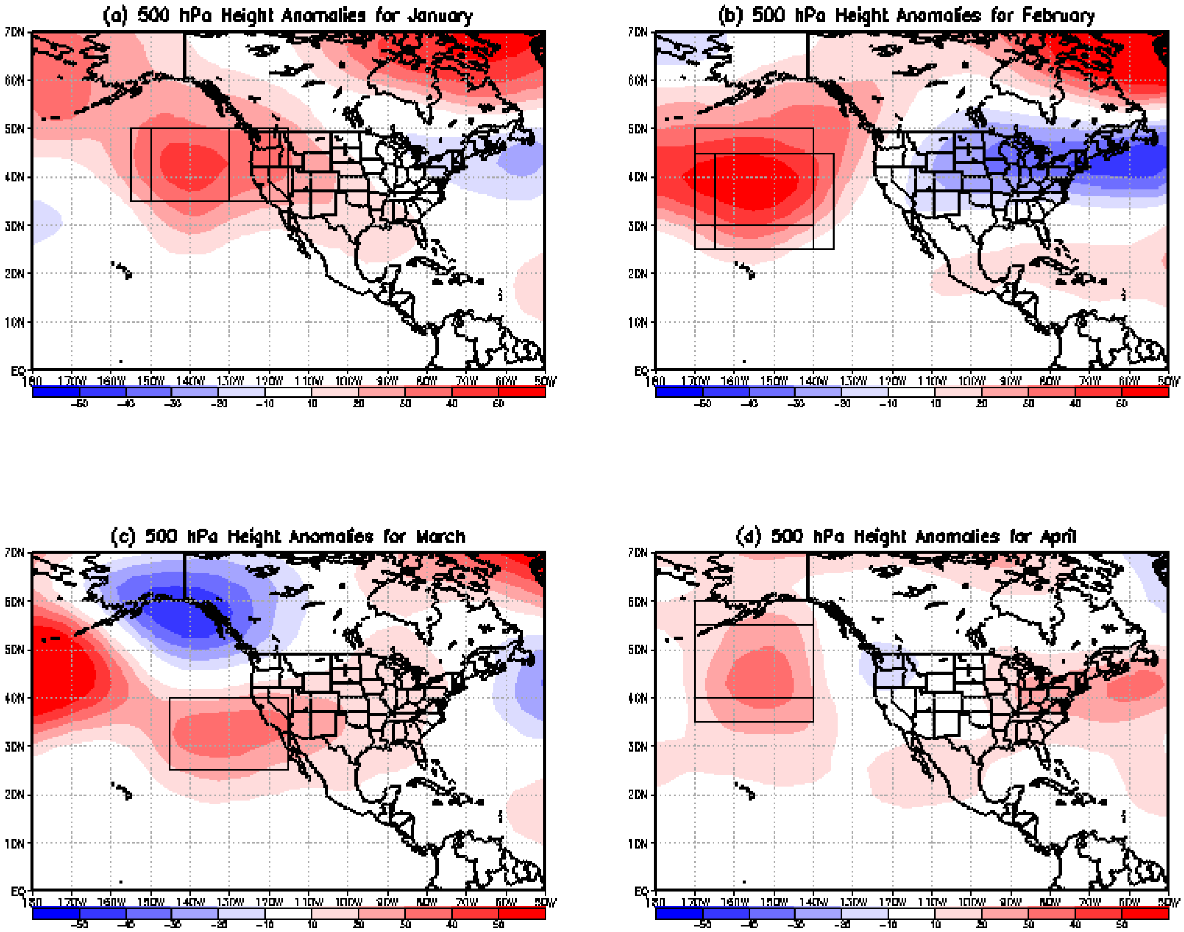

Figure 1. The 500 mb height anomalies from the last 12 years compared to previous 24 years for January (a), February (b), March (c), and April (d). The grid boxes are: January - 35-50N, 165-130W (Jbox1), 35-50N, 165-140W (Jbox2), 35-50N, 160-135W (Jbox3); February - 30-50N, 170-140W (Fbox1), 25-45N, 170-140W (Fbox2), 25-45N, 165-135W (Fbox3); March – 25-40N, 145-115W (Mbox1); April – 40-60N, 170-140 (Abox1), April – 40-60N, 170-140 (Abox2).

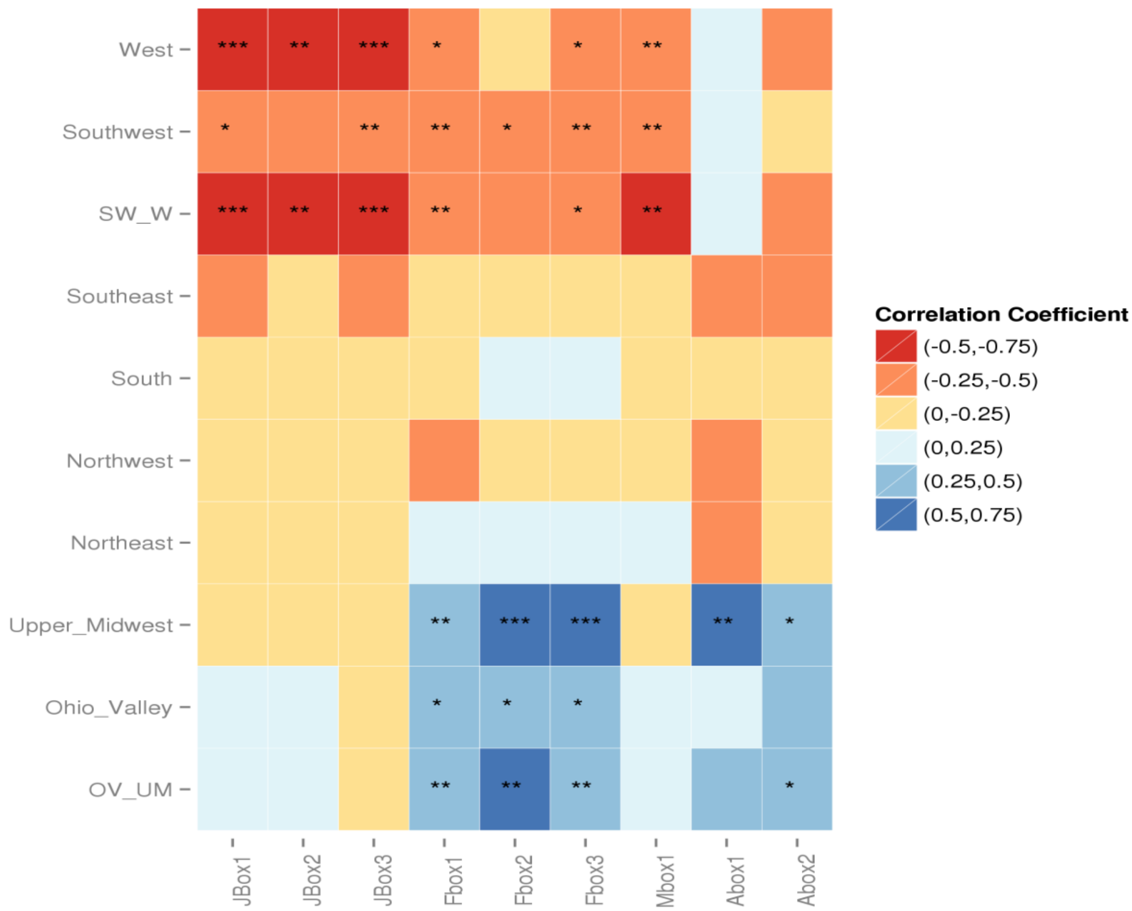

Figure 2. Heat map that shows correlation coefficients between each of the grid boxes (x-axis) and the precipitation anomalies of various climate regions (y-axis). OV_UM stands for "Ohio Valley + Upper Midwest" and SW_W stands for "Southwest + West". The correlation coefficient values that are positive have the same trend and negative values have opposite (i.e. increasing height anomalies decreases the precipitation is a negative value). Stars represent the level of significance: three stars is a 99.9% confidence level, two stars is a 99% confidence level, and 1 star is a 95% confidence level.

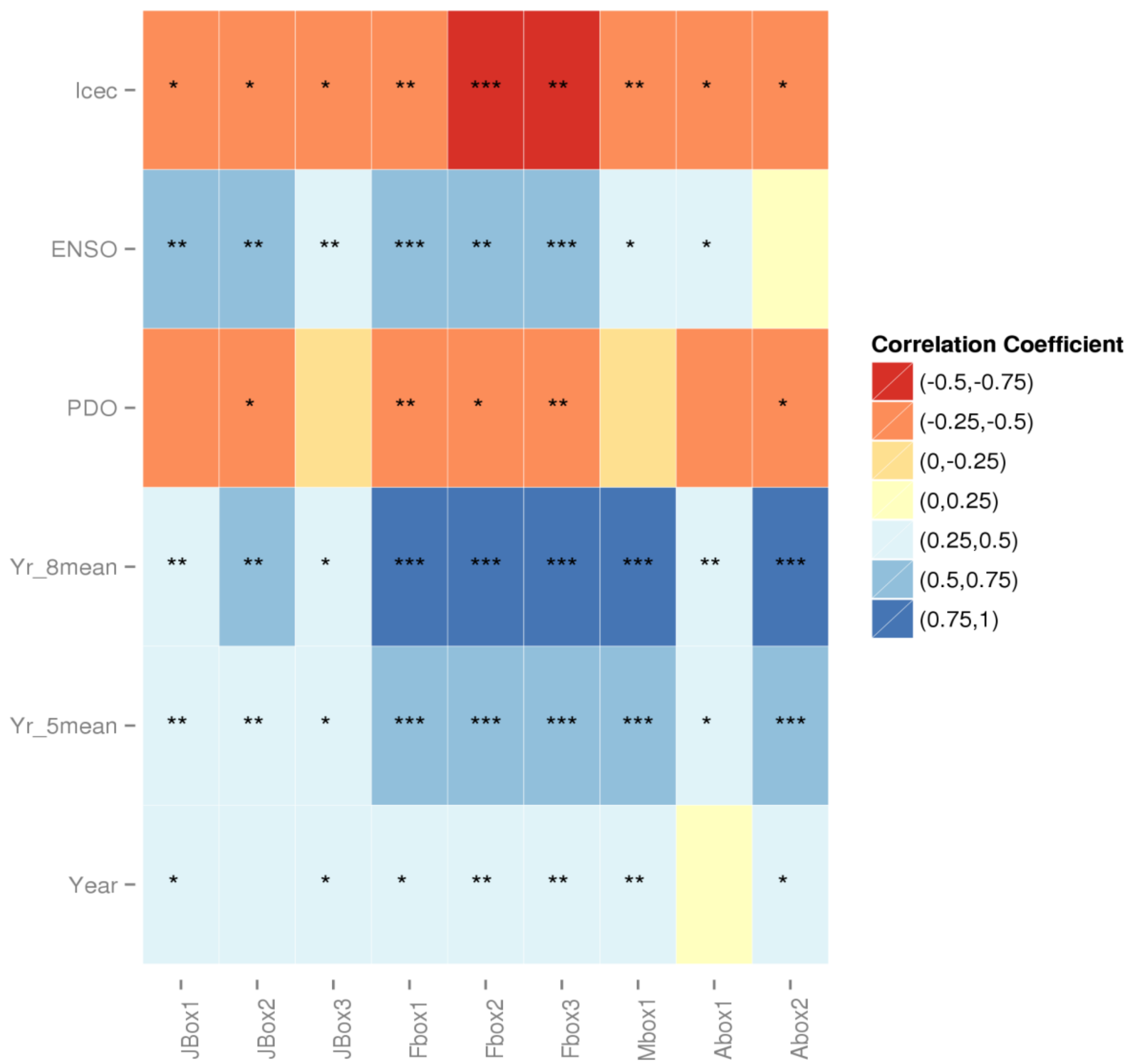

Figure 3. Heat map that shows correlation coefficients between each of the grid boxes (x-axis) and a various number of climate indices or time series (y-axis).Stars represent same significance as figure 2. ICEC stands for Ice concentration values as August averages + September averages for each year. Yr_8mean is the correlation between grid box count and time on an 8 year running mean. Likewise, Yr_5mean and Year are the 5 year running mean and yearly mean, respectively.

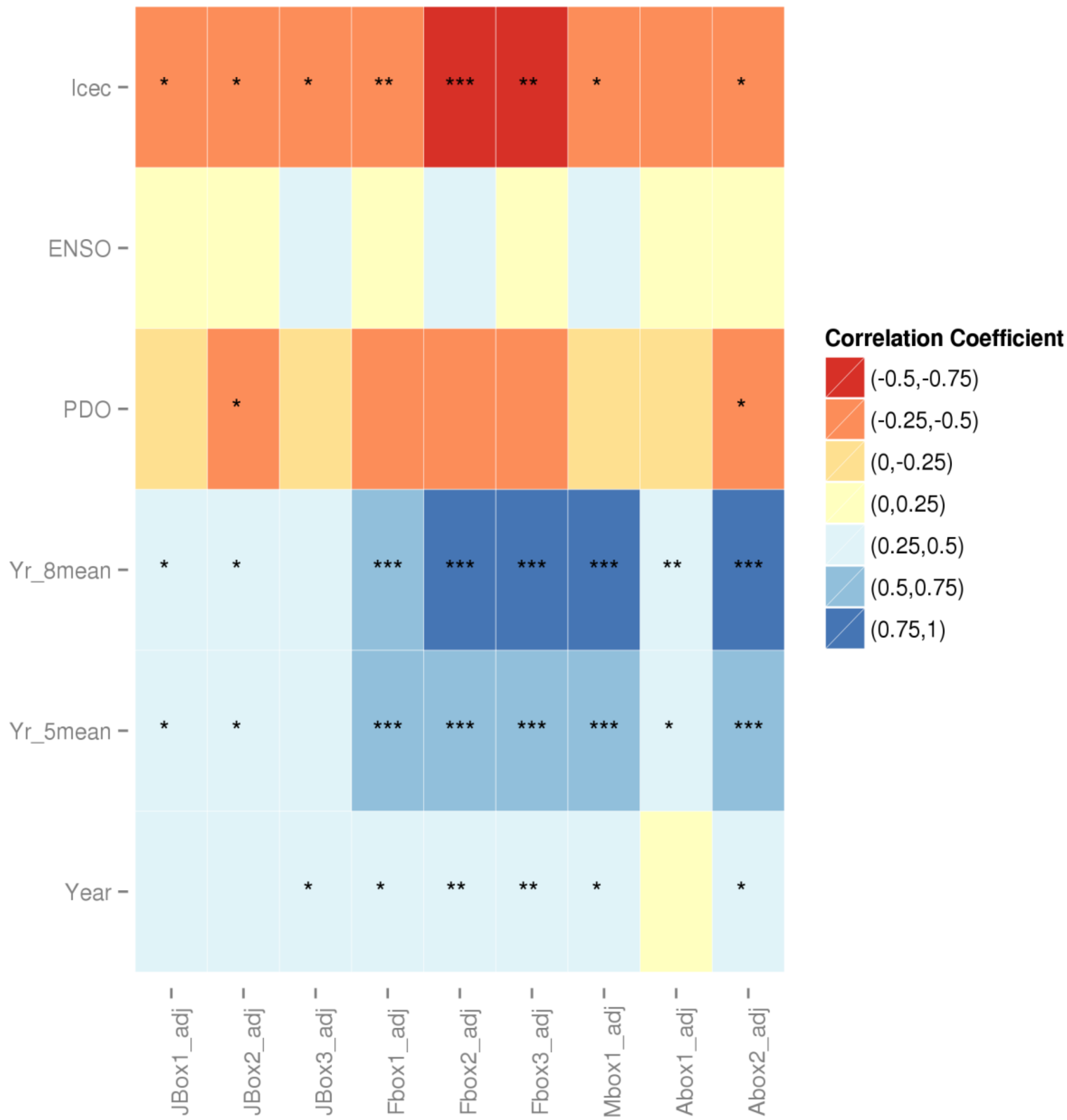

Figure 4. Same as Figure 3, but with adjusted height threshold count values on the x-axis.

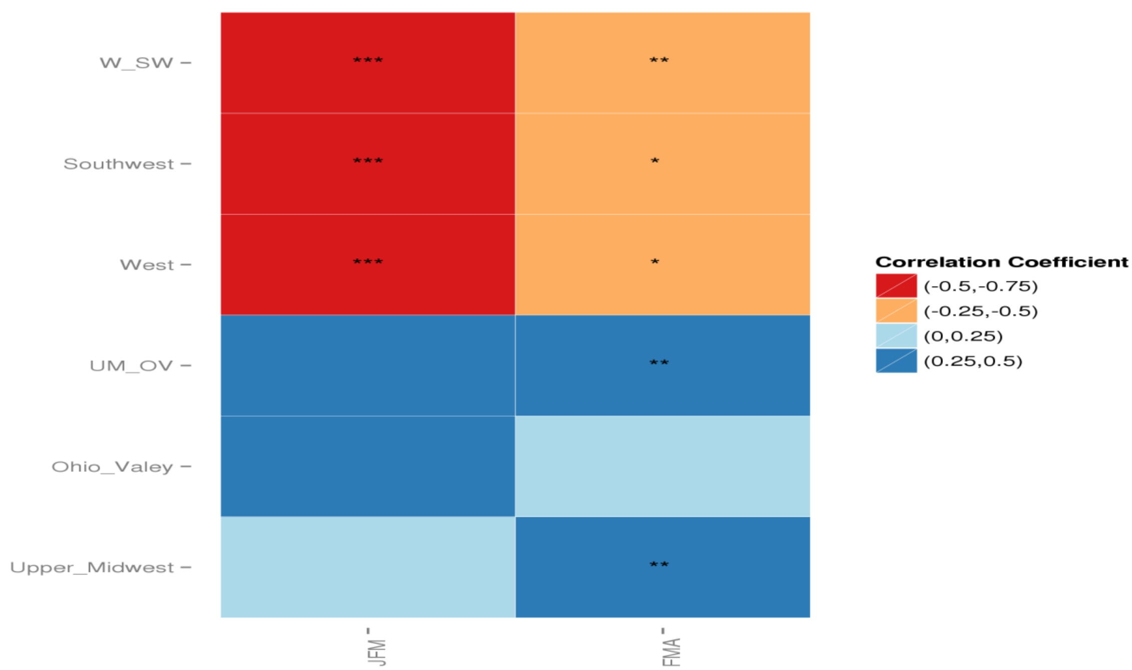

Figure 5. Format remains the same as Figures 2, 3, and 4. Seasonal height threshold count values are generated by taking a grid box from each of the months in the 3 month time span. (JFM = Jbox1, Fbox1, Mbox1; FMA = Fbox2, Mbox1,Abox2)

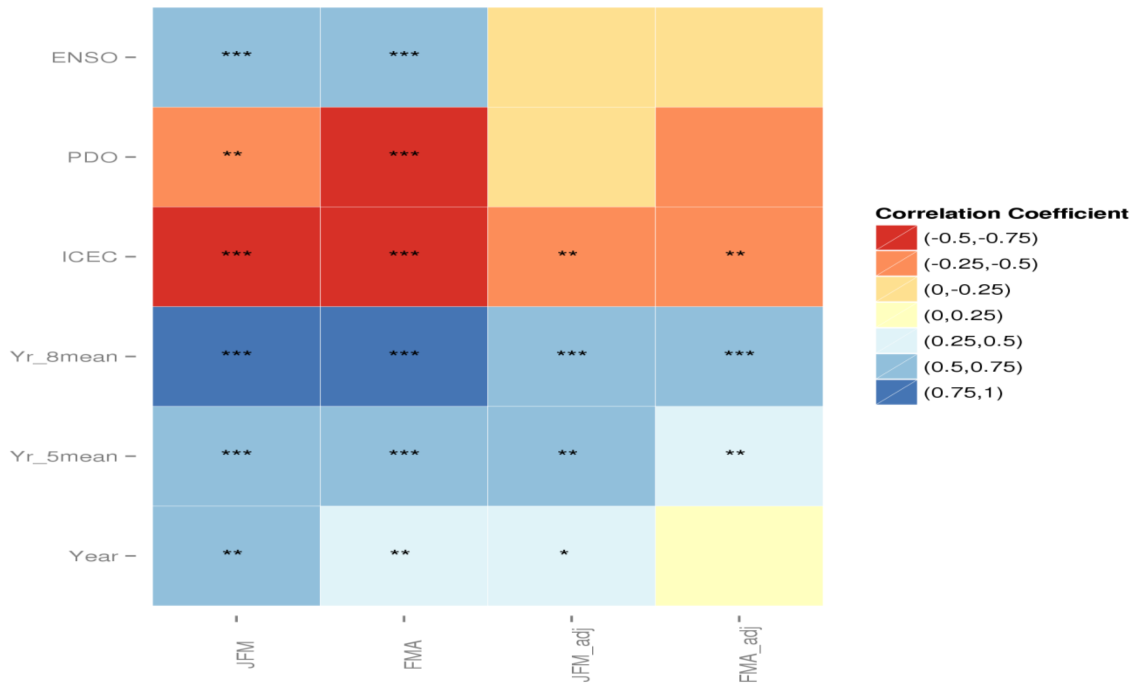

Figure 6. Same format as figures 3 and 4 combined on the y-axis using the seasonal height count values from Figure 5.

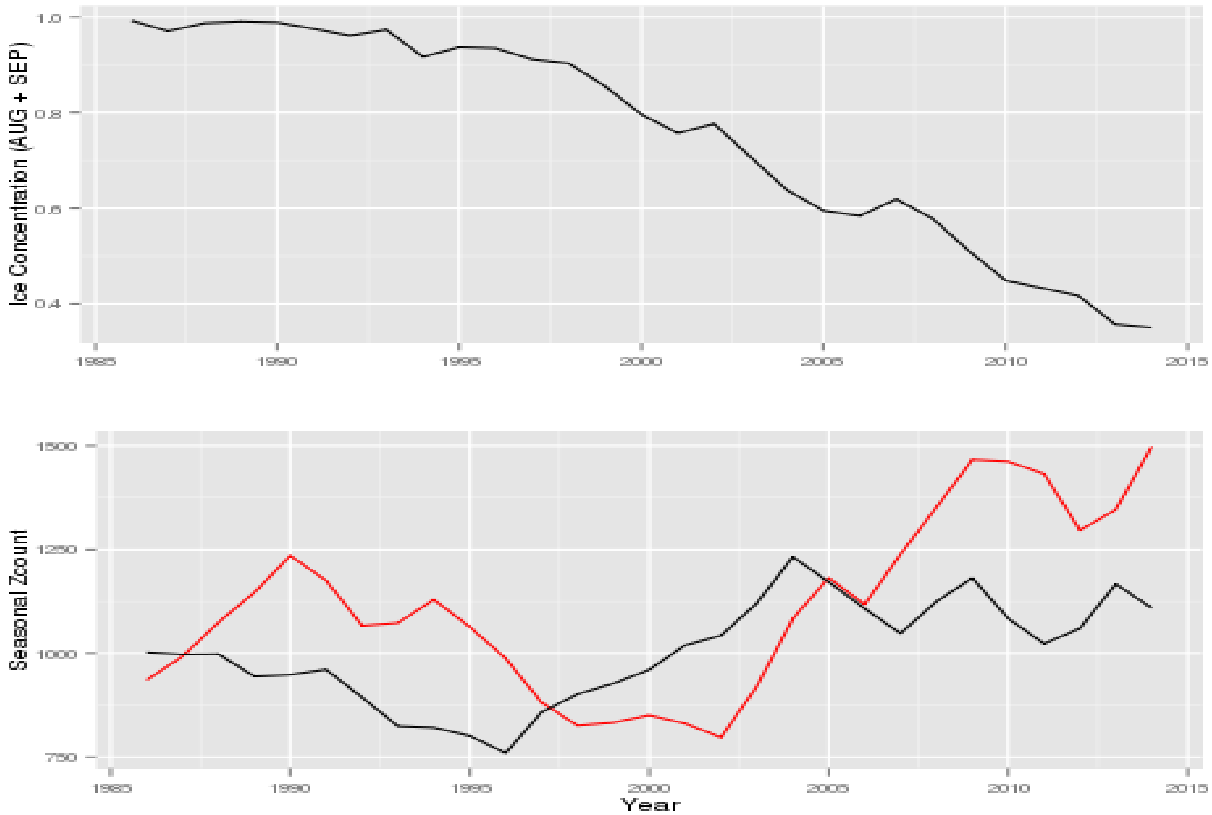

Figure 7. (a) 8 year running mean for August + September sea ice concentration (top); (b) 8 year running means for seasonal height count (bottom): JFM (red) and FMA (black)

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