

UCLA

UCLA Electronic Theses and Dissertations

Title

The Influence of the Zonal Wave Three on Antarctic Sea Ice during the Ice Advance Season

Permalink

<https://escholarship.org/uc/item/0rg7r1zc>

Author

Khan, Hana Mariam

Publication Date

2015

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA

Los Angeles

The Influence of the Zonal Wave Three
on Antarctic Sea Ice during the Ice Advance Season

A thesis submitted in partial satisfaction of the degree of Master of Arts
in Geography

by

Hana Mariam Khan

2015

ABSTRACT OF THE THESIS

The Influence of the Zonal Wave Three on Antarctic Sea Ice during the Ice Advance Season

by

Hana Mariam Khan

Master of Arts in Geography

University of California, Los Angeles, 2015

Professor Marilyn N. Raphael, Chair

This study examines the influence of an atmospheric circulation pattern, known as the zonal wave three (ZW3), in terms of the sea ice's seasons from 1979-2009 in order to better understand the response of the sea ice. An index to represent the amplitude of the ZW3 was calculated using zonal anomalies of 850 hPa geopotential heights taken from the ERA-Interim data set. Statistical analysis showed sea ice concentrations, taken from the Hadley sea ice and sea surface temperature data set, to be significantly dependent upon the ZW3 in parts of the Ross Sea, the ice edge in the Amundsen-Bellingshausen Seas and off the Amery ice shelf during the ice advance season. The results suggest that the ZW3 plays a role in the occurrence of the observed sea ice trends in the Ross Sea, Amundsen-Bellingshausen Seas, Weddell Sea and off the Amery ice shelf regions during the ice advance season, the critical period for sea ice growth.

The thesis of Hana Mariam Khan is approved.

Yongkang Xue

Thomas Welch Gillespie

Marilyn N. Raphael, Committee Chair

University of California, Los Angeles

2015

Table of Contents

List of Figures	v
Chapter 1: Introduction	2
Chapter 2: Literature Review	4
Background	4
Zonal Wave Three	6
Chapter 3: Methodology	11
Chapter 4: Results and Analysis	14
4.1: Correlation between atmosphere/zonal anomaly and sea ice sectors.....	14
4.2: ZW3 Index trends.....	21
4.3: ZW3 and SIC Correlation and Regression.....	24
4.4: Discussion	27
Chapter 5: Conclusion.....	30
References	32

List of Figures

FIGURE	Page
1. Map of meridional flows and index of ZW3.....	9
2. Map showing the boundaries of Antarctic sectors.....	12
3. Maps showing correlations between zonal anomalies at 850 hPa geopotential height and SIE during advance season.....	15
4. Maps showing correlations between geopotential height at 850 hPa and SIE during advance season.....	19
5. ZW3 indices spanning from 1979-2013.....	22
6. Correlations between ZW3 and SIC from 1979-2009 with de-trended data during advance and retreat seasons.....	24
7. Regression coefficients of SIC regressed on ZW3 during advance and retreat seasons from 1979-2009.....	25
8. Map of sea ice trends in terms of fractional ice coverage per decade for 1979-2012.....	28

Chapter 1: Introduction

Since satellite measurements began in 1979, total Antarctic sea ice extent (SIE) has shown a small yet significant increase. Antarctic SIE hit record-breaking coverage of over 20 million square kilometers in September of 2014, the third year in a row to break the maximum sea ice extent (SIE) record (Reid et al., 2015). This trend is interesting especially since it is seemingly paradoxical to what might be the expected response to increasing greenhouse warming and is in contrast to what is happening in the Arctic, where SIE has been decreasing within about the same time period. Sea ice is a key player in the ice-atmosphere-ocean system. It serves as a barrier between the ocean and the atmosphere limiting the exchange of moisture, gases and momentum, insulating the ocean from the relatively cooler atmosphere (Allison and Moritz, 1995; Leiser et al., 2013). The ice albedo feedback is another important role of sea ice in the system since sea ice reflects significantly more shortwave radiation than the open ocean, which will allow sea ice to increase in area and further increase the shortwave radiation reflected in this positive feedback loop. Sea ice formation and melting also affects the salinity and density of the underlying water column by rejecting brine during ice formation and reintroducing fresher water when sea ice melts. These functions make sea ice a sensitive indicator of climate change (Leiser et al., 2013).

Because of the various roles sea ice plays in the ice-atmosphere-ocean system, investigating how and why Antarctic sea ice has been changing is of significant interest and importance. Studies by Powell et al. (2005), Zhang (2007) and Bintanja et al. (2013) have examined the role of freshwater input from increased precipitation and/or basal melting from ice shelves as significant contributors to Antarctic sea ice expansion. Others like Holland and Kwok (2012) and Haumann et al. (2014) argue that wind-driven changes associated with

atmospheric circulation could help explain observed sea ice trends. Recent work by Raphael and Hobbs (2014) finds that different atmospheric mechanisms such as the Southern Annular Mode (SAM), the Pacific-South American pattern (PSA), the Amundsen Sea Low (ASL) and Zonal Wave Three (ZW3) have preferred regions and ice seasons of influence on sea ice around Antarctica. This is important because although total Antarctic SIE is increasing, there are large regional and opposing trends found in the Pacific and Weddell Sea regions (e.g. Stammerjohn et al., 2012).

ZW3, a quasi-stationary atmospheric circulation pattern found in the extratropical Southern Hemisphere, has preferred regions of meridional flow that can influence sea ice around the Antarctic both dynamically and thermodynamically through advection and transport of warm/cold air (Raphael, 2004; Raphael, 2007). Prior work by Raphael (2007) found sea ice to be most strongly influenced by ZW3 in the outflows of the Ross and Weddell Seas and off the Amery ice shelf. Raphael and Hobbs (2014), on the other hand, found a weak correlation relationship between the SIE in the Weddell and Amundsen-Bellingshausen Seas and ZW3 during the ice advance season, the time of the year the sea ice grows and advances, which deserves further exploration. This M.A. project will focus on examining the impact of ZW3 on sea ice in the Weddell, Ross and Amundsen-Bellingshausen Seas, the regions with the largest sea ice trends (Turner et al., 2015), during the sea ice seasons.

Chapter 2: Literature Review

Background

There has been an overall increase of SIE trend of 1.5% per decade around the Antarctic from 1979-2013 (Turner et al., 2015). There is, however, considerable regional variability in the sea ice trends around the Antarctic. The regions with the largest trends are found in the Bellingshausen Sea and the Ross Sea sectors (Yuan and Li, 2008; Stammerjohn et al., 2008). Over the 1979-2007 period, the Amundsen/Bellingshausen Sea (ABS) experienced a SIE reduction of 6.63% per decade while the Ross Sea has seen an increase of about 4.63% per decade (Turner et al., 2009). The sea ice season length has also changed in these regions, with the duration of the ice season becoming shorter in the Bellingshausen Sea by about three months and longer in the Ross Sea by over two months (Stammerjohn et al., 2012). Differences in trends are also found within the Weddell Sea sector as positive trends in the ice season duration emerge in the eastern Weddell Sea while the western and northern parts of the Weddell Sea have been experiencing negative trends (Maksym et al., 2012). The East Antarctic is characterized by areas of strongly positive and negative ice season duration trends (Leiser et al., 2013). The differences in signs and strength of the trends just described demonstrate how examining only the total SIE trends over the Antarctic will mask the larger variability in sea ice that occurs at the regional level, including the regions experiencing a decreasing SIE trend.

There is a variety of mechanisms that have been proposed to help explain observed sea ice trends. Powell et al. (2005) and Zhang (2007) found that an increase in precipitation as a result of a warming climate would produce increasing SIE trends due to more snow-ice formation. Bintanja et al. (2013) argue that increased freshwater input from basal melting of ice shelves has also played a significant role in sea ice expansion by cooling and freshening the

surface layer to allow ice to freeze more easily. Swart and Fyfe (2013), however, find that this freshwater input is not significant enough to produce sea ice to match the observed sea ice increase. Simulations in coupled climate models ran by Goosse and Zunz (2014) to evaluate the role of the ice-ocean feedback in explaining the SIE trends found a positive ice-ocean feedback that enhances sea ice variations through stabilizing mechanisms in the water column. They, however, also recognized the important role of wind changes in determining the spatial distribution of the ice concentration trend. Holland and Kwok (2012) argue for examining the influence of atmospheric circulation on sea ice motion and concentration. The atmospheric circulation can impact sea ice dynamically through wind-driven advection of sea ice in the direction of wind flow. Southerly/northerly flow can also affect sea ice thermodynamically through its transport of relatively cooler/warmer air.

Atmospheric circulation patterns that have been examined include the Southern Annular Mode (SAM), the Semi-annual Oscillation (SAO), zonal wave three (ZW3), the Amundsen Sea Low (ASL) and ENSO-related teleconnections, such as the Pacific-South America pattern (PSA). Previous studies have often focused on the SAM to explain sea ice trends, along with ENSO events which are believed to have a reinforcing effect on climate and sea ice when coinciding with certain SAM phases (Hall and Visbeck, 2002; Stammerjohn et al., 2008). A shift to more positive phase of SAM means a steeper pressure gradient between the middle and high southern latitudes resulting from lower geopotential heights over the South Pole. In response to the steeper gradient the westerlies become stronger, causing an enhancement of the northward transport of sea ice by Ekman drift and the resultant expansion of SIE through advection (Hall and Visbeck, 2002). Zhang (2007) suggests that the observed trends of sea ice increasing in some regions and decreasing in others can be explained by the recent changes in the SAM and ENSO,

which he argues would result in more sea ice in the eastern Ross-Amundsen region and less ice in the Bellingshausen and northern Weddell sectors. Although the SAM is the dominant mode of atmospheric variability in the southern high latitudes, it fails to account for all of the regional sea ice trends observed around the Antarctic. Liu et al. (2004), for instance, argue in their paper that ENSO and SAM cannot explain all of the sea ice trends. Yuan and Li (2008) also find that SAM actually has a smaller influence on sea ice than previously believed. In fact, they found that the PSA pattern and ZW3 have higher correlations with sea ice than SAM and SAO do, especially in the western hemisphere. They also found that the PSA dominates the field in the South Pacific along with the strongest branch of ZW3 also existing in this sector. The SAM and SAO are mostly influential in the southwest Pacific and South Indian Ocean, with the SAM having weaker contributions in the sea level pressure (SLP) variability than the SAO (Yuan and Li, 2008). With respect to seasons, the SAM is found to be stronger during the summer (Yuan and Li, 2008), ZW3 in the winter (Raphael, 2004), and SAO in the spring and fall (Yuan and Li, 2008).

Zonal Wave Three

ZW3 is a quasi-stationary atmospheric circulation pattern found in the extratropical Southern Hemisphere, that influences the meridional (north-south) transport of warm or cold air around the Antarctic (Raphael, 2004). While the SAM might be said to represent the zonal symmetry in the flow, ZW3 represents the asymmetry. Its three ridges, shown in Figure 1a, are generally found south of the southern continents. The ridge and trough system of ZW3 creates preferred regions of northerly flows, which are poleward winds that bring in warm air, and southerly flows, which are equatorward winds that bring cold air from Antarctica. For this reason, ZW3 has the potential to influence sea ice through different channels: sea surface

temperatures, surface air temperatures, wind direction and even precipitation since snow loading influences sea ice development (Raphael, 2007). An index was created by Raphael (2004) to capture the changing amplitude of the ZW3 pattern (Figure 1b). Trends in this index show that since around 1979, the ZW3 index has been increasing in amplitude, signifying a shift towards more meridional flow (Raphael, 2007).

When examining the impact of ZW3 on sea ice, Raphael (2007) found the influence of ZW3 to be significant during the periods of ice growth and expansion in the preferred regions of meridional flow, which demonstrates the ability of ZW3 to influence regional variability of sea ice. The ridges of ZW3 are located over the Weddell Sea and Ross Sea outflows and off the Amery ice shelf in East Antarctica. These also happen to be important regions where sea ice is advected (transported horizontally) after production near the coast. In these three regions, ZW3 is positively correlated with sea ice expansion while negative correlations are found for most of the other areas, such as the Amundsen-Bellingshausen seas (Raphael, 2007). A positive trend in the ZW3 index would mean an enhancement of northerly flow (bringing warmer air) in regions with negative correlation between ZW3 and sea ice and an increase in southerly flow (bringing colder air from the continent) in regions with positive correlation.

The study carried out by Raphael and Hobbs (2014) aimed to distinguish which atmospheric circulation mechanism is primarily responsible for the variability of ice in different sea ice regions and to identify which of these mechanisms were important during sea ice retreat and advance. They argue that clear links have not been established between sea ice and atmospheric circulation mechanisms in previous works largely because 1) total SIE is used instead of regional SIE trends and 2) the response of sea ice is evaluated in terms of atmospheric

seasonal cycles rather than the sea ice's seasonal cycle of advance and retreat. They reason that a better understanding of the sea ice variability can be possible when using sea ice's seasonal cycle rather than the atmosphere's citing published research that demonstrated the dependence of SIE on the degree and timing of ice advance and retreat (Stammerjohn et al., 2008, 2012; Harangozo, 2004).

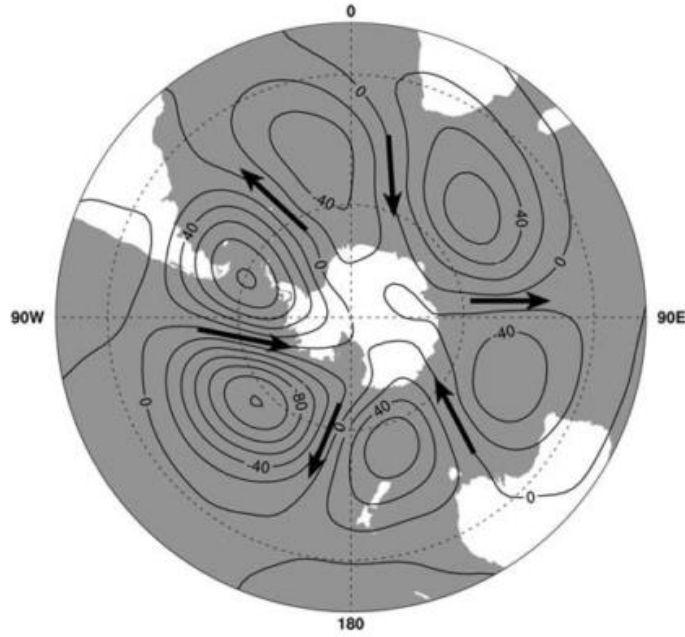
In that study, the ice advance period was defined as starting in March and ending in August for all sectors except the King Hakon VII sector, where the advance period ends in September, and the retreat period occurring from October to February for all sectors except the Hakon VII, where it lasts from November to February. The total SIE was found to respond primarily to the SAM during the ice advance season based on negative correlations found between total SIE and 500 hPa geopotential height over the continent and southeast Pacific region during this season. Individual regions were found to respond preferentially to different atmospheric circulation mechanism. Their results demonstrate the importance of examining sea ice trends and their driving mechanisms by region, as the total SIE masks the regional SIE trends and gives an unclear picture of which mechanisms are important in influencing sea ice.

Of direct importance to the research undertaken here is the finding that the SIE in the Weddell Sea was correlated with ZW3 during ice advance season (Raphael and Hobbs, 2014). ZW3 influences the Weddell Sea region through one of its troughs, which brings cold southerly winds from the continent to increase SIE during ice advance season thermodynamically (by increasing ocean-atmosphere energy flux to promote ice growth) and dynamically (by advecting sea ice northwards). The influence of ZW3 is particularly important in the Weddell Sea as this region is also where sea ice extends the furthest north and its influence is found during the

advance season, a time the ZW3 itself is highest in amplitude (Raphael, 2007). Raphael and Hobbs (2014) also found ZW3 important in the ABS during advance season.

This project will further explore the relationships suggested by Raphael and Hobbs (2014; hereafter referred to as RH2014), between ZW3 and the sea ice variability in the Weddell, Ross and the Amundsen-Bellingshausen Seas (ABS). Their findings highlight the importance of examining regional variability and identifying relevant atmospheric circulation mechanisms correlated with each region during advance and retreat seasons, with one of these mechanisms being ZW3. Prior works by Raphael (2007) and Yuan and Li (2008) demonstrate the ability of ZW3 to influence regional variability of sea ice in particular regions associated with the wave's ridges. The results of this study should further our understanding of the observed regional sea ice variability around Antarctica and the role played by ZW3 during the ice advance season.

a.



b.

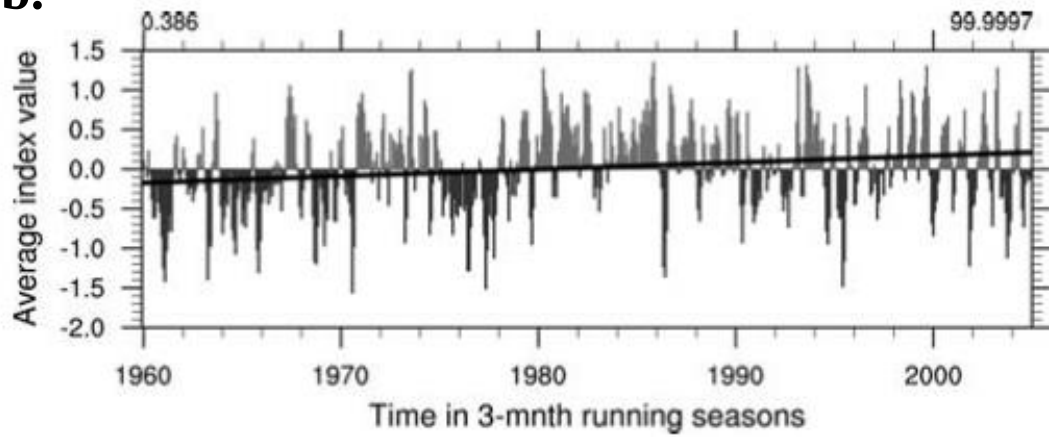


Figure 1. Map of meridional flow and index of ZW3. Figures taken from Raphael (2007) showing a) directions of meridional flow around the Antarctic associated with the ZW3 and b) a 3-month running mean time series of the ZW3 index from 1958-2005 calculated from zonal anomalies of geopotential heights at 500 hPa from the NCEP-NCAR Reanalysis.

Chapter 3: Methodology

The primary sea ice data used here is the Hadley Center sea ice and sea surface temperature (SST) data set (Rayner et al., 2003). This data set contains monthly values of SST and sea ice concentration (SIC) on a 1° x 1° latitude-longitude grid. The secondary sea ice data set used is the monthly Goddard-merged passive microwave sea ice concentrations data available from the [National Snow and Ice Data Center](#) (Meier, 2013). Sea ice sectors were delineated by Raphael and Hobbs (2014), using this dataset.

The ERA-Interim data set containing monthly averages of 850 hPa geopotential height was used to update the ZW3 index to extend from January 1979 to December 2013 (the ERA-Interim datasets begin January 1, 1979). Using the NCAR Command Language (NCL) analytical package, zonal anomalies, the departures from the zonal mean, were extracted from 850 hPa geopotential height and used to calculate the index with the following formula defined in Raphael (2007):

$$I_i = (X_{\text{mthly}} - \bar{X}_{\text{mthly}}) / \sigma_{\text{mthly}}$$

X_{mthly} represents the monthly zonal anomaly of geopotential height at 850 hPa, $\bar{X}_{\text{mthly}}$ is the climatological mean and σ_{mthly} is the standard deviation of the monthly value. I_i is the resulting index value calculated at a grid point. Using zonal anomalies to calculate the index allows the focus to be on the changes in zonal asymmetry over time. The final ZW3 index is the average of the index calculated at three points at latitude 49°S and longitudes 76°W, 50°E and 166°E. These three points represent the annual average locations of the wave's three ridges. Raphael (2004) found that the index calculated from these three points were not significantly

different from an areally averaged index. The zonal anomalies initially extracted from the ERA-Interim data set were correlated with the sea ice sectors identified by RH2014.

Statistical analysis was then conducted using NCL to identify and plot trends of the ZW3 index, analyze correlations between de-trended ZW3 and sea ice data and estimate the dependency of sea ice on ZW3 using regression analysis. These analyses were done with the data integrated for sea ice advance and retreat seasons. The sea ice advance period for the Ross, Weddell and ABS begins in March and ends in August while their sea ice retreat season starts in October and ends in February. Both the ZW3 and SIC were averaged over the advance and retreat seasons before statistical analysis was conducted.

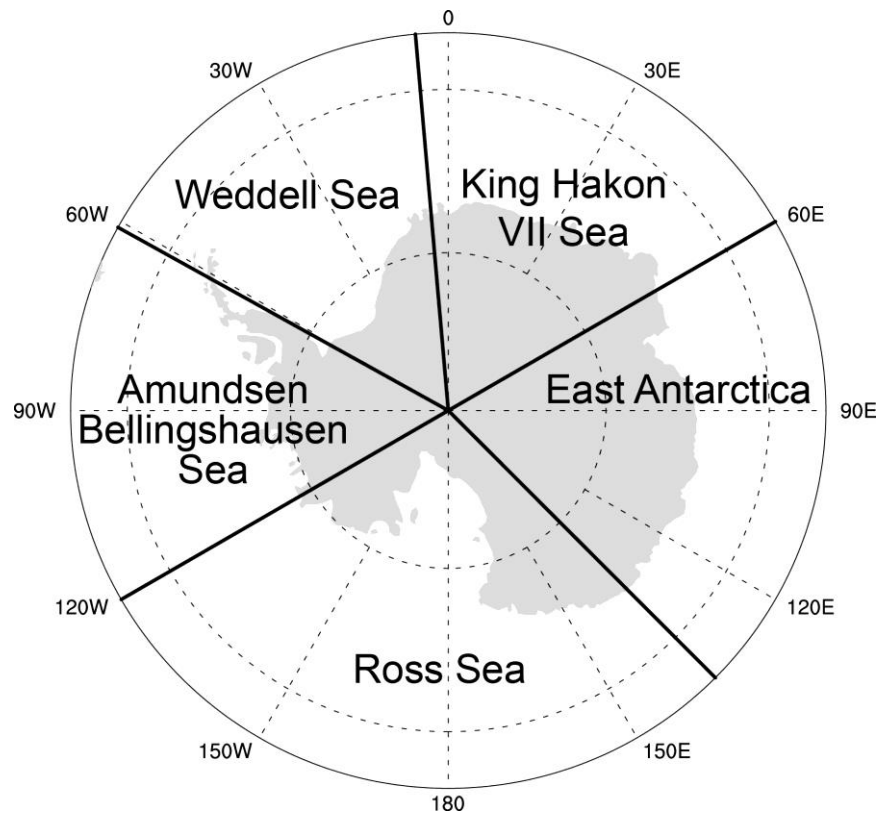


Figure 2. Map showing the boundaries of Antarctic sectors. Source: M. N. Raphael.

Chapter 4: Results and Analysis

4.1: Correlation between atmosphere/zonal anomaly and sea ice sectors

Ross/Amundsen Sea sector

Figure 3a-c illustrates the correlation between zonal anomalies 850 hPa geopotential height and SIE during advance season from 1979-2010 for the selected sea ice sectors for this study: the Ross/Amundsen Sea, the Amundsen/Bellingshausen Sea and the Weddell Sea. Figure 3a shows that total SIE in the Ross/Amundsen Sea sector is negatively correlated with zonal anomalies over the ABS and Ross/Amundsen regions and positively correlated with the anomalies over the Weddell Sea and over parts of East Antarctica. The correlations in these regions are significant with coefficient values of ± 0.4 and higher, reaching around ± 0.6 in the Amundsen and Weddell Seas regions. The pattern of flow associated with the negatively correlated zonal anomalies over the ABS and Ross/Amundsen sea region is clockwise around a low, resulting in stronger southward, warmer flow in the eastern arm and enhanced northward, cooler flow in the western arm. The correlation suggests that this area of northward flow contributes to an increase in SIE in the Ross/Amundsen Sea. This area of negative correlations also corresponds to the trough of the ZW3 found in this region. The positive correlation in the Weddell Sea, on the other hand, corresponds to a ridge of the ZW3. Taken together both correlations suggest that as the trough (ridge) becomes deeper (higher) when the ZW3 is amplified, the zonal anomalies are negative (positive) resulting in larger SIE in the Ross/Amundsen sector. Amplification of the ZW3 is associated with more meridionality in the otherwise zonal flow manifested through the deeper troughs and higher ridges of the ZW3 that have sides of northerly and southerly flows. Where the flow is northerly, the ice is pushed south, thereby restricting its northward expansion while the warmer air transported by the northerly flow acts to melt the ice. The opposite happens with southerly flow, which pushes ice northwards

and enhances sea ice production by transporting cooler air that will steepen the vertical temperature gradient and therefore increase the loss of energy from the surface.

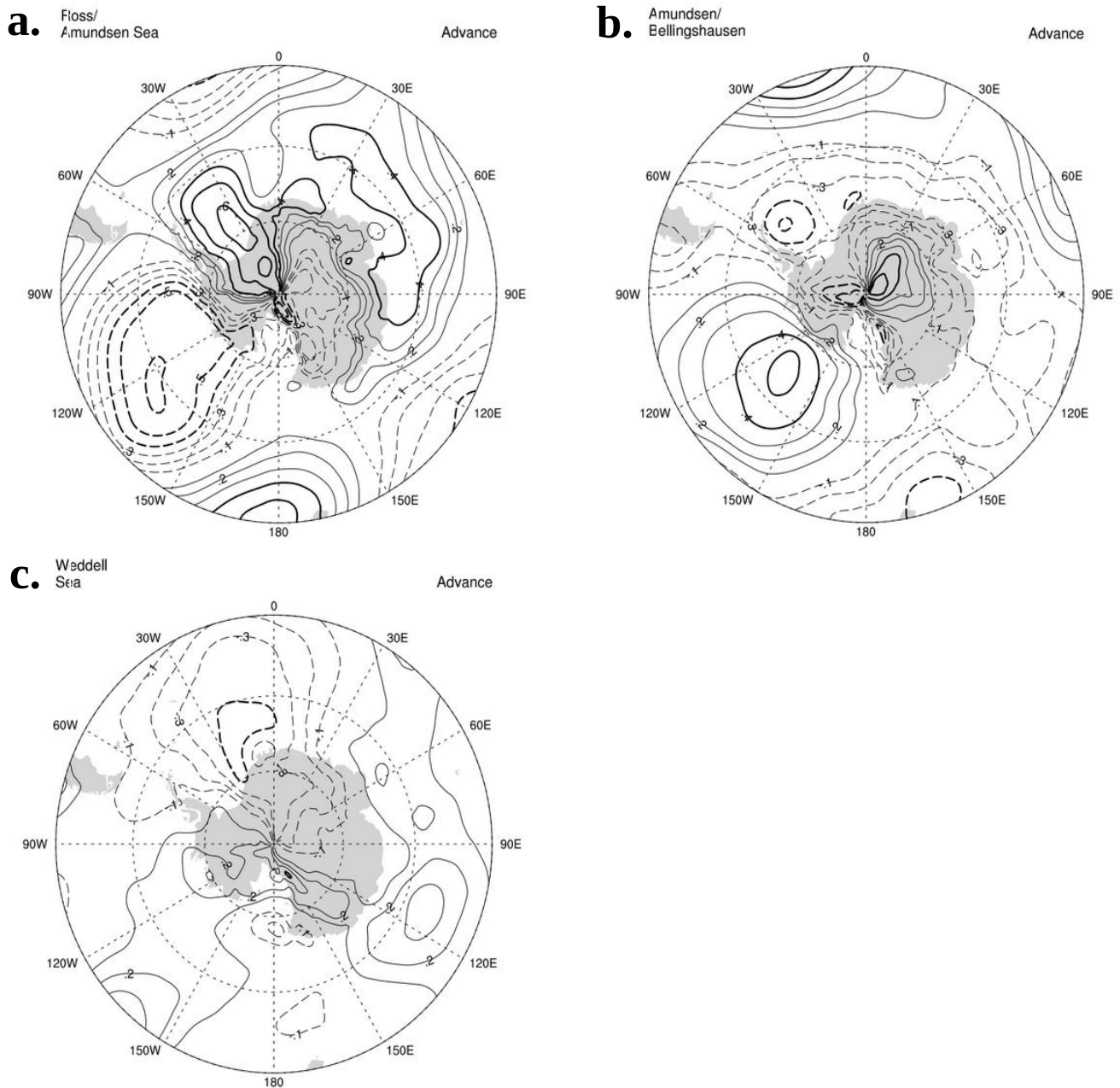


Figure 3. Maps showing correlations between zonal anomalies at 850 hPa geopotential height and SIE during advance season from 1979-2010 for a) Ross/Amundsen Sea, b) Amundsen/Bellingshausen, and c) Weddell Sea sectors. Bolded lines indicate correlations of ≥ 0.4 or ≤ -0.4 (dashed lines for negative correlations and solid lines for positive correlations). Monthly 850 hPa geopotential height data was retrieved from ERA-Interim analysis and monthly SIE data was taken from the National Snow and Ice Data Center. Shaded regions indicate continents.

Amundsen/Bellingshausen sector

The SIE in the Amundsen/Bellingshausen sector is positively correlated and statistically significant at $\alpha=0.05$ with zonal anomalies over the Ross/Amundsen Sea region and negatively correlated with zonal anomalies over a small region over the Weddell Sea close to the Antarctic Peninsula. The correlation implies a presence of clockwise flow around a low pressure over the ABS-Ross/Amundsen area that is bringing in warmer, northerly air towards the ABS region through its eastern flank, therefore contributing to a decrease in SIE in the ABS sector. The positive correlation with zonal anomalies in the Ross/Amundsen Sea corresponds to the trough found in this region while the negative correlations with zonal anomalies in the western Weddell region corresponds to the ridge over this area. Taken together, as the trough (ridge) becomes deeper (higher) in the Ross/Amundsen (western Weddell) region, the zonal anomalies are negative (positive), resulting in less SIE in the ABS region. The correlations with the ridge and trough of ZW3 suggest that the SIE in the ABS region may be influenced by the ZW3. The locations of the trough and ridge in these regions show a slight westward shift from the Ross/Amundsen (Figure 3a) to the ABS (Figure 3b).

Weddell Sea sector

Although not as strongly correlated as that in the ABS and Ross/Amundsen seas, the SIE in the Weddell Sea is significantly negatively correlated with zonal anomalies over a relatively small region in the southern Atlantic (Figure 3c). The correlation suggests the presence of a clockwise flow associated with a low pressure in this area bringing cooler air from the continent northwards in its western flank. This pattern corresponds to the trough associated with the ZW3 that is present over this region so as the zonal anomalies become more negative and the winds become stronger with the deepening of the trough, the winds will push sea ice northwards and

the cooler air from the pole will enhance sea ice production resulting in an increase in SIE in the Weddell sector.

Sector comparison

The regions of significant correlations in both the Ross/Amundsen and ABS sectors seem to correspond to the same trough and ridge system found over the Amundsen Sea and western Weddell regions respectively, as seen in Figure 1a. Their opposite correlations in sign indicates opposite sea ice responses to an increase in ZW3 amplitude, which is confirmed by observations of increasing sea ice trends in the Ross/Amundsen sea regions and decreasing sea ice trends in the ABS region (Stammerjohn et al., 2012; Turner et al, 2009; Yuan and Li, 2008). Relatively weaker but statistically significant negative correlation was found between SIE in the Weddell Sea sector with zonal anomalies located in the eastern Weddell Sea sector associated with a trough found in this region.

RH2014 correlated these sea ice sectors with the geopotential height at 500mb and found evidence of a relatively weak but clear correlation between ZW3 and sea ice in the Weddell Sea and ABS regions during the ice advance period. Figures 4a-4c show correlation between the whole 850 hPa field and SIE by each sector. In Figure 4a, there is a large region of significant negative correlation between the geopotential field and SIE in the Ross/Amundsen Sea in the South Pacific region. For the Amundsen/Bellingshausen Sea sector, there is a region of significant positive correlation in the Ross/Amundsen region. SIE in the Weddell Sea sector, on the other hand, has a small region of significant negative correlation in the South Atlantic. Figure 4a resembles the corresponding plot from RH2014 for the Ross/Amundsen Sea but shows some difference in the ABS and Weddell Sea plots. In RH2014, there is greater significant negative correlation in the South Atlantic that is also larger in area. Although the sign of correlation and

magnitude is about the same for SIE in the ABS sector, the location of significant positive correlation is more westwards in the corresponding RH2014 plot, which may be due to the difference in geopotential heights level and/or length of datasets used in that study.

Correlating SIE with zonal anomalies instead of the whole field in the 850 hPa geopotential height field revealed some different patterns of correlation but showed overall similarity in sign and location of correlations, except in the Weddell Sea sector where the area of significant negative correlation was smaller in size and located further north in the South Atlantic when correlating the whole field. Nevertheless, both sets of correlations demonstrate signs of ZW3's influence on SIE in the Weddell and ABS regions along with the Ross/Amundsen sector. It is also possible, however, that the correlation trends found in the ABS and Ross/Amundsen sectors could be influenced by the Amundsen Sea Low, which has been found to influence the climate and sea ice extent in the area from the Ross Sea to the ABS (Turner et al., 2012). The following sections will investigate the influence of ZW3 on SIC in the Ross, Weddell and ABS regions during ice advance season.

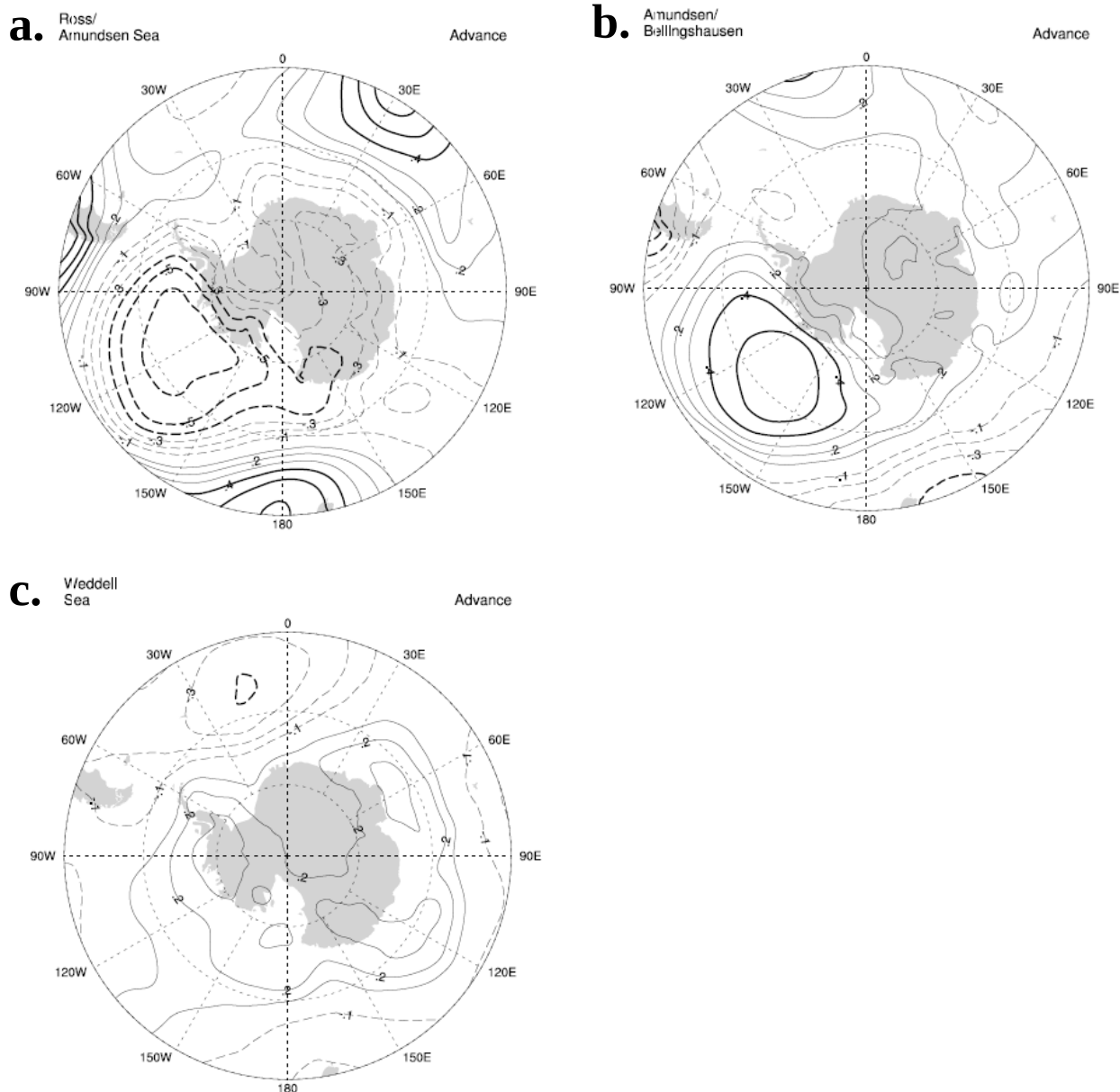


Figure 4. Maps showing correlations between geopotential height at 850 hPa and SIE during advance season from 1979-2010 for a) Ross/Amundsen Sea, b) Amundsen/Bellingshausen, and c) Weddell Sea sectors. Bolded lines indicate correlations of ≥ 0.4 or ≤ -0.4 (dashed lines for negative correlations and solid lines for positive correlations). Monthly 850 hPa geopotential height data was retrieved from ERA-Interim analysis and monthly SIE data was taken from the National Snow and Ice Data Center. Shaded regions represent continents.

4.2: ZW3 Index trends

Figure 5a shows the monthly ZW3 Index from 1970-2013, computed from the ERA-Interim 850 hPa geopotential height dataset. This index represents the amplitude of the ZW3. A positive index means that the geopotential height field is strongly meridional due to an enhancement of the ZW3's trough and ridge system, indicating stronger north/south airflow and transfer of energy, while a negative index indicates a strongly zonal geopotential height field, resulting in a reduced north/south transfer of airflow and energy. Intraseasonal variation can be seen in the index with the index often being positive during early winter and usually negative during spring. This significant difference between winter/spring phases occurs as the quasi-stationary ZW3 shifts from its winter location to its spring location. A large negative excursion in the index is apparent around late 1995, which coincides with when circulation patterns were found to be strongly zonal (Raphael, 2004).

While the previous section looked at the correlation between zonal anomalies and SIE during the advance season only, since that is when the ZW3 is expected to have the most influence on sea ice, this section will consider both seasons (advance and retreat) for comparison purposes. Figures 5b and 5c show the ZW3 index averaged over the advance and retreat seasons respectively (with different scales on the y-axis). Both show periods when the averaged index over the season is positive, indicating more meridional flow, as well as negative, indicating less meridional flow. Interestingly, the averaged index reaches highest values in the retreat seasons of 1985, 1993 and 2005 (suggesting strongly meridional flow during those seasons) while the index during the advance seasons of these same years were weaker in amplitude.

The slope of the trend spanning this period is not statistically significant unlike the trend found in Raphael (2007). However, that index spanned from 1958 to 2005, allowing a more

positive trend in the index starting from around 1979 to be revealed. It indicated a shift to more positive values, hence meridional flow. The trend could not be re-created here since the ERA-Interim data set used in this project to calculate the index starts from 1979.

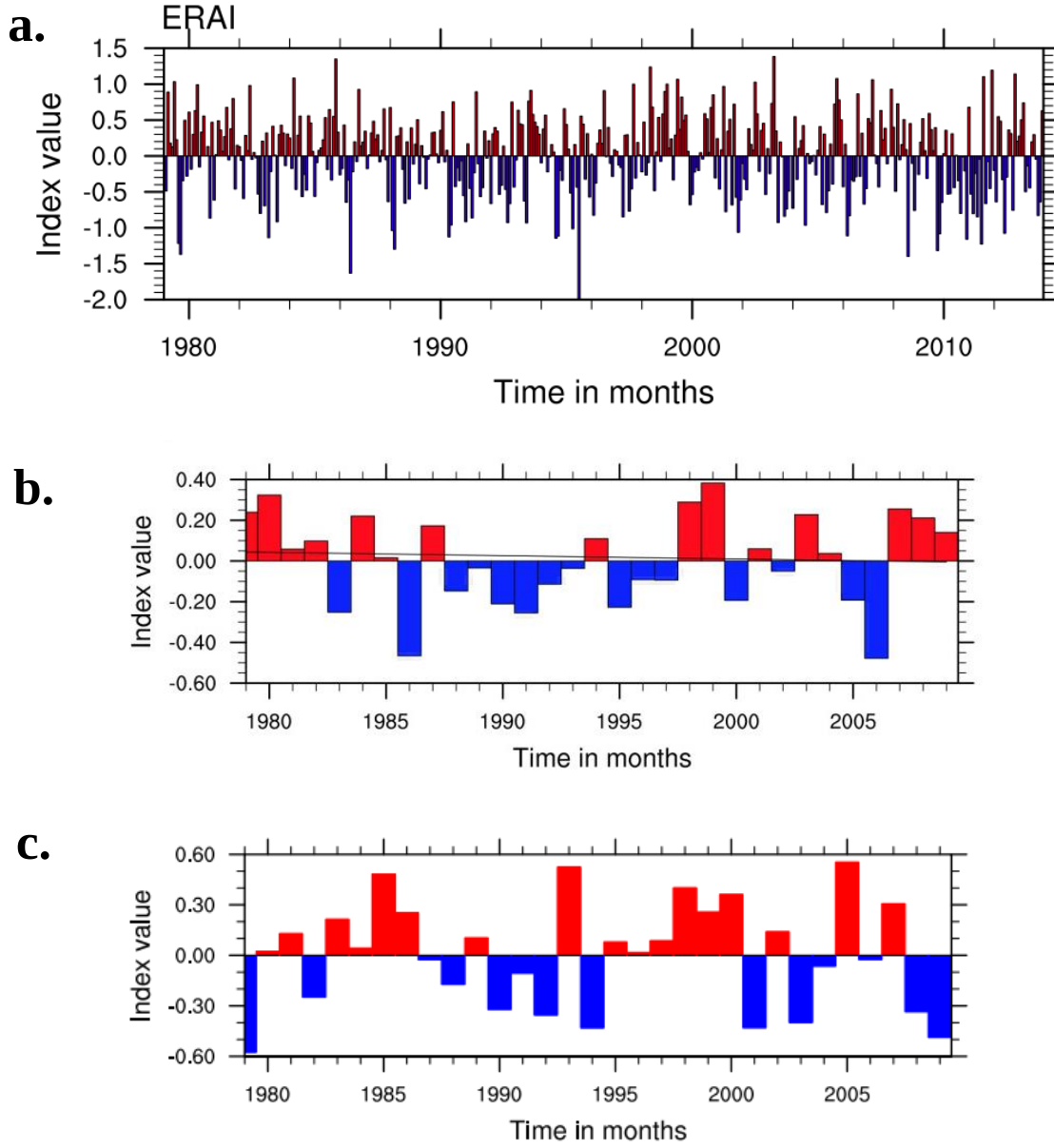


Figure 5. ZW3 indices spanning from 1979-2013. a) Monthly ZW representing the amplitude of the ZW3 and b) the ZW3 index averaged over the advance season (Mar-Aug) and c) retreat season (Oct-Feb). Index was calculated using zonal anomalies at the 850 hPa geopotential height from the ERA-Interim data set.

4.3: ZW3 and SIC Correlation and Regression

In order to examine the influence of ZW3 on SIC, the ZW3 index during advance and retreat seasons of each year was correlated with the SIC during advance and retreat seasons. The correlation relationship after de-trending both the ZW3 and SIC is depicted in Figure 6. Both positive and negative correlations can be found around the Antarctic sea ice field creating a pattern reminiscent of a wave three. During the advance season, significant positive correlation (coefficients being greater than or equal to 0.35) between sea ice and ZW3 is found in parts of the Ross Sea, northwestern regions of the Weddell and off the Amery ice shelf. The ABS region shows significant negative correlation near the northern sea ice edge as well as an area along the west Antarctic Peninsula (wAP). The overall patterns are similar between de-trended and trend-included (not shown) plots, especially during the retreat seasons, but with some small differences during the advance season in the western Ross Sea, the ABS region and a region along the wAP. Correlations during the retreat seasons are similar to what was found during the advance season and also show a wave three pattern. Some differences between the two include a larger area of significant correlation off the Amery ice shelf region and an area of significant negative correlation appearing in the western Ross Sea region during the retreat season. The shape of the correlation pattern in the Ross Sea also differs considerably between the two seasons.

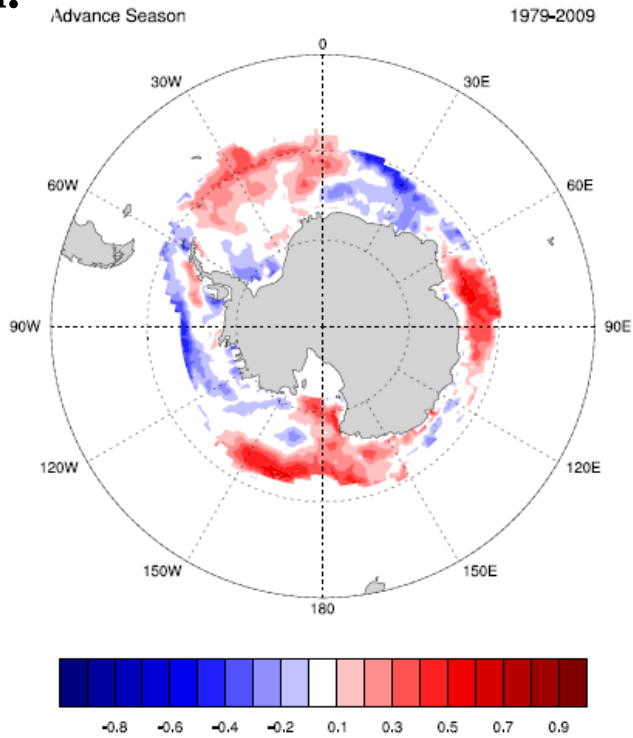
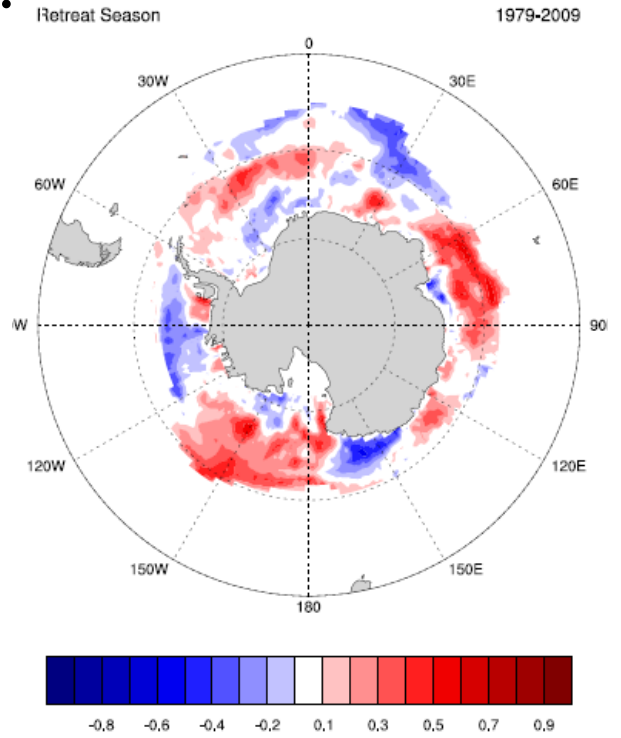
a.**b.**

Figure 6. Correlations between ZW3 and SIC from 1979-2009 with de-trended data during a) advance and b) retreat seasons. Correlation coefficients of ± 0.35 or higher are considered significant at $\alpha = 0.05$. Sea ice concentration data taken from the Hadley Center sea ice and sea surface temperature (SST) data set.

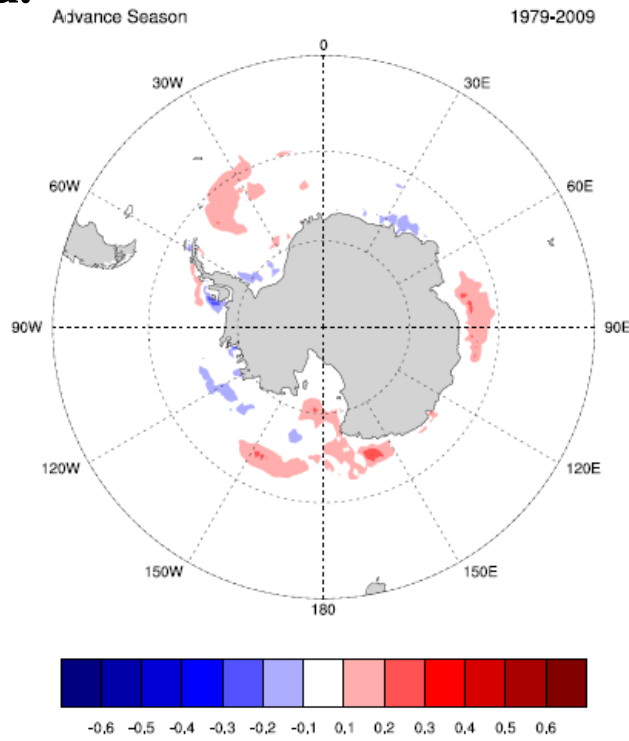
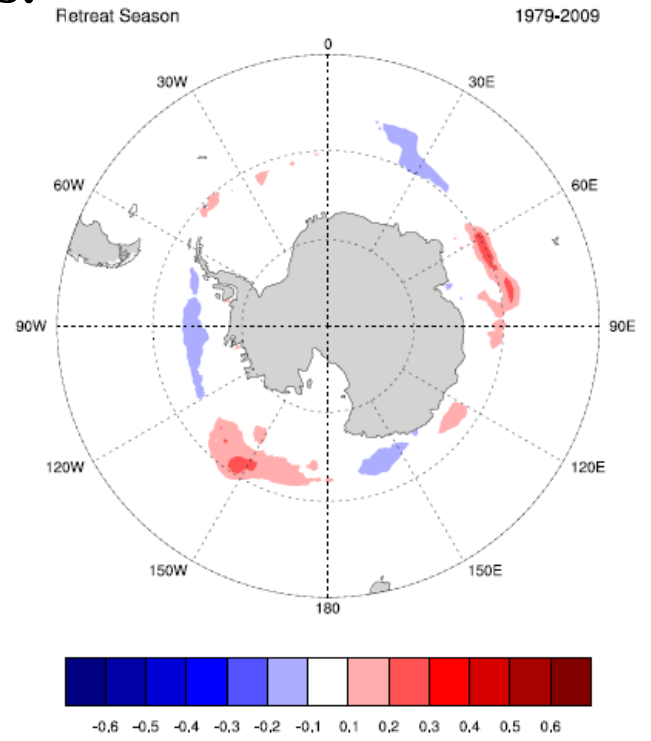
a.**b.**

Figure 7. Regression coefficients of SIC regressed on ZW3 during a) advance and b) retreat seasons from 1979-2009. Both SIC and ZW3 data sets were de-trended before regressing. Sea ice concentration data taken from the Hadley Center sea ice and sea surface temperature (SST) data set.

Regression between the ZW3 index during advance and retreat seasons of each year with the SIC during advance and retreat seasons showed a similar relationship and indicates where sea ice is dependent on ZW3 at a significant level. Figure 7 illustrates the regression coefficients obtained by regressing sea ice, the dependent variable in this analysis, on ZW3 index during advance and retreat seasons. Positive regression coefficients at significant levels (found using p-value test of <0.05) during the advance season were found in the inner, northern and western Ross Sea and off the Amery ice shelf. Significant negative coefficient values were found in some parts of the ice edge in the ABS region. Regression analysis during the retreat season indicates a significantly positive relationship between sea ice and ZW3 in the ice edge regions for both the Amundsen/Ross Sea and the Amery ice shelf regions and significantly negative relationship in the area along the wAP, the same area identified in the correlation plot from Figure 6. While the regression coefficients are smaller and the areal coverage is less than the correlation coefficients in the previous plots, the relationships depicted are still similar and serve to demonstrate where sea ice depends on ZW3 at a statistically significant level.

4.4: Discussion

The correlation between SIC and ZW3 during the advance season shows a clear wave three pattern influence. Regions of SIC found to be positively correlated during the advance season with ZW3 align with where southerly, equatorward flow associated with the wave are found, particularly in the Ross and Weddell Seas and off the Amery ice shelf (see Figure 1a). This southerly flow helps advect sea ice northwards dynamically through wind (increasing SIE) and increases SIC thermodynamically when the cooler air from the continent forces an increase in the upward flux from the ocean into the atmosphere (Holland and Kwok, 2012). Regions with negative correlation during the advance season, such as the ABS region, similarly align with

where northerly, poleward flow are found which brings warmer air from the lower latitudes and pushes sea ice towards the continent. The influence of ZW3 on sea ice through meridional transport of warmer or cooler air can be understood by examining the net sensible heat flux (and latent), or the transfer of sensible and latent heat between the atmosphere and ocean, associated with the flow. Regions with equatorward flow tend to have a positive sensible and latent heat flux due to an enhanced temperature gradient between the atmosphere and the ocean as a result of cooler air flow, which means more ocean heat loss to the atmosphere and therefore more sea ice production. The opposite is true for regions with poleward flow that brings warmer air and results in a negative sensible heat flux.

The correlation pattern in the Ross Sea resembles the shape of the mean SIC trends from 1979-2012, as seen in Figure 8 (King, 2014), suggesting that ZW3 may be contributing to the observed trend. The significance and direction of the regression analysis further suggests that SIC (and therefore SIE) is dependent upon ZW3. Both the regression and correlation plots indicate an influence of ZW3 on sea ice during the retreat season as well. As Figure 5c demonstrates, the index reaches high positive values on average during some years in the retreat season, indicating a relatively large amplitude of the wave occurring during this season.

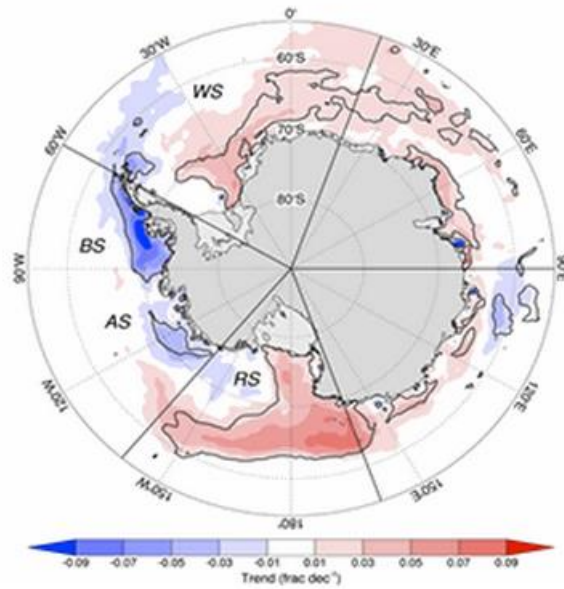


Figure 8. Map of sea ice trends in terms of fractional ice coverage per decade for 1979-2012 taken from King (2014). Bold line indicates enclosed areas where the trend is significant at 5% level. Sea ice data from the National Snow and Ice Data Center. Image from British Antarctic Survey.

Chapter 5: Conclusion

The results of this study suggest that ZW3 plays a role in the occurrence of the observed sea ice trends in the Ross Sea, ABS and off the Amery ice shelf regions as well as parts of the Weddell Sea during the ice advance season, the critical period for sea ice growth. Statistical analyses showed a significant dependence of SIC on ZW3 in the key regions associated with the wave. Sea ice extent reduced (increased) in the ABS region when ZW3 strengthened (weakened) since a poleward arm of the wave is found here during the advance period. Sea ice increased (reduced) in the Ross Sea, off the Amery ice shelf and parts of the Weddell Sea when the ZW3 strengthened (weakened). These regions are associated with equatorward arms of ZW3 as shown in Figure 1a. The dependency of sea ice on ZW3 found during retreat seasons in the ice edge of the ABS and parts of the wAP deserves further exploration. Previous work by Raphael (2007) examined the influence of ZW3 on SIC during April, May and June, months associated with the strongest phase of ZW3. This work re-examined the same relationship and did so in terms of the sea ice's seasonal cycles rather than atmosphere's in order to characterize better the sea ice response to ZW3 and also included four more years of data. The correlations from both the advance season period and AMJ show similar wave three pattern but closer comparison shows areas of more negative correlation during AMJ than the entire advance period. Furthermore, the correlation pattern in the Ross Sea in the advance season plot resembles the shape of the mean sea ice trends (Figure 8). These differences demonstrate that examining the influence on sea ice in terms of the ice seasons may provide a better understanding of the ZW3's impact on sea ice.

Overall, the results demonstrate that the ZW3 plays a role in influencing sea ice during the advance season in the Ross Sea, ABS as well as parts of the Weddell Sea and may help explain the recent sea ice trends, particularly in the Ross and ABS regions where the largest SIC

trends have been observed in the past three decades. This study, however, did not quantify the relative contribution of the ZW3 on influencing SIC/SIE nor did it take into account the spatial shift of ZW3 from its winter to spring location. However, the results suggest that re-examining and quantifying the influence of other atmospheric patterns on sea ice in terms of the sea ice seasons would allow firmer connections between the atmospheric circulation patterns and sea ice to be established. Creation of an index for ZW3 with a phase shift component also deserves important consideration in future works. Finally, based on the results of this study, the influence of ZW3, a predominantly winter mode, on sea ice during the retreat season also deserves further exploration.

References

- Allison, I., & Moritz, R. (1995). Sea ice in the global climate system: Requirements for an ocean observing system. Retrieved from http://oopc.info/documents/oosdp/oosdp_br7.pdf
- Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B., & Katsman, C. A. (2013). Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience*, 6(5), 376–379. doi:10.1038/ngeo1767
- Goosse, H. & Zunz, V. (2014). Decadal trends in the Antarctic sea ice extent ultimately controlled by ice–ocean feedback. *The Cryosphere*, 8, 453–470. www.the-cryosphere.net/8/453/2014/. doi:10.5194/tc-8-453-2014
- Hall, A., & Visbeck, M. (2002). Synchronous variability in the Southern Hemisphere atmosphere, sea ice, and ocean resulting from the Annular Mode. *Journal of Climate*, 15(21), 3043–3057.
- Harangozo, S. A. (2004). The relationship of Pacific deep tropical convection to the winter and springtime extratropical atmospheric circulation of the South Pacific in El Niño events. *Geophysical Research Letters*, 31(5). doi:10.1029/2003GL018667
- Haumann, F. A., Notz, D., & Schmidt, H. (2014). Anthropogenic influence on recent circulation-driven Antarctic sea-ice changes. *Geophysical Research Letters*, 41(23). doi:10.1002/2014GL061659
- Holland, P. R., & Kwok, R. (2012). Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience*, 5(12), 872–875. doi:10.1038/ngeo1627
- King, J. (2014). Climate science: A resolution of the Antarctic paradox. *Nature*, 505, 491–492. doi:10.1038/505491a
- Lieser, J.L., Massom, R.A., Fraser, A.D., Haward, M.G., Heil, P., Lannuzel, D., Meiners, K.M., Melbourne-Thomas, J., Press, A.J., & Williams, G.D. (2013). Position analysis: Antarctic sea ice and climate change 2014. *Antarctic Climate & Ecosystems Cooperative Research*

Centre.

- Liu, J., Curry, J., & Martinson, D. G. (2004). Interpretation of recent Antarctic sea ice variability. *Geophysical Research Letters*, 31 (2), L02205. doi:10.1029/2003GL018732
- Maksym, T., & Stammerjohn, S. (2012). Antarctic sea ice-A polar opposite? *Oceanography*, 25(3), 140–151. Retrieved from <http://ecite.utas.edu.au/82631>
- Meier, W. N., F. Fetterer, M. Savoie, S. Mallory, R. Duerr, & Stroeve, J. (2013). NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, 2nd ed., NSIDC, Boulder, Colorado.
- The NCAR Command Language (Version 6.2.1) [Software]. (2014). Boulder, Colorado: UCAR/NCAR/CISL/TDD. <http://dx.doi.org/10.5065/D6WD3XH5>
- Powell, D. C., T. Markus, & Stössel, A. (2005). Effects of snow depth forcing on Southern Ocean sea ice simulations. *Journal of Geophysical Research*, 110, C06001. doi:10.1029/2003JC002212.
- Raphael, M. N. (2004). A zonal wave 3 index for the Southern Hemisphere. *Geophysical Research Letters*, 31(23). doi:10.1029/2004GL020365
- Raphael, M. N. (2007). The influence of atmospheric zonal wave three on Antarctic sea ice variability. *Journal of Geophysical Research*, 112(D12), D12112. doi:10.1029/2006JD007852
- Raphael, M.N., & Hobbs, W. (2014). The influence of the large-scale atmospheric circulation on Antarctic sea ice during ice advance and retreat seasons. *Geophysical Research Letters*, 41, 5037–5045. doi:10.1002/2014GL060365.
- Reid, P., Stammerjohn, S., Massom, R., Scambos, T., & Lieser, J. (2015). The record 2013 Southern Hemisphere sea-ice extent maximum. *Annals of Glaciology*, 56(69). doi:10.3189/2015AoG69A892

- Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., & Kaplan, A. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, 108, 4407. doi:10.1029/2002JD002670
- Stammerjohn, S. E., Martinson, D. G., Smith, R. C., Yuan, X., & Rind, D. (2008). Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–Southern Oscillation and Southern Annular Mode variability. *Journal of Geophysical Research*, 113(C3), C03S90. doi:10.1029/2007JC004269
- Stammerjohn, S., Massom, R., Rind, D., & Martinson, D. (2012). Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. *Geophysical Research Letters*, 39(6). doi:10.1029/2012GL050874
- Swart, N. C., & Fyfe, J. C. (2013). The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends. *Geophysical Research Letters*, 40, 4328–4332, doi:10.1002/grl.50820
- Turner, J., Comiso, J.C., Marshall, G.J., Lachlan-Cope, T.A., Bracegirdle, T., Maksym, T., Meredith, M.P., Wang, Z., & Orr, A. (2009). Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. *Geophysical Research Letters*, 36(8). doi:10.1029/2009GL037524
- Turner, J., Phillips, T., Hosking, S., Marshall, G.J., & Orr, A. (2012). The Amundsen Sea Low. *Internal Journal of Climatology*, 33, 1818–1829. doi:10.1002/joc.3558
- Turner, J., Hosking, J.S., Bracegirdle, T.J., Marshall, G.J., Phillips, T. (2015). Recent changes in Antarctic sea ice. *Philosophical Transactions Royal Society A*, 373: 20140163. <http://dx.doi.org/10.1098/rsta.2014.0163>
- Yuan, X., & Li, C. (2008). Climate modes in southern high latitudes and their impacts on Antarctic sea ice. *Journal of Geophysical Research*, 113(C6), C06S91. doi:10.1029/2006JC004067
- Zhang, J. (2007). Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. *Journal of Climate*, 20(11), 2515–2529. doi:10.1175/JCLI4136.1