The Combined Influence of ENSO and SAM on Antarctic Climate Variability in

Austral Spring

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ABSTRACT

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The Combined Influence of ENSO and SAM on Antarctic Climate Variability in Austral Spring

Director of Thesis: Ryan L. Fogt

Recent studies have identified significant warming trends across West Antarctica and the Antarctic Peninsula, which is likely linked to tropical forcing. Consistent with the warming trends are significant changes in sea ice concentration in the Ross, Amundsen, and Bellingshausen Seas. This study investigates changes in the regional circulation associated with the Amundsen-Bellingshausen Seas Low (ABSL) and the role that these changes have on the temperature trends during austral spring. Further, this study investigates temporal variations in El Niño-Southern Oscillation (ENSO)-related tropical forcing and Southern Annular Mode (SAM)-related forcing on the ABSL and the regional climate during austral spring.

Based on gridded climatological data, a statistically significant deepening of the ABSL in the Ross Sea region and increases in pressure/geopotential height to the northeast of the Antarctic Peninsula during austral spring over the period 1979-2012 is detected. Consistent with these trends are a strengthening of the meridional winds, with increased warm (cold) air advection onto western West Antarctica (the Ross Sea) associated with the deepening pressure in the Ross Sea region, and increased warm air advection onto the western Antarctic Peninsula associated with the strengthening high pressure to the northeast of the Peninsula. The ABSL trends
in the Ross Sea are likely related to outgoing longwave radiation (OLR) in the Niño 1+2 region in the far eastern tropical Pacific, and the pressure/geopotential height trends to the northeast of the Antarctic Peninsula are likely associated with trends in the Southern Oscillation Index (SOI), a measure of ENSO variability. Based on these connections, more than half of the warming along the Antarctic Peninsula is congruent with trends in the SOI (towards more La Niña-like conditions), while nearly half of the warming across western West Antarctica is congruent with trends in the Niño 1+2 region.

This study also finds a spatial and temporal dependency regarding the impacts that SAM and ENSO have on the Antarctic Peninsula during austral spring: relationships with ENSO and Antarctic Peninsula climate are persistent and statistically significant across the western Peninsula, while relationships with the SAM are persistent and statistically significant across the northeastern Peninsula. Other ENSO/SAM-Peninsula temperature correlations appear weak over the full period of record as they vary temporally, fluctuating in response to changing correlations between the SAM index and SOI in austral spring. Changes in the SOI-SAM correlations are due primarily to the 1988 La Niña/SAM negative event, which significantly altered the location of the ENSO teleconnection in the South Pacific Ocean and, therefore, its influence on the regional climate. Whether or not there is decadal variability in the ENSO-SAM relationship remains unclear; however, it is evident that the influence across the Peninsula varies in both space and time, related to the strength and spatial extent of the response in the Amundsen-Bellingshausen
Seas. This suggests that in order to accurately attribute the regional warming to ENSO-related tropical forcing, it is necessary to consider the role of the regional circulation manifested by the phase of each climate mode together.
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TABLE OF CONTENTS

Page

Abstract................................................................................................................................................. 3

Acknowledgments.............................................................................................................................. 6

List of Tables......................................................................................................................................... 10

List of Figures......................................................................................................................................... 11

Chapter 1: Introduction......................................................................................................................... 16

Chapter 2: Literature Review............................................................................................................... 24
  2.1 The El Niño-Southern Oscillation and Teleconnection............................................................... 24
  2.2 The Southern Hemisphere Annular Mode.................................................................................. 36
  2.3 ENSO and SAM Together.......................................................................................................... 49
  2.4 The Amundsen-Bellingshausen Seas Low.................................................................................. 66
  2.5 Antarctic Climate and Climate Change...................................................................................... 78

Chapter 3: Data and Methods............................................................................................................. 88
  3.1 Data Utilized..................................................................................................................................... 88
    3.1.1 Reanalysis Data...................................................................................................................... 88
    3.1.2 Observation Data.................................................................................................................. 90
    3.1.3 Climate Data........................................................................................................................ 92
  3.2 Analysis Techniques..................................................................................................................... 93
    3.2.1 Linear Association............................................................................................................... 93
    3.2.2 Linear Trends....................................................................................................................... 97
    3.2.3 Composite Analysis.......................................................................................................... 101
Chapter 4: Results

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Seasonal Trends and Relationships</td>
<td>104</td>
</tr>
<tr>
<td>4.2</td>
<td>SON Spatial Trends and Relationships</td>
<td>117</td>
</tr>
<tr>
<td>4.3</td>
<td>SON Linear Congruency</td>
<td>133</td>
</tr>
<tr>
<td>4.4</td>
<td>SON Time-Varying Relationships</td>
<td>138</td>
</tr>
<tr>
<td>4.5</td>
<td>SON Atmospheric Circulation Composites</td>
<td>149</td>
</tr>
<tr>
<td>4.6</td>
<td>The 1988 SON La Niña/SAM Negative Event</td>
<td>156</td>
</tr>
<tr>
<td>4.7</td>
<td>Chapter Summary</td>
<td>162</td>
</tr>
<tr>
<td>4.7.1</td>
<td>Why Spring?</td>
<td>162</td>
</tr>
<tr>
<td>4.7.2</td>
<td>Regional Circulation Changes</td>
<td>163</td>
</tr>
<tr>
<td>4.7.3</td>
<td>Combined Role of ENSO and SAM on Antarctic Peninsula Climate</td>
<td>165</td>
</tr>
</tbody>
</table>

Chapter 5: Summary and Conclusions

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chapter Summary</td>
<td>166</td>
</tr>
</tbody>
</table>

References

<table>
<thead>
<tr>
<th>References</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>174</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Page

TABLE 3.1: Antarctic Peninsula station data used in this study. .......................... 90

TABLE 4.1: Seasonal trends for Marshall (2003) SAM index and SOI (units of standardized index/decade), tropical Pacific SSTs (units of °C/decade), tropical Pacific OLR (units of W m⁻²/decade), Antarctic Peninsula and Byrd reconstructed station temperatures (units of °C/decade), West Antarctic ERA-Interim 2-meter temperature (units of °C/decade), and ABSL central pressure (units in hPa/decade), longitude (units of °East/decade) and latitude (units of °latitude/decade). Trends are calculated for the full period of record (or 1957, whichever is later) ending at 2012 (first column), and over the period 1979-2012 (second column). .............................................................. 107

TABLE 4.2a: Austral summer and autumn seasonal correlations of Antarctic temperatures and ABSL with the Marshall (2003) SAM index and SOI over the full period of record (as indicated in TABLE 4.1) and 1979-2012. ............. 112

TABLE 4.2b: Austral winter and spring seasonal correlations of Antarctic temperatures and ABSL with the Marshall (2003) SAM index and SOI over the full period of record (as indicated in TABLE 4.1) and 1979-2012. ............. 113

TABLE 4.3: SON temperature trends (units of °C/decade; as in Table 4.1) and linear congruency with SOI and OLR 1+2. The temperature trends are located in columns 1 and 3. The linearly congruent portion of the temperature trends (congruent) with respect to the SOI and OLR 1+2 trends is located in columns 2 and 5, respectively. The linearly independent portion of the temperature trends (residual) with respect to the SOI and OLR 1+2 trends is located in columns 3 and 6, respectively. ................................................................. 134

TABLE 4.4: SON detrended regression coefficients and 95% confidence intervals for Antarctic temperature data and ABSL minimum pressure, and SOI, OLR 1+2, and Marshall (2003) SAM index over the period 1979-2012. Units are °C/standardized index for temperature data and hPa/standardized index for ABSL pressure data. .................................................................................. 139

TABLE 4.5: SON years (in rank order) used to create the anomaly composites for Fig. 4.10. The phases are based on when the climate index (SAM index and either the SOI or Niño 3.4 SSTs) is above or below the 70th or 30th percentile, respectively. LN = La Niña, EN = El Niño. ................................................................. 154
LIST OF FIGURES

FIG. 1.1: Map of Antarctica and surrounded seas. Displayed on the map are
the names and locations of automated and manned Antarctic weather stations.
From Colwell et al. (2012). ................................................................. 18

FIG. 2.1: The equatorial east-west vertical circulation for the peak of (a) an
El Niño event (January 1998) and (b) a La Niña event (January 1999).
Streamlines represent the atmospheric flow calculated from the divergent
component of the winds, and upward/downward vertical motions are
shaded (note positive shading = upward vertical motion). From Lau and
Yang (2002). .................................................................................................. 27

FIG. 2.2: Schematic illustration of upper tropospheric height anomalies over
the Pacific Ocean during (a) the early stage of an El Niño event during austral
winter and (b) the mature stage of an El Niño event during austral summer.
The gray shading represents the region of enhanced tropical convection in
the central tropical Pacific, and the arrows represent the zonal wind
anomalies in the jet streams. From Karoly (1989). .............................................. 29

FIG. 2.3: The two leading empirical orthogonal functions (EOFs) for the 200
hPa eddy streamfunction field. Note that both EOFs represent the two
leading PSA modes. From Mo and Higgins (1998). .............................................. 31

FIG. 2.4: Austral winter (June–August) 500 hPa height anomalies across the
extratropical South Pacific during (a) eight El Niño and (b) six La Niña cases

FIG. 2.5: Leading eigenvector map of (top) daily SLP anomalies during DJF
and (bottom) daily 500 hPa height anomalies during DJF. Solid lines indicate
positive numerical values, and dashed lines indicate negative numerical
values. From Rogers and van Loon (1982). .................................................. 37

FIG. 2.6: Leading EOFs of the (left column) SH monthly mean 850 hPa height
anomalies and (right column) NH monthly mean SLP anomalies for (top)
November–April and (bottom) May–October. Displayed as regression maps
based on their standardized principal component (PC) time series. From
Thompson and Wallace (2000). ................................................................. 39

FIG. 2.7: Multimodel average of the annular principal component (PC)
composited according to whether the model includes (red) or omits (blue)
forcing by stratospheric ozone. From Miller et al. (2006). ................................ 44

FIG. 2.9: (top; a) Annually averaged correlation between the seasonal mean SLP and the seasonal mean SAM index for the period 1960-1999. (bottom; b) Annually averaged regression (in Pascals) between the seasonal mean SLP and the seasonal mean SAM index. Modified from Lefebvre et al. (2004). .......... 48

FIG. 2.10: Monthly mean zonal-mean (left) zonal wind anomalies and (right) temperature anomalies regressed onto inverted CTI time series values for (top) austral summer (November – February) and (bottom) austral winter (May – August). Shading denotes significance at $p<0.05$ based on a one-tailed $t$-test. From L’Heureux and Thompson (2006). .............................................. 50

FIG. 2.11: Annual spatial correlations of ERA-40 MSLP and the SOI for (a) the 1980s and (b) the 1990s. Station MSLP-SOI correlations are also plotted for select stations south of 30°S. Shading denotes significance of the correlations. From Fogt and Bromwich (2006). ............................................. 52

FIG. 2.12: Annual NNR MSLP anomaly composites for ENSO and SAM events occurring separately (a-d) and together (e-h). From Fogt et al. (2011). ............ 54

FIG. 2.13: Schematic showing the role of subtropical jet and mid-latitude jet in shaping the SAM during nonsummer seasons. From Ding et al. (2012). ...... 59

FIG. 2.14: ERA-40 300 hPa average zonal wind over the period 1979–2001 (shaded) by season for SAM+ (a, c, e, g) and SAM- (b, d, f, h). Contours denote regions where the correlation of the ERA-40 transient asymmetric SAM indices (during 1979–2001) with the 300-hPa zonal wind is statistically different from zero at the $p<0.05$ level. From Fogt et al. (2012b). ................................................................. 60

FIG. 2.15: Decadal composite differences (1990s minus 1980s) of sea ice advance (color shading) and MAM SLP (color contours) anomalies for (a) 1990s La Niña/SAM+ minus 1980s El Niño/SAM- events and (b) 1990s SAM+ minus 1980s SAM-. From Stammerjohn et al. (2008). ............ 63

FIG. 2.16: Correlations (colored dots) between the transient asymmetric SAM indices and station temperatures by season for SAM+ (a, c, e, g) and SAM- (b, d, f, h). Correlations calculated over the period 1958-2001. Contours are the transient asymmetric SAM pattern. From Fogt et al. (2012b). ..................... 65
FIG. 2.17: Map displaying the ABSL region (45°-75°S, 180°-60°W), including the Ross, Amundsen, and Bellingshausen Seas. From Fogt et al. (2012a).

FIG. 2.18: Seasonal cycles of the latitude (a-c), longitude (d-f), and magnitude (g-i) of the monthly minimum pressure in the ABSL region from three different atmospheric reanalyses. The dark shaded region represents the interquartile range, and the light shaded region bounds the minimum and maximum values of each variable over the period 1979-2001. From Fogt et al. (2012a).

FIG. 2.19: Comparison of the climatological (1979-2001) ABSL magnitude and position with the magnitude and position of maximum cyclone density and minimum cyclone central pressure. Cyclone and ABSL data are shown for ERA-40, JRA-25, and NNR reanalyses. From Fogt et al. (2012a).

FIG. 2.20: Map of Antarctica with locations of the 19 selected research stations represented by labeled dots. From Turner et al. (2005).

FIG. 2.21: Mean annual temperature trends (in degrees Celsius per decade) from infrared satellite reconstruction. Depicted are mean annual trends for a) 1957-2006 and b) 1969-2000, and 1957-2006 mean seasonal trends for c) austral winter, d) spring, e) summer, and f) autumn. From Steig et al. (2009).

FIG. 2.22: Temperature time series from the reconstructed Byrd Station record for a) annual, b) summer, c) autumn, d) winter, and e) spring. Red dots represent periods where greater than 1/3 of the observations are missing. The grey line represents the 5-year running average temperature, and the grey histograms represent the number of monthly mean temperature observations available per year (a) or per season (b-e). From Bromwich et al. (2013).

FIG. 4.1: Map showing the locations of the ABSL region and the Antarctic Peninsula stations used in the study. From Clem and Fogt (2014).

FIG. 4.2: ERA-Interim SON trends for a) 500 hPa geopotential height, b) MSLP, c) 2-meter temperature, and d) 10-meter meridional wind (positive=southerly wind) over the period 1979-2012. Trend values are contoured and labeled on the map, trend units are labeled in the titles, and statistical significance is shaded.

FIG. 4.3: As in Fig. 4.2, except for the West Antarctic/Antarctic Peninsula region only.
FIG. 4.4: SON Detrended teleconnection maps between the SOI and ERA-Interim a) 500 hPa geopotential height, b) MSLP, and c) 2-meter temperature. Correlation coefficient values are contoured and labeled on the map, and the significance of the correlations is shaded. ........................................ 126

FIG. 4.5: As in Fig. 4.4, except for OLR in Niño 1+2 region. ........................................ 129

FIG. 4.6: As in Fig. 4.5, except for Byrd station temperatures. ........................................ 132

FIG. 4.7: Running SON decadal correlation (i.e., 1980 represents the 1980-1989 10-year correlation) for a) persistent correlations between the SOI and the SAM index and Antarctic Peninsula temperatures and b) time-varying correlations between the SOI and the SAM index with Antarctic Peninsula temperatures. In both Figs. 2a and 2b, the running SON decadal correlation between the SOI and the SAM index is plotted as a solid black line. ................................................................. 143

FIG. 4.8: Running SON decadal correlations for the SOI and the SAM index with the ABSL minimum central pressure. ................................................................. 147

FIG. 4.9: Anomaly composites of top simultaneous strong (top 70th percentile) in-phase ENSO and SAM austral spring events based on the ERA-Interim reanalysis compared to the 1981-2010 climatology. Composites are for a) La Niña / SAM+ MSLP; b) El Niño / SAM- MSLP; c) La Niña / SAM+ meridional wind; d) El Niño / SAM- meridional wind. Shading indicates anomalies statistically different from zero at $p<0.10$, $p<0.05$, and $p<0.01$. ........................................................................................................... 150

FIG. 4.10: As in Fig. 4.9, but for ERA-Interim MSLP anomalies vs. the 1981-2010 climatology during the top five highest (Warm) and lowest (Cold) spring temperatures across the Antarctic Peninsula. The western Peninsula (W, Figs. 5a,c) consists of Rothera and Faraday stations, while the northeast Peninsula (NE; Figs. 5b,d) consists of Esperanza and Marambio stations (see Table 3.1 for reference and Fig. 4.1 for locations). ................................................................. 153

FIG. 4.11: SON decadal running correlation between the SOI and the SAM index with (solid line) and without (dashed line) the 1988 La Niña/SAM negative event. ................................................................. 157
FIG. 4.12: ERA-Interim 1988 SON La Niña/SAM- event compared to La Niña years (left column; La Niña conditions contoured, 1988 anomalies shaded) and the 1981-2010 climatology (right column; anomalies contoured and standard deviations from climatology shaded) for a-d) SON; e-f) October 1988 only. a-b;e-f) 500 hPa height; c-d) 2 m temperature. Nine La Niña events during SON identified by the CPC (1983, 1984, 1988, 1995, 1998, 1999, 2000, 2007, 2010) were used in creating the composites for the right column.

FIG. 4.13: Schematic showing the SON warming across West Antarctica and the Antarctic Peninsula (red shading), the pressure trends (red L=negative pressure trends; blue H=positive pressure trends), and associated warm, northerly wind trends (red arrows). Modified from Fogt et al. (2012a).
CHAPTER 1: INTRODUCTION

Over the last several years, studies have revealed that West Antarctica and the Antarctic Peninsula are among the most rapidly warming places on earth (Turner et al. 2005; Steig et al. 2009; Bromwich et al. 2013). One of the first studies to examine trends in the Antarctic observation data was conducted by Turner et al. (2005), who found statistically significant warming trends along the western flank of the Antarctic Peninsula that were five times stronger than the global average warming. In particular, in this study the warming along the Peninsula was observed to be strongest during austral winter (June-August, hereafter JJA). Statistically significant warming has also been observed across West Antarctica (Steig et al. 2009; Bromwich et al. 2013). Recent temperature reconstruction studies by Steig et al. (2009) and Bromwich et al. (2013) found the warming across West Antarctica to be most marked during austral spring (September-November, hereafter SON).

Consistent with the warming trends are changes in the nearby sea ice conditions, especially in the Amundsen and Bellingshausen Seas. Stammerjohn et al. (2008, 2012) showed statistically significant decreases in sea ice season length in the Bellingshausen Sea and eastern Amundsen Sea (off the west coast of the Antarctic Peninsula), including a later than normal advance in sea ice during austral autumn (March-May, hereafter MAM) and an earlier than normal retreat in sea ice during SON. In addition to a decrease in sea ice season length, Comiso (2010) and Massom et al. (2012) observed an overall decrease in sea ice concentration and extent in the Bellingshausen Sea.
Interestingly, neither the temperature trends nor the sea ice trends are uniform across interior and coastal Antarctica. In the Steig et al. (2009) temperature reconstruction study, weak cooling trends were observed across much of East Antarctica over the period 1969-2000. Although not statistically significant, the sign of the temperature trends are opposite of those across West Antarctica. There also exists a regional disparity in sea ice trends around Antarctica. Zwally et al. (2002) found that over the period 1979-1998, the total Antarctic sea ice extent exhibited a statistically significant annual increase. Further, Stammerjohn et al. (2008, 2012) observed that sea ice has been advancing earlier than normal during MAM in the Ross Sea region, and the overall sea ice season length has also been increasing in this region. In contrast, the sea ice season was decreasing in the adjacent Amundsen and Bellingshausen Seas, where sea ice extent was also decreasing. These studies provide evidence that the temperature and sea ice trends across the high latitude Southern Hemisphere are not uniform across space, and that there exists strong regional variations.

A map of the regions discussed above is provided below in Fig. 1.1. From Fig. 1.1, it is evident that there is a geographical asymmetry in the continent, with East Antarctica extending much more uniformly equatorward, and West Antarctica positioned further poleward and with less zonal symmetry along the coast. Depicted in Fig. 1.1 also are the surrounding Seas. The Bellingshausen Sea is located off the west coast of the Antarctic Peninsula, and the Bellingshausen, Amundsen, and Ross Seas comprise the coastal waters of West Antarctica. These three seas are located in the South Pacific sector of the Southern Hemisphere. The Ross Sea lies partially in both the Western and Eastern
FIG. 1.1: Map of Antarctica and surrounded seas. Displayed on the map are the names and locations of automated and manned Antarctic weather stations. From Colwell et al. (2012).

Hemisphere, and thus occupies the coastal portion that separates the geographical boundary between West and East Antarctica in the South Pacific/Indian Ocean sector.

A possible explanation for the asymmetry in observed temperature and sea ice trends across and around Antarctica are changes in the regional atmospheric circulation. Recall that the sea ice season length and concentration have been decreasing in the Amundsen and Bellingshausen Seas regions and temperatures have been increasing across the Antarctic Peninsula and West Antarctica. In contrast, sea ice season length and extent has been increasing in the nearby Ross Sea region. The dominant mode of regional
atmospheric circulation in this region is a semi-permanent cyclone called the Amundsen-Bellingshausen Seas Low (ABSL). The ABSL is defined as an area of relatively low surface pressure and geopotential height found on monthly, seasonal, and annual time scales in the Amundsen and Bellingshausen Seas region, which is located in the extreme southeast portion of the South Pacific (Fogt et al. 2012a; Turner et al. 2013). Due to the clockwise atmospheric circulation around the ABSL, relatively warm, northerly flow is commonly found on the eastern side of the low pressure center, near the Antarctic Peninsula and Bellingshausen Sea region, while relatively cold, southerly flow is found on the western side of the low pressure center across the Ross Sea and Ross Ice Shelf. Simply based on the geostrophic winds around this low pressure center, the strength and position of the ABSL strongly affects the local climate in this region, including temperature, precipitation, and sea ice conditions (Stammerjohn et al. 2008, 2012; Hosking et al. 2013). Fogt et al. (2012a) demonstrated that the ABSL is comprised of persistent, individual cyclones moving within the vicinity, and that the strength of the cyclones has been increasing during SON in the Ross Sea sector of the ABSL region. Although not explicitly linked, the increasing strength of cyclones in the Ross Sea region would be associated with an increase in the poleward transport of relatively warm, maritime air onshore across West Antarctica, consistent with the warming across West Antarctica during SON.

Recent studies have pointed to the important role that forcing from the tropics plays in altering the atmospheric circulation in the Amundsen and Bellingshausen Seas region, which could also be linked to the observed warming across West Antarctica and
the Antarctic Peninsula (Schneider and Steig 2008; Ding et al. 2011; Schneider et al. 2012a,b). In particular, several studies have noted strong temporal variability in the tropical forcing across the South Pacific, including in the Amundsen and Bellingshausen Seas, especially when considering teleconnections arising from the El Niño – Southern Oscillation (ENSO; Fogt and Bromwich 2006; Fogt et al. 2011). During La Niña events, negative sea level pressure and geopotential height anomalies are found in the high latitude South Pacific, signifying a deepening of the ABSL, while the ABSL tends to be weaker than normal during El Niño events (Turner 2004).

Another pattern of large-scale climate variability known to influence the Antarctic climate, and therefore likely related to the ongoing warming, is the Southern Annular Mode (SAM). Defined as the strength of the meridional (north-to-south) pressure gradient between the middle and high southern latitudes, the SAM is the leading pattern of atmospheric variability across the extratropical Southern Hemisphere. When the SAM is in its negative phase, the strength of the meridional pressure gradient is weaker than normal, while a stronger than normal pressure gradient is observed during positive phases of the SAM. The sign and magnitude of the SAM strongly influences the strength and position of the polar front jet that flows west to east around the Antarctic continent, and therefore is associated with temperature variability across coastal and interior Antarctica (Thompson and Wallace 2000; Thompson and Solomon 2002).

While it may appear that tropical (SAM) forcing on the Antarctic climate is independent of the SAM (tropics), this is not entirely the case. Fogt and Bromwich (2006) and Fogt et al. (2011) found that the strength of the ENSO teleconnection to the
South Pacific is strongly influenced by the sign and magnitude of the SAM. Fogt and Bromwich (2006) and Fogt et al. (2011) found that when an El Niño (La Niña) event occurs with a negative (positive) SAM event, the two climate modes are said to be ‘in phase’, and the ENSO teleconnection to the South Pacific is stronger than average. In contrast, they note that when ENSO and SAM are ‘out of phase’ (when an El Niño (La Niña) event occurs with a positive (negative) SAM event), the teleconnection is significantly weakened or altogether absent.

As it stands currently, the many possible mechanisms described above are likely in some way related to the warming trends and the overall climate variability from the Antarctic Peninsula and West Antarctica. From Fogt et al. (2012a), it is possible that strengthening of cyclones in the Ross Sea region could be linked to the warming across West Antarctica. However, there is no literature explicitly linking the strengthening of the ABSL to warming across West Antarctica; these mechanisms are only suggested and never proven definitively. Further, there is no literature explaining why the ABSL is strengthening in the Ross Sea, nor does the literature explain how outside atmospheric forcing, such as local forcing from the SAM and external forcing from the tropics, interact with the ABSL to modulate regional circulation changes and local climate. Nevertheless, it is concluded from the literature that the cause of the asymmetric warming and sea ice changes across Antarctica is rooted in changes in the regional atmospheric circulation, but explicit physical and statistical relationships have yet to be established. Further, despite a well-established relationship between ENSO and atmospheric pressure variability in the ABSL region, many of the studies discussed here have only
demonstrated that tropically induced pressure variability in the ABSL region is consistent with the observed warming and sea ice trends; again, an explicit relationship between the tropics and the West Antarctic and Antarctic Peninsula climate has yet to be made, especially during seasons of maximum warming (austral spring and winter). Lastly, other than the relationship between ENSO and SAM influencing the strength of the ENSO-induced pressure and geopotential height signal in the ABSL region, there is very little known about the combined influence that ENSO and SAM have on modulating the regional climate.

To fill in these gaps in the literature, this study will investigate the role that changes in local circulation in the ABSL region have on influencing the local West Antarctic and Antarctic Peninsula climate. Further, this study will examine the combined role that ENSO and SAM have on modulating circulation variability in the ABSL region, and how the combined role of ENSO and SAM influence the ABSL to ultimately induce changes in the local climate. Unlike previous studies, precise statistical relationships will be established, and the circulation changes and patterns will be investigated to provide a physical understanding behind the ongoing changes in the regional climate. By better understanding how changes in the ABSL influence the local climate and how these changes are linked to forcing mechanisms such as ENSO and SAM, scientists will be able to more fully diagnose the causes of the warming and sea ice changes across the Antarctic Peninsula and West Antarctic region. Further, with an improved understanding of how the ABSL responds to ENSO and SAM and how this response influences the
local climate, scientists will be able to better predict how the Antarctic climate will change in the future.
2.1 The El Niño–Southern Oscillation and Teleconnection

The El Niño–Southern Oscillation (ENSO) is a natural component of the global climate system. It represents the zonal advance and retreat, or oscillation, of sea surface temperature (SST) anomalies across the tropical Pacific Ocean, and the associated atmospheric response to these anomalies. The atmospheric component of this phenomenon, called the Southern Oscillation, was first discovered by H. H. Hildebrandsson in 1897 and later confirmed by W. J. S. Lockyer in 1902 as they noticed an apparent interannual “seesaw” in atmospheric pressure along the tropical Pacific between South America and Indonesia (Mock 1981). Walker and Bliss (1932, 1937) were the first to officially name this oscillating atmospheric pressure dipole the Southern Oscillation (SO), as they found it to influence much of the Southern Hemisphere and there already existed two oscillation patterns in the Northern Hemisphere. El Niño, meaning “little boy”, represents the associated oceanic component to the phenomenon, which was first discovered by fishermen off the coast of Peru who noticed interannual changes in SSTs (Trenberth 1997 and references therein).

As inferred above, ENSO is both an atmospheric and oceanic phenomenon, in that the ocean temperatures influence the surface air temperatures, which influence surface atmospheric pressure. This ocean-atmosphere relationship wasn’t realized until the 1960s (Rasmusson and Wallace 1983). Along the equatorial Pacific lies a
region of climatological low pressure called the equatorial low (EL), or thermal equator (Bjerknes 1966). Persistent rising motion is generally found along the EL with simultaneous sinking motion found to the north and south of the equator in the subtropics. At the surface, these two meridional pressure gradients are connected by the northeast and southeast trade winds in the Northern and Southern Hemisphere, respectively. This meridional vertical circulation is called the Hadley circulation (Bjerknes 1966). The northeast and southeast trade winds steer surface ocean water east to west across the tropical Pacific Ocean.

Relatively cold SSTs and high atmospheric pressure are found along the eastern tropical Pacific from a combination of the arrival of cold surface water from the cold California and Peruvian ocean currents, and also upwelling of cold deep-ocean water (Schell 1956). The water warms as it moves west across the equatorial Pacific, forming a region of relatively low atmospheric pressure in the western tropical Pacific near Indonesia (Trenberth and Caron 2000 and references therein). The El Niño/La Niña phenomenon is a result of a strengthening and weakening of the subtropical highs and resultant trade winds, cold ocean currents, and upwelling (Schell 1956). During La Niña conditions, the subtropical high/trade winds are stronger than normal, allowing cold SSTs (high atmospheric pressure) in the eastern tropical Pacific to advance further west into the central tropical Pacific, while warmer than normal SSTs (low atmospheric pressure) develop in the western tropical Pacific (Trenberth 1997). When the trade winds are weaker than normal, above normal SSTs (lower than normal atmospheric pressure) are found in the
central and eastern tropical Pacific, which has been termed El Niño (Acceituno 1992; Trenberth 1997; Glantz and Thompson 1981).

To balance these various pressure differences along the equator, a zonal east-west vertical atmospheric circulation arises along the equator and stretches around the entire globe (Webster 1983). The vertical component of this circulation in the tropical Pacific between Indonesia and South America is called the Walker Circulation, named after Sir Gilbert T. Walker (Bjerknes 1969; FIG. 2.1). As demonstrated by Fig. 2.1a, during an El Niño event, air converges and rises over the central tropical Pacific (approximately along the dateline; 180° meridian), and descends over Indonesia and northeast Australia (approximately 240°W). During La Niña conditions (Fig. 2.1b), air converges and rises over the western tropical Pacific (approximately 120°E) and large-scale descent is found across the eastern and central tropical Pacific (90°W-180°). In between, the surface flow moves toward (away from) the rising (sinking) motions; aloft the flow is opposite (Fig. 2.1).

The early studies of the SO and its impacts across the globe were first conducted by Sir Gilbert Walker and E. W. Bliss (i.e., Walker and Bliss 1932, 1937). These early pioneers performed correlations between the SO and global pressure, temperature, and precipitation data. What they found were correlation “centers”, or regions of same-sign correlation coefficients with centers of relatively high, significant correlation, known as teleconnections. A teleconnection is defined by the American Meteorological Society (AMS) as the significant positive or negative correlation of a meteorological parameter that is separated by a large geographic
FIG. 2.1: The equatorial east-west vertical circulation for the peak of (a) an El Niño event (January 1998) and (b) a La Niña event (January 1999). Streamlines represent the atmospheric flow calculated from the divergent component of the winds, and upward/downward vertical motions are shaded (note positive shading = upward vertical motion). From Lau and Yang (2002).
distance. In a theoretical study by Hoskins and Karoly (1981), it was demonstrated that strong convection along the equator (driven by changes in SSTs) is able to generate Rossby waves through the production of vorticity as air aloft travels poleward from the tropics and interacts with existing vorticity gradients in a persistent branch of the subtropical jet stream. Through the conservation of potential vorticity, tropical convection has the ability to in turn influence atmospheric circulation in downstream locations through the poleward propagation of Rossby wavetrains, offering an explanation to the teleconnections observed by Walker and Bliss (1932, 1937). Held et al. (1989) verified that the tropically induced Rossby wavetrains could cause major changes in the extratropical climate by altering the downstream regional circulation and influencing the location of storm tracks over the extratropical Pacific. As a result, small changes in SSTs over the tropical Pacific (and hence changes in the location and magnitude of tropical convection) can have major impacts on extratropical circulation patterns and climate.

One of the leading ENSO teleconnection patterns in the South Pacific is called the Pacific-South American (PSA) pattern (Karoly 1989; Mo and Higgins 1998; Mo and Paegle 2001). Using composite circulation analyses, Karoly (1989) described the ENSO teleconnection to the Southern Hemisphere as a wavetrain pattern of (pressure) anomalies extending poleward and eastward from Australia to South America. As demonstrated in Fig. 2.2, during the onset of an ENSO warm event (El Niño) a series of alternating upper tropospheric height (analogous to pressure in
FIG. 2.2: Schematic illustration of upper tropospheric height anomalies over the Pacific Ocean during (a) the early stage of an El Niño event during austral winter and (b) the mature stage of an El Niño event during austral summer. The gray shading represents the region of enhanced tropical convection in the central tropical Pacific, and the arrows represent the zonal wind anomalies in the jet streams. From Karoly (1989).

The extratropical South Pacific anomalies are observed from the tropical Pacific to the high latitude South Pacific. During austral winter, the regional pressure anomaly centers are more strongly defined (Fig. 2.2a), with above normal pressure anomalies observed in the subtropics surrounding the deep convection in the central tropical Pacific. Moving poleward across the South Pacific, below normal pressure is observed in the middle latitudes, anomalous high pressure is observed off the coast of West Antarctica, ending with anomalous low pressure over southern South America (Fig. 2.2a). During austral summer (Fig. 2.2b), Karoly (1989) suggests that the flow across the middle and high latitude South Pacific is more
zonally symmetric (west-to-east), with a broad zonal region of below normal pressure observed across the extratropical South Pacific.

Mo and Higgins (1998) further examined the evolution of tropical convection, and defined two separate types of PSA patterns. Using outgoing longwave radiation (OLR) as a proxy for tropical convection, they performed OLR anomaly composite analyses during the mature phase of the two leading empirical orthogonal function (EOF) PSA modes. Their study found that 5 to 10 days prior to the development of a persistent PSA event, an east-west dipole of OLR anomalies was observed across the central tropical Pacific. These findings further established the role of tropical convection at driving the downstream ENSO teleconnection to the extratropical South Pacific. Performing an EOF analysis on the 200 hPa streamfunction field, Mo and Higgins (1998) found that during the leading EOF PSA mode (PSA1; Fig. 2.3a), enhanced tropical convection was found between 140°E and 170°W, with suppressed convection over the Indian Ocean. A zonal swath of anomalies is observed in the subtropics from Australia to the central South Pacific (FIG. 2.3a).

During the second leading EOF PSA mode (PSA2; Fig. 2.3b), increased heating and enhanced tropical convection were observed a little further east between 160°E and 150°W, with suppressed convection observed over the western tropical Pacific. In this scenario, Australia is characterized by opposite sign anomalies from northwest to southeast, and opposite sign anomalies are also observed zonally over the subtropics from Australia to the central South Pacific. Also noteworthy from Mo
FIG. 2.3: The two leading empirical orthogonal functions (EOFs) for the 200 hPa eddy streamfunction field. Note that both EOFs represent the two leading PSA modes. From Mo and Higgins (1998). and Higgins (1998) is that using independent OLR anomaly composites, both of the PSA modes depicted in Fig. 2.3 emerge, verifying the robustness of the tropical convection-PSA relationship. The findings of Mo and Higgins (1998) demonstrate that the extratropical South Pacific circulation anomalies associated with the PSA are of tropical origin and are associated with tropical convection. Further, the
findings also establish the robustness of the PSA pattern, as it is not dependent on one study or one dataset.

The origin and downstream impact of the leading PSA modes are expanded upon in Mo and Paegle (2001). First, the PSA emerges as the leading EOFs in both interannual and intraseasonal timescales, expanding upon the single case study in Mo and Higgins (1998). It is also observed that on decadal time scales, the strength of PSA1 is related to SST anomalies across the central and eastern tropical Pacific, further demonstrating the robustness of the PSA’s tropical origin. Mo and Paegle (2001) also analyze the downstream impacts of the two PSA modes on regional climate. During PSA1, a precipitation dipole is observed across South America with decreased rainfall over northeast Brazil, and increased rainfall over southeastern South America. This pattern was strongest during austral summer. During austral spring, PSA2 pattern was observed to be strongest with decreased rainfall over central South America and increased rainfall over Argentina and Uruguay.

Noteworthy, Mo and Paegle (2001) demonstrate that persistence in SST and tropical convection anomalies associated with ENSO drives persistence in the downstream circulation anomalies associated with each of the two PSA patterns. Therefore, the PSA is a relatively persistent pattern in space and time consistent with the persistence of various ENSO phases. Together, Mo and Higgins (1998) and Mo and Paegle (2001) expand upon the works of Karoly (1989) to establish that the PSA is a robust atmospheric teleconnection pattern in the South Pacific. Additionally, these studies expand upon the Hoskins and Karoly (1981) study by showing in more
FIG. 2.4: Austral winter (June–August) 500 hPa height anomalies across the extratropical South Pacific during (a) eight El Niño and (b) six La Niña cases in the period 1968–99. From Turner (2004).
detail the downstream atmospheric circulation response to variations in tropical SSTs and deep convection associated with ENSO events.

Over the last few decades, numerous studies have analyzed the South Pacific high latitude response to ENSO teleconnections (Renwick and Revell 1999; Bromwich et al. 2004; Turner 2004; Yuan 2004; Lachlan-Cope and Connolley 2006). Turner (2004) performed extratropical composite analyses of 500 hPa geopotential heights using eight El Niño events and six La Niña events over the period 1968-99 (Fig. 2.4). As demonstrated in FIG. 2.4a, during ENSO warm events (El Niño conditions), positive height anomalies are observed in the high latitude South Pacific off the coast of West Antarctica and west of the Antarctic Peninsula. The sign of the anomalies is reversed during La Niña events, with negative height anomalies observed in the high South Pacific latitudes (Fig. 2.4b). As it would appear, ENSO warm events are associated with a ridging, or ‘blocking’, pattern in the high latitude South Pacific, which was also observed by Renwick (1998). van Loon and Shea (1987) and Renwick (1998) both linked this observed blocking to the convectively generated Rossby wavetrain extending from the tropics. However, a study by Jones and Simmonds (1994) suggested that the blocking off the coast of West Antarctica and the Antarctic Peninsula, represented by positive geopotential height and pressure anomalies, is actually comprised of very short-lived ridging episodes that typically exist no longer than 4 days at a time. Consequently, the apparent blocking identified over monthly timescales is not actually a persistent ridge of high
pressure; instead, it is a statistical manifestation of fewer than normal low pressures/cyclones in the region.

During various ENSO events, changes in the quantity and/or strength of cyclones in the high latitude South Pacific (especially in the Amundsen and Bellingshausen Seas) would lead to anomalous circulation across the region—across the eastern Bellingshausen Sea and western edge of the Antarctic Peninsula, the flow would be more southerly (northerly) and colder (warmer) during El Niño (La Niña) events. As a result, there should exist correlations between the southern oscillation index (SOI; index that represents the phase and magnitude of ENSO; Ropelewski and Jones 1987) and temperatures in the eastern Bellingshausen Sea and along the west coast of the Peninsula. Kwok and Comiso (2002) found that surface temperatures over the eastern Bellingshausen Sea were in fact positively correlated with the SOI (i.e., temperatures were colder during El Niño, and warmer for La Niña). Although positive SOI-temperature correlations were found across the western Peninsula, the relationship was not statistically significant across the Peninsula due to the strong influence of sea ice in the eastern Bellingshausen Sea on temperatures along the western Peninsula (Jacobs and Comiso 1997). Nevertheless, these studies demonstrate the important role that ENSO plays on geopotential height/pressure anomalies and associated atmospheric circulation in the high latitude South Pacific. Further, this variability has an impact on the regional atmospheric circulation and associated temperature variability across portions of West Antarctica and the Antarctic Peninsula.
2.2 The Southern Hemisphere Annular Mode

The atmospheric circulation patterns across the middle and high latitudes of the Southern Hemisphere (SH) are some of the most variable and least understood on the planet. The atmospheric pattern that explains the majority of large-scale atmospheric circulation and regional circulation variability in the extratropical SH is a quasi-zonally (west-to-east) symmetric structure called the SH annular mode (SAM; Limpasuvan and Hartmann 1999; Marshall 2003). Other studies have referred to this pattern as the high-latitude mode (Rogers and van Loon 1982) and the Antarctic Oscillation (AAO; Gong and Wang 1999). The SAM was first discovered using EOF analyses of extratropical (mainly poleward of 30°S) SH geopotential height and sea level pressure (SLP; Trenberth 1981a; Rogers and van Loon 1982). Rogers and van Loon (1982) performed EOF analyses on daily 500 hPa height and SLP across the extratropical SH and displayed spatial maps of the leading eigenvectors, which are often termed EOFs in climatological studies. Despite limitations in observations and atmospheric reanalysis data, Rogers and van Loon (1982) revealed that the pattern of the leading eigenvectors resembles an opposition of height and SLP variability between the middle and high southern latitudes (Fig. 2.5). Essentially, as demonstrated in Fig. 2.5, 500 hPa height and SLP over Antarctica (poleward of 60°S) fluctuate oppositely to that in the southern middle latitudes (45°-60°S). This relationship is not necessarily seasonally dependent, as it is observed during both austral summer (December–February; DJF)
FIG. 2.5: Leading eigenvector map of (top) daily SLP anomalies during DJF and (bottom) daily 500 hPa height anomalies during DJF. Solid lines indicate positive numerical values, and dashed lines indicate negative numerical values. From Rogers and van Loon (1982).
and winter (June – August; JJA); however, the zonal symmetry is most strongly defined during DJF (Fig. 2.5).

This SLP/geopotential height dipole between the middle and high latitudes was first studied in detail across the Northern Hemisphere (NH; i.e., Trenberth and Paolino 1981, Wallace and Gutzler 1981). Thompson and Wallace (1998) showed that the leading EOF of NH winter monthly SLP is dominated by a zonally symmetric, north-south seesaw in atmospheric mass (pressure) between the Arctic and northern middle latitudes. Thompson and Wallace (2000) conducted a comparison study between this relatively well-documented NH mode and the more recently discovered SH mode. Using EOF analysis, they compared the leading structures of monthly mean SLP and 850 hPa height anomalies between the two hemispheres (Fig. 2.6). Consistent with Rogers and van Loon (1982), a zonally symmetric SLP/geopotential height seesaw pattern is observed between Antarctica and the middle latitudes (Fig. 2.6a,c). The mode is “annular” in that it is ring-shaped around each respective geographic pole. Noteworthy from Fig. 2.6, the SH annular mode is more zonally symmetric than the NH annular mode. This is a result of fewer continental barriers in the SH to influence eddy activity in the high southern latitudes (Hall and Visbeck 2002). Nevertheless, the two modes in their respective hemispheres are remarkably similar in their mean state.

These two studies defined the SAM using EOFs and their related principal components. Gong and Wang (1999), and later Marshall (2003), were the first to define the SAM using differences in the mean SLP between the middle and high
FIG. 2.6: Leading EOFs of the (left column) SH monthly mean 850 hPa height anomalies and (right column) NH monthly mean SLP anomalies for (top) November–April and (bottom) May–October. Displayed as regression maps based on their standardized principal component (PC) time series. From Thompson and Wallace (2000).
latitude SH. This was made possible in part to improvements in the reliability and density of observations across the SH. Gong and Wang (1999) found a SAM pattern with their leading EOF SLP mode that was consistent with Rogers and van Loon (1982) and Thompson and Wallace (2000); however, expanding upon these previous studies, they found that the leading SAM mode could be defined as the difference in zonally averaged SLP between 40°S and 65°S. The quantitative difference from subtracting these two zonally averaged SLP values was termed the Antarctic Oscillation Index (AAO Index; Gong and Wang 1999). The AAO Index was found to explain much of the SLP variance across the extratropical SH latitudes, and more than 50% of SLP variance over continental Antarctica. Marshall (2003) used a similar method and developed an observation-based index of the SAM using the difference in zonally averaged SLP between the middle and high southern latitudes. His study was motivated by a recent realization that the NCEP-NCAR reanalysis (NNR) data, which the majority of early studies utilized to define the SAM, performed poorly across the extratropical SH. In an attempt to establish a benchmark in defining the SAM, Marshall (2003) used six station observations at 40°S and 65°S over the period 1958-2000 to calculate a proxy for the zonal mean SLP used by Gong and Wang (1999). Compared with observations, Marshall (2003) showed that the NNR data exaggerated the difference in SLP between 40°S and 65°S by a factor of 3, and the normalized SAM index was exaggerated by a factor of 2. Further, his study suggested that the European Centre for Medium-Range Weather
Forecasts (ECMWF) reanalysis, despite being shorter in length than the NNR (at the time of his study), was more reliable than the NNR at high southern latitudes.

The SAM has both a positive phase and a negative phase. During its positive phase, below normal SLP/geopotential height is observed across the polar cap (continental Antarctica) and above normal SLP/geopotential height is observed across the middle latitudes. This produces a stronger than normal middle to high latitude pressure gradient, which drives a stronger than normal polar front jet (Thompson et al. 2000). Opposite signed anomalies are observed during the negative phase of the SAM. As a result, the SAM essentially defines the strength and position of the polar front jet (Fyfe and Lorenz 2005). Thompson and Wallace (2000) demonstrated that during the high index polarity of the SAM, the polar jet is observed to be strengthened and displaced further poleward than normal.

Thompson and Wallace (2000) and the companion paper Thompson et al. (2000) investigated the role of stratospheric ozone on the phase and magnitude of the SAM. They found that during seasons of decreased ozone over Antarctica, there is increased coupling between the lower stratosphere and the troposphere, and the SAM favors more positive polarity. Thompson and Solomon (2002) and Gillett and Thompson (2003) elaborate on how ozone levels in the stratosphere influence the SAM. Thompson and Solomon (2002) suggested that ozone depletion over Antarctica occurs primarily during winter and early spring. When solar insolation returns, there is a deficiency of ozone to absorb the incoming radiation, which results in colder than normal temperatures in the lower stratosphere above
Antarctica. This produces a stronger than normal temperature gradient (and associated pressure gradient) between the low and high southern latitudes, which drives an abnormally strong lower stratospheric polar jet. Gillett and Thompson (2003) performed a modeling experiment and found that the increased strength of the stratospheric portion of the polar jet propagates downward through the lower stratosphere into the troposphere over the course of approximately one season (i.e., ozone depletion in spring would lead to an increased tropospheric polar jet in the following summer). As a result, anomalous levels of ozone in one season are related to anomalous phases of the SAM during the following season.

Over the past decade, many studies have revealed statistically significant negative trends in ozone concentrations across the SH and positive trends in the SAM (Thompson and Solomon 2002; Marshall 2003; Arblaster and Meehl 2006; Miller et al. 2006). Trends in the SAM were especially marked in summer, a season where ozone levels are strongly correlated with the previous spring’s ozone conditions (Thompson et al. 2000). As expected, the observed positive trends in the SAM were consistent with positive trends in the strength of the polar jet, and trends in below normal SLP/geopotential height across Antarctica and above normal SLP/geopotential height in the middle southern latitudes (Thompson and Solomon 2002; Miller et al. 2006). Thompson and Solomon (2002) found positive trends in the strength of the lower stratospheric polar jet to be most marked during austral summer and autumn.
Several studies during the 1990s revealed that the high southern latitudes were experiencing significant ozone loss that was linked to increased atmospheric concentrations of anthropogenic photochemicals, especially chlorofluorocarbons (Jones and Shanklin 1995; Hofmann et al. 1997). Thompson and Solomon (2002) found the decrease in stratospheric ozone over Antarctica to be consistent with positive trends in the strength of the lower stratospheric polar jet. Further, the trend toward strengthening of the polar jet was explained primarily by positive trends in the SAM (trends in the middle and high southern latitude SLP/geopotential height difference). Arblaster and Meehl (2006) used state-of-the-art global coupled climate models to attribute SAM trends to both natural and anthropogenic components of the climate system. They concluded that anthropogenic-induced stratospheric ozone depletion was the biggest contributor to the observed strengthening of the lower stratospheric polar jet during austral summer. Interestingly, Arblaster and Meehl (2006) suggested that increases in greenhouse gases are also a necessary contributor to the observed positive SAM trends, at least during summer. Using the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report ensembles of coupled ocean-atmosphere models, Miller et al. (2006) further verified that the positive trends in the SAM are anthropogenically driven (Fig. 2.7). Figure 2.7 displays various model representations of SLP trends with and without ozone depletion during austral spring and summer, the seasons where trends in the SAM are most marked. The red
FIG. 2.7: Multimodel average of the annular principal component (PC) composited according to whether the model includes (red) or omits (blue) forcing by stratospheric ozone. From Miller et al. (2006).

The red line represents expected SLP trends with ozone depletion, the blue line is the same as the red line except it omits ozone depletion, and the black line is the observed SLP trends. Figure 2.7 demonstrates that the observed SH SLP trends in the second half of the 20th century are nearly traced by the expected trends found by models that included ozone depletion. Consistent with findings from Arblaster and Meehl (2006), Miller et al. (2006) concluded that natural climate variability alone is not able to explain the observed SAM trends, and there is likely an anthropogenic component (anthropogenic increase in tropospheric concentrations of greenhouse gases and polar stratospheric ozone depletion) that is necessary to sufficiently explain the observed positive trends in the SAM. Further, Miller et al. (2006) demonstrated with their modeling study that only in the SH is the annular mode significantly influenced by changing concentrations of stratospheric ozone.
Given that the SAM is the dominant mode of extratropical circulation variability in the SH, it seems instructive that changes in the SAM will likely lead to changes in the extratropical climate. Interestingly, consistent with trends in the SAM, significant temperature trends have also been observed across Antarctica over the second half of the 20th century. Comiso (2000) observed cooling trends at a number of stations across the coast and plateau of both East and West Antarctica, while significant warming trends were observed on the northern tip of the Antarctic Peninsula. Thompson and Solomon (2002) found surface temperatures across East Antarctica during austral summer and fall (December–May) to be linearly congruent with the phase and magnitude of the SAM: when the SAM is in its positive phase, East Antarctic surface temperatures are observed to be colder than normal. Thompson and Solomon (2002) also found positive trends in the SAM to be linked to increased temperatures in the Antarctic Peninsula region, consistent with Comiso (2000). A study employing linear regression by Kwok and Comiso (2002) further verified that the observed positive trends in the SAM are significantly related to negative surface temperature trends in East Antarctica and positive surface temperature trends in the Antarctic Peninsula region.

Marshall (2007) expanded upon these studies by examining each season separately (Fig. 2.8). He found SAM-temperature correlations to be strongest across Antarctica during austral summer and autumn, with the greatest number of
significant SAM-related temperature trends observed during autumn. Fig. 2.8 displays the autumn and summer SAM-temperature correlations for each station. It is apparent that the SAM-temperature correlations during autumn and summer are all significant and of the same sign (negative) across East Antarctica, while over the Peninsula the correlations are positive or insignificant.

It is apparent from the literature that temperature trends across Antarctica associated with changes in the SAM are not uniformly distributed across the continent. Schneider et al. (2006) used ice cores to produce a temperature reconstruction across Antarctica for the last 150 years, and linked it to historic changes in the SAM. Their reconstruction revealed that despite large inter-annual and decadal timescale temperature variability, the long-term temperature trends across the Antarctic Peninsula associated with the SAM are typically opposite sign of that over the rest of continental Antarctica. The work of Schneider et al. (2006) provides increasing evidence that the SAM relationship with Antarctic temperatures is not uniform, and there are regional disparities in the sign of the relationship. The reason for the disparities is a result of two distinctly different circulation patterns associated with the SAM that are unique to East Antarctica and West Antarctica. When the SAM is in its positive polarity, the SLP anomalies and resultant geostrophic flow along the coast of East Antarctica is zonally symmetric (Fig. 2.9a; Lefebvre et al. 2004). As demonstrated in Fig. 2.9a, the zonal symmetry of the flow around East Antarctica maintains below normal temperatures across continental East Antarctica through decreased meridional (north-south) temperature advection.
FIG. 2.9: (top; a) Annually averaged correlation between the seasonal mean SLP and the seasonal mean SAM index for the period 1960-1999. (bottom; b) Annually averaged regression (in Pascals) between the seasonal mean SLP and the seasonal mean SAM index. Modified from Lefebvre et al. (2004).
Off the coast of West Antarctica, in the high latitude South Pacific region, a unique non-zonal component to the flow is observed (Fig. 2.9a). Here, temperature variability is strongly modulated by two meridional components to the circulation. In particular, relatively warm northerly flow (red arrow) is observed along the Peninsula, and cold southerly flow (blue arrow) is observed in the Ross Sea. When the SAM is in its positive phase, the meridional circulation along West Antarctica and the Antarctica Peninsula is amplified. This is demonstrated in Fig. 2.9b by a region of negative SLP−SAM regression coefficients off the coast of West Antarctica (i.e., positive phases of the SAM are associated with negative pressures in this region). Together, through assumed geostrophic flow and resultant temperature advection, FIG. 2.9a-b show that increasing temperatures along the Peninsula would be expected with increasing polarity of the SAM. This unique regional circulation feature in the high latitude South Pacific manifested in the SAM is consistent with warming trends being observed along the Peninsula while cooling trends have been observed elsewhere across Antarctica with the observed positive trends in the SAM.

2.3 ENSO and SAM Together

So far in this review, the evolution and impacts of ENSO and SAM have been examined separately in their respective states. However, over the past decade a growing number of studies have examined the features of the atmospheric circulation when ENSO and SAM occur together (i.e., L’Heureux and Thompson 2006, Fogt and Bromwich 2006, Fogt et al. 2011). L’Heureux and Thompson (2006)
FIG. 2.10: Monthly mean zonal-mean (left) zonal wind anomalies and (right) temperature anomalies regressed onto inverted CTI time series values for (top) austral summer (November – February) and (bottom) austral winter (May – August). Shading denotes significance at $p<0.05$ based on a one-tailed $t$-test. From L’Heureux and Thompson (2006).

and Fogt and Bromwich (2006) were among the first to examine the ENSO impact in the SH through relationships with the SAM. Figure 2.10 shows the austral summer (top) and austral winter (bottom) regression between the zonal-mean zonal wind and temperature anomalies, respectively, and the inverted cold tongue index (CTI; measure of ENSO activity). As depicted in Fig. 2.10, there is a statistically significant linear relationship between the CTI and the zonal wind anomalies at 40°S and 60°S in austral summer. Recall that 40°-60°S is a region also occupied by circulation features associated with the SAM. Interestingly, the statistically significant linear
relationship between the CTI and zonal winds anomalies at 60°S is distinctly
different from the subtropical jet, suggesting there is a component of the polar front
jet related to tropical/ENSO activity. Albeit slightly weaker, this relationship is also
observed with temperatures in the middle and lower troposphere. L’Heureux and
Thompson (2006) conclude that approximately 25% of the year-to-year variability
in the SAM is linearly related to fluctuations in ENSO. Also noteworthy, it is evident
from Fig. 2.10 that this tropical/high latitude atmospheric relationship is observed
only across the middle and high latitudes of the SH, and not in the NH.

Fogt and Bromwich (2006) were the first to examine high southern latitude
circulation variability associated with the coupling of ENSO and SAM. In their 2006
paper, they calculated 10-year running correlations between the Southern
Oscillation Index (SOI; measure of ENSO activity) and the SAM index. They observed
that during the 1980s, the SOI and SAM index were negatively correlated in austral
spring (SON) and summer (DJF). During the 1990s, the sign of the correlation
became significantly positive, persisting through 2001. Fogt and Bromwich (2006)
also examined correlation maps between the SOI and SH height/pressure during the
1980s and the 1990s. As demonstrated in Fig. 2.11a, the SOI correlation with mean
sea level pressure (MSLP) in the high latitude South Pacific is small in area and
significant at only $p<0.05$ during the 1980s (when the SOI-SAM index correlation
was negative). During the 1990s (when the SOI-SAM index correlation becomes
positive), the high latitude ENSO response is much broader in spatial extent and
FIG. 2.11: Annual spatial correlations of ERA-40 MSLP and the SOI for (a) the 1980s and (b) the 1990s. Station MSLP-SOI correlations are also plotted for select stations south of 30°S. Shading denotes significance of the correlations. From Fogt and Bromwich (2006).
highly significant at $p<0.01$ (Fig. 2.11b). Fogt and Bromwich (2006) suggest that changes in the strength of the SOI-MSLP field correlation in the South Pacific were primarily a result of changes in the sign of the SON and DJF SOI-SAM index correlation. For instance, when the SOI-SAM index correlation is negative (i.e., El Niño (La Niña) occurring primarily with SAM positive (negative)), ENSO and SAM are considered to be “out of phase”, and the high latitude ENSO response is weaker than normal (Fogt and Bromwich 2006). However, when the SOI-SAM index correlation is positive (El Niño (La Niña) occurring primarily with SAM negative (positive)), the two climate modes are said to be “in phase”, and the high latitude ENSO response is stronger than normal. This was the first study to suggest that the high southern latitude ENSO teleconnection is related to the sign and magnitude of the SAM index.

Studies that followed the early works of L’Heureux and Thompson (2006) and Fogt and Bromwich (2006) sought to understand the processes embedded in ENSO and SAM that led to frequent simultaneous occurrence and the varying strengths of the ENSO signal to the high latitude SH. In the studies that followed, two main theories emerged surrounding the dynamic interactions between ENSO and SAM. The first theory, developed primarily by Fogt et al. (2011) and Gong et al. (2010, 2013), is that the interaction between anomalous transient eddy momentum fluxes associated with various ENSO and SAM events plays the leading role at influencing the ENSO teleconnection to the extratropical SH.
FIG. 2.12: Annual NNR MSLP anomaly composites for ENSO and SAM events occurring separately (a-d) and together (e-h). From Fogt et al. (2011).
Expanding upon the work from Fogt and Bromwich (2006), Fogt et al. (2011) performed composite analyses of strong ENSO and SAM events to examine the relationship between SAM and the ENSO teleconnection over the period 1957-2009. Fogt et al. (2011) produced MSLP composite maps of ENSO, SAM, and ENSO-SAM together events (Fig. 2.12). The top row (Figs. 2.12a-b) represents SAM events occurring with ENSO neutral conditions, while the second row (Figs. 2.12c-d) represents ENSO events occurring with SAM neutral conditions. Months when ENSO and SAM events occurred together are presented in the third and forth rows (Figs. 2.12e-h). As demonstrated by Figs. 2.12e-f, when La Niña (El Niño) occurs with SAM positive (negative), the MSLP across the SH is approximately a linear sum of the two individual states of ENSO and SAM. For example, La Niña/SAM positive events (Fig. 2.12e) are equivalent to the sum of La Niña alone and SAM positive alone. These conditions correspond to the “in phase” scenario discussed previously, and the high southern latitude ENSO response across the South Pacific is stronger than normal.

On the other hand, when conditions are “out of phase,” as demonstrated by Figs. 2.12g-h, the individual signatures of each ENSO and SAM phase are weakened or altogether absent from the high latitude South Pacific. For example, the high latitude South Pacific La Niña signature during La Niña/SAM negative events (Fig. 2.12g) is weakened and displaced further to the north and west. Fogt et al. (2011) suggest that this discrepancy of the high southern latitude ENSO response between in phase and out of phase events can be attributed to interactions between anomalous transient momentum fluxes in the Pacific. In particular, their work
suggests that when ENSO and SAM are in phase, the anomalous transient eddy momentum fluxes work in cadence to reinforce the circulation anomalies in the middle latitudes, maintaining and amplifying the high latitude ENSO teleconnection. When the two climate modes are out of phase, the anomalous transient eddies oppose each other in the middle latitudes, significantly disrupting the propagation of the ENSO teleconnection to the high latitude South Pacific.

Results from Gong et al. (2010, 2013) also suggest it is the interaction of anomalous eddy momentum fluxes associated with ENSO and SAM that govern the resultant circulation anomalies observed during combined ENSO and SAM events. During austral spring and summer over the period 1979-2002, Gong et al. (2010) performed composite analyses on meridional potential vorticity gradient (a measure of the likelihood of atmospheric wave breaking) and the wave breaking index (WBI; an index developed to evaluate the strength of atmospheric wave breaking) during El Niño and La Niña events to investigate whether or not variations in ENSO drive variations in the SAM. Their study found that strong anticyclonic wave breaking occurs on the equatorward side of the SH eddy-driven jet (polar jet) more frequently during La Niña events, which has been found to drive positive phases of the SAM. During El Niño events, more cyclonic (weaker anticyclonic) wave breaking took place, which has been found to drive negative phases of the SAM. Therefore, Gong et al. (2010) suggest that these wave breaking characteristics associated with the background flow during different phases of ENSO are a key player in exciting a particular phase of the SAM. The anticyclonic wave
breaking associated with La Niña events is likely to drive positive phases of the SAM, while the less anticyclonic wave breaking associated with El Niño events is more likely to drive negative phases of the SAM.

Gong et al. (2013) used a general circulation model to broadly investigate how certain ENSO phases can be related to a certain phase of the SAM. This modeling study is an extension of the Gong et al. (2010) study that found La Niña favors SAM positive events, while El Niño favors SAM negative events. Gong et al. (2013) used three scenarios to investigate the causes of these observed ENSO-SAM relationships: a control run, three different El Niño runs, and three different La Niña runs. The various model runs are forced by thermal heating associated with sea surface temperature (SST) anomalies during various ENSO phases.

Results from the modeling study have both similar and contrasting results than that observed in the real atmosphere (i.e., results from Gong et al. 2010). When the thermal heating field is zonally symmetric (SST anomalies are uniformly oriented west to east along the equatorial Pacific) or a combination of zonally symmetric and zonally asymmetric (SST anomalies are not uniform in sign and/or magnitude from west to east along the equatorial Pacific), the ENSO-SAM relationship produced by the model is the same as that observed in the atmosphere (La Niña excites SAM+ and El Niño excites SAM-). However, when the ENSO heating field is asymmetric only, the relationship between ENSO and the basic flow changes, and the middle latitude meridional potential vorticity gradient is reversed. Therefore, it is the zonally symmetric, or full heating and cooling fields, of ENSO
events that contribute to the preference for La Niña to excite SAM positive events and El Niño to prefer SAM negative events. In other words, if the SST anomalies are sporadic in zonal orientation, alternating in sign and/or magnitude across the tropical Pacific, the relationship between the phase of ENSO and its preference for SAM events is not observed.

The second theory emerging around the interaction between ENSO and SAM is that there exists two components of the SAM: a mid-latitude component and a subtropical component (Ding et al. 2012). In particular, Ding et al. (2012) examined the different structures of the SAM in the Eastern and Western Hemisphere, or the Indian Ocean sector and Pacific Ocean sector, respectively. In the Indian Ocean sector, Ding et al. (2012) noted that internal dynamics (i.e., transient eddies associated with individual cyclones along the polar front) are the persistent drivers of the SAM and its more zonally symmetric structure. Ding et al. (2012) suggest that there exists a different story across the Pacific Ocean sector. First, and well supported by the literature, the Pacific sector portion of the SAM is found to be more zonally asymmetric (more north-south flow) than the Indian Ocean sector, especially outside of the austral summer season. Ding et al. (2012) suggest this zonal asymmetry in the Pacific sector is a result of tropical Pacific SST anomalies associated with ENSO, and is therefore a manifestation of the downstream Pacific-South American (PSA) pattern (Ding et al. 2012, Fogt et al. 2012b). Ding et al. (2012) argue that in the Pacific sector, the asymmetric ENSO-component of the SAM is actually a permanent signature of the SAM in space and time stemming from a
FIG. 2.13: Schematic showing the role of subtropical jet and mid-latitude jet in shaping the SAM during nonsummer seasons. From Ding et al. (2012).

depicted schematically in Fig. 2.13, Ding et al. (2012) suggest that in the Pacific, the SAM has both a subtropical jet component and mid-latitude jet component. As summarized in Fig. 2.13, the Indian Ocean sector is comprised of an internally driven zonally symmetric mid-latitude jet, while in the Pacific sector, in addition to the internally driven mid-latitude jet, a portion of the SAM is permanently forced by persistent transient eddy fluxes emanating from the tropical Pacific located within the core of the subtropical jet.

The argument presented by Ding et al. (2012) is challenged by the fact that strong SAM events have been observed during all ENSO phases including La Niña, El Niño, and ENSO neutral. Fogt et al. (2012b) take a similar but slightly different stance on the topic. First, as suggested by Ding et al. (2012), Fogt et al. (2012b) agree that the SAM asymmetry in the Pacific sector is of tropical origin. However,
FIG. 2.14: ERA-40 300 hPa average zonal wind over the period 1979–2001 (shaded) by season for SAM+ (a, c, e, g) and SAM- (b, d, f, h). Contours denote regions where the correlation of the ERA-40 transient asymmetric SAM indices (during 1979–2001) with the 300-hPa zonal wind is statistically different from zero at the $p<0.05$ level. From Fogt et al. (2012b).
Fogt et al. (2012b) slightly expand upon the study of Ding et al. (2012) by examining the SAM structure by phase and by individual season. Fogt et al. (2012b) find that the zonal asymmetry is most pronounced in austral winter and spring. As depicted in Fig. 2.14, the SAM is nearly zonally symmetric at all longitudes surrounding the continent and during all seasons; the only exception to is found in the Pacific sector. Further, the 300 hPa zonal wind in the Pacific sector is strongly correlated with the transient asymmetric SAM indices, an index developed to identify the magnitude of the SAM asymmetry by subtracting the zonal component of the flow from the observed flow. However, due to the complicated relationship between ENSO and SAM with respect to the extreme variance of simultaneous occurrences (i.e., strong SAM events occurring with ENSO neutral conditions, strong SAM events occurring in the opposite phase expected from wave breaking in the tropics), Fogt et al. (2012b) do not suggest that the Pacific sector of the SAM has a permanent ENSO component; instead, during unique occurrences of out of phase SAM/ENSO events, there likely exists a significant internal component of the SAM across all longitudes, including the Pacific sector.

Whether or not the SAM is a result of having two components, a tropically driven jet and an internally driven jet, or it is a result of wave mean flow interactions, recent studies have found that ENSO and SAM together interact to influence climate and sea ice across Antarctica (Stammerjohn et al. 2008, 2012; Fogt et al. 2012b). This is especially true across and just offshore of West Antarctica where the ENSO-related SAM asymmetry is most marked. Stammerjohn et al. (2008,
examined ENSO-SAM related influences on sea ice variability across the high
latitude South Pacific. These studies were motivated by contrasting trends in sea ice
season length across the high latitude South Pacific in the vicinity of the SAM
asymmetry: sea ice season length has been decreasing in the western Antarctic
Peninsula/ southern Bellingshausen Sea region and increasing in the Ross Sea
region (Stammerjohn et al. 2008).

Stammerjohn et al. (2008) used an approach similar to Fogt and Bromwich
(2006) to examine austral fall (March – May; MAM) sea ice advance when ENSO and
SAM are in phase and out of phase. They defined the ENSO-SAM in phase period as
the 1990s (when ENSO and SAM are positively correlated) and the out of phase
period as the 1980s (when ENSO and SAM are negatively correlated; Fogt and
Bromwich 2006). The results of the study are summarized well by Fig. 2.15, which
shows the composite differences between anomalous MAM sea ice advance for in
phase ENSO/SAM events during the 1980s versus the 1990s (Fig. 2.15a). Figure
2.15a presents the difference in sea ice advance between La Niña/SAM+ events
during the 1990s and El Niño/SAM- events during the 1980s. Figure 2.15b shows
the differences in SAM+ only events during the 1990s and SAM- only events during
the 1980s.

First evident in Fig. 2.15a are the changes in sea ice advance (color shading).
Compared to El Niño/SAM- conditions during the 1980s, sea ice advance during La
Niña/SAM+ conditions in the 1990s is substantially later across the western
Antarctic Peninsula/Bellingshausen Sea region and earlier across the western Ross
FIG. 2.15: Decadal composite differences (1990s minus 1980s) of sea ice advance (color shading) and MAM SLP (color contours) anomalies for (a) 1990s La Niña/SAM+ minus 1980s El Niño/SAM- events and (b) 1990s SAM+ minus 1980s SAM-. From Stammerjohn et al. (2008).

Sea, consistent with the overall observed trends. Looking at SAM only events (Fig. 2.15b), the later than normal sea ice advance in the Peninsula/Bellingshausen Sea region is observed for SAM+ compared to SAM-; however, the earlier than normal sea ice advance in the Ross Sea region is not observed. This suggests that the contrasting trends in sea ice between the western Peninsula/Bellingshausen Sea region and Ross Sea region are not SAM related only, but also ENSO related. Further, and evident in both Fig. 2.15a and Fig. 2.15b, below normal sea level pressure (SLP; color contours) is observed in the center of the two contrasting sea ice trends,
indicating that a stronger than normal low pressure between the two sea ice trends is the dominant atmospheric feature between the 1990s and the 1980s. Results from Stammerjohn et al. (2012) are consistent with and further verify the results presented here from Stammerjohn et al. (2008). Notably, results from both these studies are consistent with a stronger than normal ENSO-related pressure signal in the high latitude South Pacific during the 1990s compared to the 1980s (Fogt and Bromwich 2006; Fogt et al. 2011).

Fogt et al. (2012b) examined the South Pacific SAM asymmetry relationship with Antarctic temperatures. Presented in Fig. 2.16 are seasonal correlations between the transient asymmetric SAM indices (as defined above) and Antarctic station temperatures. Across the Antarctic Peninsula, the correlations are significant and positive during austral fall, winter, and spring, while significantly negative correlations are observed in the Ross Sea region (Fig. 2.16). The seasons of greatest significance in the correlations is consistent with periods where the SAM asymmetry is most marked in the South Pacific sector (depicted as contours in Fig. 2.16), namely during all seasons except for summer. The location and magnitude of the correlations with the asymmetric SAM indices indicates that the regional circulation in between the Ross Sea and the Antarctic Peninsula, a region marked with a strong ENSO related SAM zonal asymmetry, is likely responsible for the regional temperature discrepancies. This suggests that the significant, contrasting sea ice and temperature trends between the Antarctic Peninsula and Ross Sea regions are likely linked to the asymmetrical component of the SAM.
FIG. 2.16: Correlations (colored dots) between the transient asymmetric SAM indices and station temperatures by season for SAM+ (a, c, e, g) and SAM- (b, d, f, h). Correlations calculated over the period 1958-2001. Contours are the transient asymmetric SAM pattern. From Fogt et al. (2012b).
The results presented in this section suggest that ENSO and SAM together play an important role in modulating atmospheric circulation in the South Pacific through zonal asymmetries in the SAM. Further, this regional circulation variability, highly supported by literature to be of tropical/ENSO origin (but to what extent is still unknown), influences sea ice and temperatures on either side of the circulation anomalies. On the eastern side of the circulation anomalies, increasing temperature and decreasing sea ice season length trends are observed, namely across the western Antarctic Peninsula and Bellingshausen Sea region. On the western side of the circulation anomalies, decreasing temperature and increasing sea ice season length trends are observed, namely in the Ross Sea region.

2.4 The Amundsen-Bellingshausen Seas Low

The Amundsen-Bellingshausen Seas Low (hereafter, ABSL) is a semi-permanent region of low atmospheric pressure that encompasses the southeast portion of the high latitude South Pacific. As its name suggests, it is most commonly observed in the vicinity of the Amundsen and Bellingshausen Seas, in the region of 45°-75°S and 180°-60°W (Fogt et al. 2012a; Fig. 2.17). In reference to geographic features, this is the region including and between the eastern Ross Sea and the west coast of the Antarctic Peninsula. The ABSL has also been referred to as the Amundsen Sea Low since it is most commonly observed in the center of this region over the Amundsen Sea (Turner et al. 2013).
FIG. 2.17: Map displaying the ABSL region (45°-75°S, 180°-60°W), including the Ross, Amundsen, and Bellingshausen Seas. From Fogt et al. (2012a).
The ABSL is the dominant atmospheric circulation feature in the high latitude South Pacific. As a result, the strength and position of the ABSL largely affects the broadscale climate across the region (Hosking et al. 2013). Interestingly, it is the region occupied by the ABSL, along and just offshore of West Antarctica and the Antarctic Peninsula, where rapid and statistically significant changes in sea ice, outlet glaciers, and temperatures have been observed over the last 50 years (Shepherd et al. 2001; Thompson and Solomon 2002; Lefebvre et al. 2004; Stammerjohn et al. 2008; Steig et al. 2009; Wingham et al. 2009; O’Donnell et al. 2011; Bromwich et al. 2013). Therefore, it is imperative to understand variability of the ABSL before attributing regional atmospheric circulation variability to the observed temperature and sea ice trends across West Antarctica and the Antarctic Peninsula.

The ABSL is similar to all other semi-permanent climatological pressure centers. Its best Northern Hemisphere counterpart is the Aleutian Low, a semi-permanent low pressure located in the high latitude North Pacific near the Aleutian Islands of Alaska. Other commonly known semi-permanent pressure centers across the globe include the Icelandic Low, the Azores/Bermuda High, and the Mascarene High, to name a few. As it would seem, more is known about Northern Hemisphere climatological features compared to the Southern Hemisphere. This is likely due to a smaller population size that is affected by many of these Southern Hemisphere pressure centers and shorter, less dense meteorological observation records over the vast oceans of the Southern Hemisphere. Even compared to other semi-
permanent pressure centers in the Southern Hemisphere, very little is known about
the ABSL also due to its remote geographic location (surrounded by the Southern
Ocean and not easily accessible) and the extremely harsh weather conditions and
seasonal sea ice cover in its vicinity. However, in a changing climate, atmospheric
features like the ABSL can have indirect effects on humans as they can warm polar
regions and consequently melt ice sheets (such as Greenland and Antarctica), raise
sea levels, and potentially change global atmospheric circulation patterns.

There are two unique features of the ABSL region that promote such strong
and persistent underlying cyclonic activity that give rise to this climatological
circulation signature. The first driving force is the asymmetric geography of the
Antarctic continent, which promotes cyclonic activity in the vicinity of the ABSL. The
spatial coverage of Antarctica is not symmetrically distributed around the South
Pole; instead, East Antarctica extends further equatorward and has a higher
elevation than the majority of West Antarctica (excluding the Antarctic Peninsula).
Planetary waves and associated cyclones are typically generated along the coast of
East Antarctica along the polar front, and travel eastward into the Amundsen and
Bellingshausen Seas (Lachlan-Cope et al. 2001) following the mean upper level
atmospheric flow. The atmospheric circulation diverges in the Amundsen and
Bellingshausen Seas as it flows around the Antarctic Peninsula, which acts to
produce a prime region for synoptic activity (Baines and Fraedrich 1989).

The second factor is the topography of the region, which prevents many of
the cyclones from leaving the region (Lachlan-Cope et al. 2001). Cyclones associated
with the polar front (the planetary waves eluded to earlier) track generally west to east from the Ross Sea to the Bellingshausen Sea. Often, cyclones will propagate poleward from the polar front toward West Antarctica, following patterns of low level baroclinicity (instability) and/or upper level vorticity gradients (Simmonds et al. 2003). Other cyclones will continue westward until they reach the Antarctic Peninsula (Simmonds et al. 2003; Uotila et al. 2009, 2011). As these storms approach West Antarctica and/or the Antarctic Peninsula, they encounter extremely steep and rugged terrain. Some blocking and occluding (weakening/decay) of the cyclones occurs along the coast of West Antarctica, where the coastal ice shelves quickly rise to 1,000+ meters in elevation. Even stronger blocking occurs along the Antarctic Peninsula, which protrudes equatorward from the continent and is comprised of a rugged mountain range with peaks exceeding 2,000 meters. As a result, cyclones typically are generated off the coast of Antarctica by the asymmetric geography, track east and occlude, and then collect in Amundsen and Bellingshausen Seas as they struggle to overcome the Antarctic Peninsula, which gives rise to this region of persistent low pressure (Baines and Fraedrich 1989; Lachlan-Cope et al. 2001).

A modeling experiment by Walsh et al. (2000) demonstrated that even if the elevation of West Antarctica and the Antarctic Peninsula was zero, the ABSL would still emerge, albeit weaker, as a climatological low pressure feature in this region. This is because of the persistent cyclonic activity that occurs along the polar front along these latitudes (45°-75°S), and also because of a persistent equivalent-barotropic trough of low pressure that is commonly observed in this region from the
asymmetry of the Antarctic coast (Lachlan-Cope et al. 2001; Raphael 2004). Raphael (2004) demonstrated that the ABSL is one of three semi-permanent low pressures that surround the Antarctic continent, associated with a zonal wave number 3 circulation. The ABSL, however, owing mainly to the aforementioned topographic and geographic features of the region, is the most prominent and persistent of the three low pressures.

Like all semi-permanent pressure systems, the ABSL is not permanent in space, time, or magnitude. In fact, the ABSL magnitude and position has both a seasonal cycle and large year-to-year variability (Fogt et al. 2012a). Figure 2.18 shows that the ABSL is located furthest north and east during austral summer and shifts south and west during austral winter. Also, the ABSL magnitude is weakest during austral summer and deepest during austral winter and spring. The large spread of the minimum and maximum values (light shaded region) indicates that there is large variability from year to year, and there is no one value that can truly represent the normal monthly ABSL conditions.

Several studies have examined the underlying synoptic activity that comprises the ABSL (Fogt et al. 2012a; Turner et al. 2013; Hosking et al. 2013). Using a cyclone finding and tracking scheme, Fogt et al. (2012a) used multiple atmospheric reanalysis datasets to investigate the characteristic variability of the ABSL. This study demonstrated that the region of greatest cyclone density and deepest cyclone strength essentially defines the climatological ABSL magnitude and position (Fig. 2.19). From Fig. 2.19, it is apparent that the location and magnitude of
FIG. 2.18: Seasonal cycles of the latitude (a-c), longitude (d-f), and magnitude (g-i) of the monthly minimum pressure in the ABSL region from three different atmospheric reanalyses. The dark shaded region represents the interquartile range, and the light shaded region bounds the minimum and maximum values of each variable over the period 1979-2001. From Fogt et al. (2012a).
cyclone strength and cyclone density is consistent with the location and magnitude of the climatological ABSL. Further, cyclone strength and cyclone density shows a similar seasonal cycle as the ABSL; both the ABSL and its underlying synoptic activity are located furthest south during austral spring, furthest west during austral winter, and furthest north and east during austral summer.

The magnitude of the ABSL and the underlying synoptic-scale cyclones (as well as the spatial density of these cyclones) also varies by season. The ABSL and cyclone pressure deepens in winter and spring, with the lowest pressure values observed during austral spring (Figs. 2.18g-i, Figs. 2.19 g-i). This is consistent with the cyclone density, with the greatest number of cyclones also observed during austral winter and spring. A noteworthy observation from Fig. 2.19 is that the strongest cyclones (dotted, central pressure line) are typically located north of the ABSL and the region of maximum cyclone density (Fig. 2.19a-c). This further highlights the fact that the ABSL is primarily influenced by the Antarctic topography as cyclones collect (density increases) south of the polar front nearer to the coast (Lachlan-Cope et al. 2001).

In an attempt to link the ABSL to the observed warming across West Antarctica, Fogt et al. (2012a) calculated trends in cyclone characteristics within smaller basins of the ABSL region. Cyclone pressure and density trends were calculated in the Ross, Amundsen, and Bellingshausen Seas. Despite very strong interannual variability, statistically significant decreases in cyclone central pressure (deepening of the cyclones) were found across the Ross Sea portion of the ABSL.
FIG. 2.19: Comparison of the climatological (1979-2001) ABSL magnitude and position with the magnitude and position of maximum cyclone density and minimum cyclone central pressure. Cyclone and ABSL data are shown for ERA-40, JRA-25, and NNR reanalyses. From Fogt et al. (2012a).
region during austral spring. Deeper cyclones in this region can be interpreted as a regional deepening of the ABSL as it progresses west into the Ross Sea during winter. Although not explicitly linked to temperature trends, the trend toward deeper cyclones in the Ross Sea is consistent with the warming trends observed across West Antarctica, as this would enhance the onshore advection (northerly flow) of relatively warm and most air across West Antarctica.

In the Southern Hemisphere, air circulates clockwise around areas of low atmospheric pressure, as the surrounding air moves inward toward the center of lowest pressure (driven by the pressure gradient force) and is deflected to the left by the Coriolis force. As a result, two regions of meridional (north-south) flow are found on the eastern and western side of the ABSL. On the eastern side, a relatively warm and moist (maritime polar/mP) north-to-south flow typically develops. This region of warm, poleward-moving air is commonly located in the Bellingshausen Sea and/or along the western flank of the Antarctic Peninsula (see Fig. 2.17). It is important to quantify the warm, onshore flow associated with cyclones and the cause of their strengthening in the Ross Sea because much of the basal topography beneath the West Antarctic ice sheet lies below sea level. For this reason, West Antarctica is considered ‘unstable’, and it susceptible to rapid melting and possible collapse in a warming climate (Joughlin and Alley 2011). On the western side of the ABSL, cold and dry (continental arctic/cA) air flows equatorward from continental West Antarctica across the Ross Ice Shelf/Ross Sea. Differences in the magnitude
and position of the ABSL have strong influences on the strength and position of these regions of warm and cold air advection.

The regional wind patterns that result from variability in the ABSL play a major role in governing both the climate and sea ice conditions across West Antarctica and the Antarctic Peninsula. When the ABSL is stronger than normal, the aforementioned circulation pattern is amplified. Across the Bellingshausen Sea and the western flank of the Antarctica Peninsula, warmer than normal temperatures are typically observed, as warmer air from lower latitudes is transported poleward into the region (Stammerjohn et al. 2008). Decreases in sea ice extent are also observed in this region during stronger than normal ABSL events, owed primarily to increases in the negative meridional (onshore; poleward) component of the wind and increases in the magnitude of the wind (Lefebvre et al. 2004; Stammerjohn et al. 2008). A stronger than normal ABSL also tends to compact sea ice into smaller, higher density clusters along the eastern West Antarctic coast and western Antarctic Peninsula coast (Holland and Kwok 2012). Further west across the Ross Sea, a stronger than normal ABSL tends to increase both the concentration and extent of sea ice, as the air flowing over the Ross Sea is colder than normal (originating from inland West Antarctica and the Ross Ice Shelf) and the northward wind direction enables sea ice to advance further equatorward (Holland and Kwok 2012). Opposite conditions are essentially observed when the ABSL is weaker than normal (Stammerjohn et al. 2008, 2011).
Changes in sea ice conditions play a major role in modulating the local climate of the region (Schneider et al. 2012a). First, sea ice influences the surrounding sensible and latent heat flux. For example, increases in sea ice would thermodynamically cool the surrounding air by a reduced surface sensible and latent heat flux to the low levels of the atmosphere (just as the cold or frozen surface of the Great Lakes from winter keeps the lakeshore locations relatively cool when spring arrives in the Northern Hemisphere). Second, sea ice and ice shelves can also act as a buffer across the Antarctic coast (De Angelis and Skvarca 2003). Increases in sea ice would prevent large ocean swells/waves from impacting the main ice shelves, ice sheets, and outlet glaciers of the continent (Hellmer et al. 1998). An increase in sea ice would also assist in preventing the relatively warm ocean water from melting the coastal ice shelves and ice sheets from beneath (Joughin and Alley 2011). Decreases in sea ice would have opposite influences on the continent. The sea ice surrounding Antarctica responds both dynamically (changes in the wind field that moves the ice) and thermodynamically (changes in the sensible and latent heat) to variations in the regional circulation (Holland and Kwok 2012). Therefore, changes in the magnitude and position of the ABSL play a major role in modulating sea ice conditions, which in turn influences the local climate (Schneider et al. 2012a; Holland and Kwok 2012; Stammerjohn et al. 2008, 2011).

Recent studies (Fogt et al. 2011, 2012a; Turner et al. 2013; Hosking et al. 2013) have linked the strength of the ABSL to changes in the SAM. When the SAM is in its positive phase (below normal pressure across the polar cap and above normal
pressure in the middle latitudes), the ABSL tends to be deeper than normal, amplifying the aforementioned circulation and sea ice conditions. The ABSL is typically weaker when the SAM is more negative (above normal pressure over the polar cap, below normal pressure across the middle latitudes). The profound impact the SAM has on the ABSL is not surprising, given that the SAM is the leading mode of climate across the Southern Hemisphere and explains over 40% of the atmospheric variability across the hemisphere, including a large center of action in the South Pacific (Thompson et al. 2000).

### 2.5 Antarctic Climate and Climate Change

In this final section of the literature review, a closer look at the climate of Antarctica will be conducted through a review of the major peer-reviewed studies over the past decade. The goal of this final section is to provide evidence that Antarctica is experiencing some of the most rapid climatic changes on the planet, with a particular focus on temperatures.

The first major study to examine the climate of Antarctica through an observational standpoint was performed by Turner et al. (2005). In this study, trends of monthly mean near-surface temperature, mean sea level pressure (MSLP), and wind speed for 19 stations (with near complete records) across Antarctica were analyzed. Figure 2.20 displays a map of Antarctica and the location of the stations used in Turner et al. (2005). The atmospheric data utilized in the study were from the Reference Antarctica Data for Environmental Research (READER) project. The
FIG. 2.20: Map of Antarctica with locations of the 19 selected research stations represented by labeled dots. From Turner et al. (2005).
trends were calculated over the longest available period with complete data, ranging mainly from 1951-2000 and 1961-2000.

The results of Turner et al. (2005) were alarming. To begin, eleven of the stations exhibited warming trends while seven exhibited cooling trends, indicating that the temperatures across the continent were changing, but the sign of the temperature trends was not spatially uniform. The strongest and most statistically significant warming trends were found across the Antarctic Peninsula, where temperatures at Faraday/Vernadsky station were observed to be increasing over the period 1951-2000 at a rate of 0.56°C per decade, and 1.09°C per decade during the austral winter season. More spatially consistent trends were observed in MSLP, with negative annual MSLP trends observed at all stations except one, where there was no trend. The MSLP trends are consistent with the positive trends observed in the SAM that were discussed earlier, where a decrease in MSLP and geopotential height would be expected across continental Antarctica. Finally, all but two of the stations exhibited positive trends in wind speed.

As demonstrated by Fig. 2.20, of the 19 stations used by Turner et al. (2005), there are no complete station records located in West Antarctica; complete station data records are only available across East Antarctica and the Antarctic Peninsula. Steig et al. (2009) were among the first to investigate temperatures across West Antarctica. To investigate near-surface temperature trends in West Antarctica, Steig et al. (2009) reconstructed annual mean surface temperatures for the entire Antarctic continent over the period 1957-2006, later separating the temperatures
into the geographic East and West Antarctic regions. Steig et al. (2009) used passive infrared brightness measurements from the Advanced Very High Resolution Radiometer (AVHRR) satellite, and calibrated and verified the temperature data using near-surface temperature observations from 42 occupied stations and 65 automated stations from the READER data set. As demonstrated in Fig. 2.21, the reconstruction revealed significant surface warming trends extending well beyond the Antarctic Peninsula to also encompass much of West Antarctica (Steig et al. 2009). In fact, annual warming trends are observed across both West and East Antarctica over the 1957-2006 period (Fig. 2.21a), although the warming was found to be statistically significant only across West Antarctica. Over the period 1969-2000 (Fig. 2.21b), West Antarctica (in addition to the Peninsula) is the only region exhibiting warming trends, with slight cooling actually observed across much of East Antarctica. Quantitatively, results from the reconstruction suggested that West Antarctica warmed between 1957 and 2006 at an annual rate of 0.17±0.06°C per decade (95% confidence interval), with the overall warming significant at p<0.01 (Steig et al. 2009). Seasonally, Steig et al. (2009) demonstrated that the strongest warming trends in West Antarctica are observed in austral winter and spring (Fig. 2.21c-d), with the strongest cooling trends in East Antarctica observed during austral autumn (Fig. 2.21f).
FIG. 2.21: Mean annual temperature trends (in degrees Celsius per decade) from infrared satellite reconstruction. Depicted are mean annual trends for a) 1957-2006 and b) 1969-2000, and 1957-2006 mean seasonal trends for c) austral winter, d) spring, e) summer, and f) autumn. From Steig et al. (2009).
The results of Steig et al. (2009) were subject to scrutiny a couple years later in a study by O’Donnell et al. (2011), who suggested the methods used by Steig et al. (2009) to calibrate the satellite data and infill its spatial structure were not robust. More specifically, O’Donnell et al. (2011) note that data from the AVHRR is not continuous and is suspect to many errors that change with the time and location of observation. Therefore, O’Donnell et al. (2011) suggest that the AVHRR data needs to be calibrated to the ground data, instead of using the ground data as the explanatory variables and the infilling algorithm as the calibration (as in Steig et al. 2009). Using this new and “improved” method, O’Donnell et al. (2011) find the warming across Antarctica over the period 1957-2006 to be less marked in West Antarctica than reported by Steig et al. (2009), with major warming confined mainly to the Antarctic Peninsula, as noted by Turner et al. (2005). In particular, O’Donnell et al. (2011) find the annual warming across West Antarctica to be approximately half that reported by Steig et al. (2009). Seasonally, the continent-wide trends during austral fall and winter are of the largest difference between the two studies. Steig et al. (2009) suggest that statistically significant continent-wide warming is occurring in both fall and winter, while O’Donnell et al. (2011) report that there is no significant continent-wide warming in these two seasons.

Bromwich et al. (2013) provide the most recent examination of temperature trends across West Antarctica. As alluded to earlier, the main challenge facing scientists at coming to a consensus on West Antarctic temperature trends is the lack of observations in West Antarctica. In fact, only one station exists in West Antarctica
FIG. 2.22: Temperature time series from the reconstructed Byrd Station record for a) annual, b) summer, c) autumn, d) winter, and e) spring. Red dots represent periods where greater than 1/3 of the observations are missing. The grey line represents the 5-year running average temperature, and the grey histograms represent the number of monthly mean temperature observations available per year (a) or per season (b-e). From Bromwich et al. (2013).

(namely Byrd station), which is located in central West Antarctica and has substantial gaps in observations and is therefore an incomplete temperature record. Using global atmospheric reanalysis data (namely the ERA-Interim reanalysis) and spatially interpolated observations from other Antarctic stations, Bromwich et al.
(2013) present a reconstruction of the Byrd station temperature record that fills in the missing data (Fig. 2.22). The temperature reconstruction at Byrd station reveals an annual mean warming trend of $0.47 \pm 0.23^\circ C$ per decade over the period 1958-2011, statistically significant at the 99% confidence level ($p<0.01$; Fig. 2.22a). The temperature trends presented by Bromwich et al. (2013) are consistent with trends presented by Steig et al. (2009) and comparable to the warming observed at Faraday/Vernadsky on the west coast of the Antarctic Peninsula (Turner et al. 2005). From a seasonal standpoint, significant warming is observed at Byrd Station across all seasons except fall, with the warming most marked in winter and spring (Fig. 2.22). Further, the temperatures at Byrd station are found to be highly correlated ($r>0.8$) with the surrounding West Antarctic region (through spatial autocorrelation), suggesting that the significant surface warming at Byrd Station is representative of much of the surrounding West Antarctic ice sheet.

In addition to establishing a consensus on the warming across West Antarctica, several recent studies have suggested that the warming is linked to changes in the tropical Pacific sea surface temperatures (SSTs). Ding et al. (2011) were the first to suggest that changes in tropical Pacific SSTs are leading to widespread warming across continental West Antarctica. Using a variety of sources of data, Ding et al. (2011) found that an increase in central tropical Pacific SSTs leads to changes in regional atmospheric circulation in the Amundsen Sea (off the coast of West Antarctica), which leads to increased warm air advection onto the Antarctic continent. The high latitude regional atmospheric circulation is linked to
the tropics through the generation and propagation of Rossby waves from anomalously deep tropical convection produced by anomalously warm SSTs in the tropical Pacific. Using a general circulation model, Ding et al. (2011) find the high latitude circulation response to changes in the central tropical Pacific SSTs to be linked through the Pacific-South American pattern, which was discussed earlier in the ENSO section. The tropical component to the West Antarctic warming is most marked during austral winter, and to a lesser extent in austral spring.

Schneider et al. (2012a) examined the warming in austral spring, a season where warming is most marked across West Antarctica. The results of this study again suggest the West Antarctic warming to be linked to high latitude regional circulation changes emanating from the tropical Pacific. More specifically, Schneider et al. (2012) find that regional circulation trends in the high latitude South Pacific project onto the two Pacific South American (PSA) modes. In contrast to Ding et al. (2011), Schneider et al. (2012a) find that increased SSTs in the southwestern tropical Pacific, associated with anomalously deep convection and a strengthened Rossby wave-train to the high latitude South Pacific, are consistent with the warming across West Antarctica and also the decrease (increase) in sea ice area across the Bellingshausen (Ross) Sea.

In summary, Turner et al. (2005) found that significant warming at an annual rate of 0.56°C per decade is ongoing on the west coast of the Antarctic Peninsula, most marked in the austral winter season. Steig et al. (2009) and Bromwich et al. (2013) present strong evidence that the warming across the Antarctica Peninsula
extends beyond the Peninsula to encompass much of continental West Antarctica, with the warming here found to be between 0.17±0.06°C per decade over the period 1957-2006 and 0.47±0.23°C per decade (Byrd station) over the period 1958-2011. The results of these three studies suggest that the Antarctic Peninsula and continental West Antarctica are among the most rapidly warming regions on the planet. Together, Ding et al. (2011) and Schneider et al. (2012a) suggest that the observed temperature changes across West Antarctica are a result of changes in the high latitude regional atmospheric circulation, driven primarily from changes in tropical Pacific SSTs.
CHAPTER 3: DATA AND METHODS

3.1 Data Utilized

3.1.1 Reanalysis Data

To examine past atmospheric conditions and fill in the gaps between fixed observation locations, atmospheric reanalysis data are employed. An atmospheric reanalysis is a comprehensive, global dataset of the atmosphere that represents ‘snapshots’ of past atmospheric states. Reanalyses are created using a fixed data assimilation scheme that incorporates a consistent network of surface, upper-air, and satellite observations into an atmospheric model (Kalnay et al. 1996). The final product is a gridded model representation of the atmosphere at 6-hour intervals that span multiple decades into the past. Reanalysis data are not equivalent to observations; however, they are constrained by observations, routinely checked for accuracy, and have been proven very useful in a wide range of meteorological and climate studies because of their consistent spatial and temporal resolution and the large number of atmospheric variables generated as output.

The main atmospheric reanalysis dataset used in this study is the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis (Dee et al. 2011; hereafter ERA-Int). Other reanalyses exist, such as the United States’ National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (NNR; Kalnay et al. 1996) and the Japan Meteorological Agency and Central Research Institute of Electric Power Industry 25
year reanalysis (JRA-25; Onogi et al. 2005); however, the ERA-Int has been shown to have the highest skill at replicating both surface and upper-level atmospheric pressure and temperature across the high southern latitudes, and in particular, over continental Antarctica (Bracegirdle and Marshall 2012). Therefore, this study will only use ERA-Int data to examine atmospheric variability across the study area.

Atmospheric reanalysis data are calculated at several spatial and temporal resolutions and for hundreds of atmospheric parameters. This study will utilize ERA-Int data calculated at a 1.5° x 1.5° grid spacing. This spatial resolution means that over the entire globe there are 240 longitude and 121 latitude grid cells that have a horizontal dimension of 1.5° longitude x 1.5° latitude. The reanalysis parameters utilized in this study include mean sea level pressure (MSLP), 2-meter temperature (also referred to as near-surface temperature), 10-meter wind speed and wind direction, and geopotential height throughout the troposphere. The atmospheric parameters are analyzed over monthly, seasonal, and annual time scales using the monthly-mean data downloaded freely from the internet (http://dataportal.ecmwf.int/data/d/interim_full_moda) and archived on the Scalia Laboratory data server at Ohio University. Reanalysis data are analyzed over the period 1979-present. Only data after 1979 are used because: ERA-Interim data is only available from 1979 onwards, and studies have shown that reanalyses perform poorly over the high southern latitudes prior to the modern satellite era (1979), when satellite data first began to be assimilated (Bromwich and Fogt 2004).
3.1.2 Observation Data

In addition to reanalysis data, this study also employs observation data. Antarctic meteorological observation data are obtained from the quality controlled online Reference Antarctic Data for Environmental Research (READER) archive (Turner et al. 2004). These data are easily accessible and freely available for download from the internet (www.antarctica.ac.uk/met/READER/). Here, station temperature, pressure, and wind data is available for each study; however, this study will primarily use temperature data. As with the reanalysis data, only monthly-mean temperature data will be employed. The majority of stations with complete meteorological observation records in relative proximity to the study area (high latitude South Pacific (45°-70°S, 180°-60°W), West Antarctica, and the Antarctic Peninsula) are located only on the Antarctic Peninsula. Table 3.1 below details the station data used and the years of record and completeness (across all months) of the temperature record.

<table>
<thead>
<tr>
<th>Station</th>
<th>Elevation (m)</th>
<th>Latitude (°S)</th>
<th>Longitude (°W)</th>
<th>Starting Year</th>
<th>Percent Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellingshausen</td>
<td>16</td>
<td>-62.2</td>
<td>-58.9</td>
<td>1968</td>
<td>99.6</td>
</tr>
<tr>
<td>Esperanza</td>
<td>13</td>
<td>-63.4</td>
<td>-57.0</td>
<td>1957</td>
<td>98.1</td>
</tr>
<tr>
<td>Faraday/Vernadsky</td>
<td>11</td>
<td>-65.4</td>
<td>-64.4</td>
<td>1950</td>
<td>99.5</td>
</tr>
<tr>
<td>Marambio</td>
<td>198</td>
<td>-64.2</td>
<td>-56.7</td>
<td>1970</td>
<td>97.1</td>
</tr>
<tr>
<td>Rothera</td>
<td>32</td>
<td>-67.5</td>
<td>-68.1</td>
<td>1977</td>
<td>98.9</td>
</tr>
</tbody>
</table>
For temperature data across interior West Antarctica, this study uses the recently reconstructed Byrd station temperature record from Bromwich et al. (2013). This temperature record is a “patched” record that contains a blend of observations and reconstructed data to fill in periods of missing observations. The patched record is consistent with West Antarctic temperature reconstructions (i.e., Steig et al. 2009; O’Donnell et al. 2011), providing high confidence of its reliability, and serves as the only long-term station-based record of temperature across West Antarctica.

Satellite-observed outgoing longwave radiation (OLR) data are also employed in this study, and mainly used as a proxy to quantify the location and intensity of deep tropical. Longwave radiation is fundamentally heat emitted by the Earth’s surface as it converts incoming shortwave radiation from the sun into outgoing longwave radiation, or heat. Clouds effectively reflect incoming shorwave radiation from the sun and trap terrestrial outgoing longwave radiation from the Earth’s surface. Therefore, anomalously high (low) OLR values are associated with anomalously low (high) cloud cover and/or anomalously warm (cold) temperatures. Across tropical latitudes, the majority of cloud development is convective, so monitoring the location and magnitude of OLR is a useful way to track the location and magnitude of deep tropical convection. As mentioned, cloud cover and OLR have an inverse relationship: regions of increased cloud cover (increased tropical convection) are associated with relatively low OLR values, while areas of decreased cloud cover (decreased tropical convection) are associated with relatively high OLR
values. Satellite-derived monthly mean 2.5° x 2.5° grid spacing OLR data are obtained freely on the internet from the National Oceanic and Atmospheric Administration’s (NOAA) Earth System Research Laboratory (http://www.esrl.noaa.gov/).

3.1.3 Climate Data

The two large-scale modes of climate variability examined in this study are the El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). ENSO activity is monitored using tropical Pacific sea level pressure (SLP) anomalies and sea surface temperature (SST) anomalies. To quantify SLP anomalies related to ENSO activity, this study uses the Southern Oscillation Index (SOI) obtained online from the Climate Prediction Center (CPC; www.cpc.ncep.noaa.gov). The SOI is calculated using the pressure differences between Tahiti, French Polynesia (central tropical Pacific) and Darwin, Australia (western tropical Pacific). Tropical Pacific SST anomalies associated with ENSO are monitored using the SST anomalies in the following regions: Niño 3.4 (5°N-5°S, 170°W-120°W), Niño 4 (5°N-5°S, 160°E-150°W), Niño 3 (5°N-5°S, 150°W-90°W), and Niño 1+2 (0°-10°S, 90°W-80°W). The SST data are also obtained online from the CPC. The different regions of SST anomalies allows for an investigation of the role changes in SST structures (and the associated implied atmospheric convection) play in modulating the high southern latitude ENSO teleconnection.
For SAM events, this study utilizes the observation-based index of Marshall (2003). As outlined in the Marshall (2003) paper, this index is calculated by subtracting the zonally-averaged SLP across 12 stations, 6 each located approximately along 40°S and 65°S. The Marshall (2003) SAM index is available online (www.antarctica.ac.uk/met/gjma/sam.html).

3.2 Analysis Techniques

All statistical analyses used in this study are performed assuming that the data are normally distributed. This is reasonable, because climate variables such as pressure, geopotential height, temperature, and various wind components (i.e., meridional and zonal components) tend to cluster around the average, and the probability decreases nearly uniformly and symmetrically moving away from the average (following a normal distribution).

3.2.1 Linear Association

To investigate linear relationships in the data, a variety of statistical methods are employed. The first method is the Pearson product-moment correlation. The Pearson product-moment correlation coefficient ($r$) is used to measure the linear
association between two datasets. The formula for the Pearson correlation coefficient is:

\[ r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \]  

(3.1)

where \( r \) is the correlation coefficient, \( x_i \) and \( y_i \) are the variables comprising each dataset, and \( \bar{x} \) and \( \bar{y} \) are the respective means of each dataset. The Pearson correlation coefficient is equivalent to the covariance of \( x \) and \( y \) divided by the product of their standard deviations, simplified as:

\[ r = \frac{\text{cov}_{(X,Y)}}{S_x S_y} \]  

(3.2)

where \( \text{cov}_{(X,Y)} \) is the covariance of \( x \) and \( y \), and \( S_x \) and \( S_y \) are the standard deviations of \( x \) and \( y \), respectively. The correlation coefficient, \( r \), ranges between 1 and -1. Correlation coefficient values of 1 and -1 represent perfect positive and negative linear relationships between \( x \) and \( y \), respectively, and a coefficient value of zero represents no linear relationship. Correlation analysis is very useful in climate studies because it measures how much two variables change (vary) together over some independent field (usually time) and helps identify what variables in large datasets are related.
Correlation analysis is used in this study to investigate both long-term and short-term relationships. Long-term relationships are analyzed by correlating two datasets over their full period of record. For example, the SOI is correlated with the temperature record at an Antarctic Peninsula station to investigate whether or not changes in ENSO are linearly related to temperature changes on the Peninsula. Long-term correlations are useful at finding persistent relationships. However, when long-term correlations appear weak, there sometimes can exist time-varying correlations, which may be meaningful on shorter timescales. To investigate short-term relationships, this study utilizes 10-year running correlations. This method has been proven useful in the literature, such as in Fogt and Bromwich (2006) who performed 10-year running correlations between the SOI and the SAM index and found that the sign of the correlation coefficient changed substantially over time. As a result, the correlation between the SOI and SAM index over the long-term appeared weak despite having periods of strong SOI-SAM index correlations on shorter time scales. In summary, long-term correlations are used in this study to find persistent relationships, and short-term running correlations are used to find time-varying relationships.

A two-tailed Student’s t-test is performed to find the significance of the correlations. The correlation coefficients are tested against a null hypothesis of zero, meaning it is expected that no linear relationship exists between the two samples. The alternative hypothesis is that the correlation coefficient is not zero. Due to a large range of possible scenarios regarding linear relationships across the high
latitude Southern Hemisphere climate system, it is unclear whether or not the correlation coefficients calculated throughout this study will be positive or negative. Therefore, it is important to use a two-tailed $t$-test with an alternative hypothesis of either a positive or negative correlation coefficient (i.e., not zero). The formula for the Student’s $t$-test is:

\[
t_{n-2} = \frac{r \sqrt{n-2}}{\sqrt{1-r^2}}
\]  

where $r$ is the correlation coefficient and $n$ is the sample size. Essentially, the two-tailed Student’s $t$-test calculates the critical values for the $t$-statistic, which can be converted to specific probability values ($p$-value) using statistical tables and the degrees of freedom, $n-2$. Since the analysis in this thesis is based on seasonal means, it is assumed that each year is independent from the next, and therefore the degrees of freedom is the sample size minus two (i.e., it does not need to be adjusted for any autocorrelation within the data). This probability is the likelihood that the correlation coefficient is zero while allowing for the possibility that it could be positive or negative under the alternative hypothesis. Probabilities of $<10\%$ ($p<0.10$) are often considered statistically “significant,” in that they represent a less than 10% probability that the correlation is zero (or, a greater than 90% chance that the correlation is not zero). As such, this study will focus primarily on relationships with $p$-values less than 0.10 ($p<0.10$), and when possible $p<0.05$, to remove as many coincidental correlations as possible.
Correlation analysis will also be utilized to make teleconnection maps. For this technique, a variable at a specific geographic point is correlated across a gridded spatial dataset, typically of a meteorological variable (i.e., pressure). A climate index can be substituted for data at a specific geographic point to investigate how an index correlates with a meteorological variable across space. For example, SST at a certain grid point, or a climate index, such as the SOI, could both be correlated over time with gridded reanalysis SLP across the Southern Hemisphere. Teleconnection maps are useful because they show how the atmospheric variability in specific places is linearly related (correlated) over time to another point in space. The correlation coefficient and statistical significance are calculated at each grid point of the spatial field using equations 3.1-3.3.

3.2.2 Linear Trends

To investigate linear trends in the data, a technique called linear regression is employed. Linear regression calculates the slope of a dataset by creating a line that best fits the data, by minimizing the distance from the regression line to the actual data. The equation of the line is:

\[ y = bx + a \]  

(3.4)

where \( y \) is the dependent variable (predictand; usually the meteorological or climate variable of interest), \( x \) is the independent variable (predictor; usually time), \( a \) is the
intercept, and $b$ is the regression coefficient (slope). The regression coefficient is calculated between $x$ and $y$ using the equation:

$$ b = \frac{n \sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{n \sum_{i=1}^{n} (x_i)^2 - (\sum_{i=1}^{n} x_i)^2} \quad (3.5) $$

which simplifies to:

$$ b = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (3.6) $$

The regression coefficient is equivalent to the covariance of $x$ and $y$ divided by the variance of $x$ (the independent variable). For this study, linear regression is mainly used to find trends in meteorological dependent variables (station temperatures, pressure, etc.) and climate indices (SOI, SAM index, etc.) over time (years, the independent variable). The standard error of the slope, $s_b$, is calculated using the following equation:

$$ s_b = \sqrt{\frac{1}{n(n-2)} \left[ n \sum_{i=1}^{n} (y_i)^2 - (\sum_{i=1}^{n} y_i)^2 \right] \left[ \frac{n \sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{n \sum_{i=1}^{n} (x_i)^2 - (\sum_{i=1}^{n} x_i)^2} \right]^2} \quad (3.7) $$
The statistical significance of the trend can be calculated using the standard error and the equation:

\[ t_{n-2} \approx \frac{b-b_0}{s_p} \]  

(3.8)

where \( b_0 \) is the hypothesized slope and \( b \) is the actual slope from Eqns. (3.5-3.6). Again, the slope is tested against the null hypothesis of zero, so equation 3.8 can be expressed as the slope divided by the standard error. A two-tailed \( t \)-test is used to allow for the alternative slope to be either positive or negative, because it is unknown in advance exactly what sign various trends may be. As with testing for the significance of correlations, probabilities less than 10% \((p<0.10)\) are considered significant, but again this study aims to find \( p \)-values less than 5% \((p<0.05)\), which indicate very high confidence the trends are not zero.

Lastly, this study employs linear congruency to investigate how much of a linear trend (slope) is related to a trend in a third dependent variable over the same independent variable (i.e., time). Thompson et al. (2000) used this technique to calculate how much of an observed trend in SLP across the Northern Hemisphere was congruent with a trend in the Arctic Oscillation index. This technique provides two results: a component of the two trends that is linearly congruent and a component that is linearly independent, or the residual. Linear congruency is very useful for investigating how trends in one variable are related to trends in another variable. For this study, it will most commonly be used to see if trends in a climate...
index or trends in SST anomalies are congruent with trends in observed climate across the Antarctic Peninsula and West Antarctica.

Linear congruency is calculated using an algebraic manipulation of the techniques already described in this section. First, the time trend (slope) of the climate index or SST anomaly is calculated, followed by the time trend of the climate variable (temperature, pressure, etc.). Second, the regression coefficient is calculated between the climate index and the climate variable (the two previous dependent variables). The congruent portion of the trend is the product of the regression coefficient and the time trend of the climate index, written as:

\[
\text{linear congruent portion} = b_{xy} b_x
\]  

(3.9)

where \(b_{xy}\) is the regression coefficient of the climate index with the climate variable and \(b_x\) is the time trend of the climate index over the time period of interest. The residual is the difference between the time trend of the variable and the linearly congruent portion, or:

\[
\text{residual} = b_y - \text{linear congruent portion}
\]  

(3.10)

where \(b_y\) is the time trend of the climate variable.
3.2.3 Composite Analysis

The final statistical method used in this study is composite analysis. Composite analysis, or anomaly composites, is a technique used in climate studies to investigate the difference in means between two groups of data. For this study, groups of data with same sign anomalies are compared to normal conditions. For example, to investigate the anomalous circulation associated with La Niña events, the SLP averaged over 5 La Niña years could be compared to the 1981-2010 climatological average SLP. Composite analysis is very useful for investigating the anomalous conditions associated with specific, same-sign events (i.e., La Niña events) by combining several samples into one. Typically, the conditions during similar events (i.e., La Niña events) are grouped together, averaged, and compared to the average conditions of other events (i.e., ENSO neutral conditions).

To define groups of events for compositing, the data of interest are either standardized (using the climatological time period 1981-2010 as the base mean period) and sorted based on standardized value, or sorted based on percentiles. For this study, the years associated with same-sign anomalies are used to define a group of similar events. Reanalysis data are employed to examine atmospheric circulation (including pressure, geopotential height, and winds) and temperatures associated with various groups of events. For example, climate variables (i.e., SLP) during the top 5 warmest years at an Antarctic Peninsula station can be averaged and compared to the 1981-2010 climatological average SLP to see what anomalous circulation patterns are associated with warm events across the Peninsula.
Equally important is the significance, or uniqueness, of the differences between the groups. To calculate significance, a two-tailed Student’s t-test is used. After defining a group, the pooled sample variance, $S_p^2$, is calculated using the equation:

$$S_p^2 = \frac{(n-1)S_X^2 + (m-1)S_Y^2}{m + n - 2} \tag{3.11}$$

where $n$ and $m$ are the sample sizes of the two groups being compared (i.e., anomalous events compared to climatology), and $S_X^2$ and $S_Y^2$ are the sample variance of each respective group. Once the pooled sample variance is calculated, the two-tailed $t$-values are calculated using the equation:

$$t_{m+n-2} = \frac{\overline{X} - \overline{Y} - (\mu_X - \mu_Y)}{S_p \sqrt{\frac{1}{n} + \frac{1}{m}}} \tag{3.12}$$

where $\overline{X}$ and $\overline{Y}$ are the respective means of each group, $\mu_X$ and $\mu_Y$ are the hypothesized means for each group ($\mu_X - \mu_Y$ is zero because we hypothesize the difference of the two means to be zero), and $S_p (\sqrt{S_p^2})$ is the pooled sample standard
deviation. Significance for $p$-values less than 10%, 5%, and 1% are plotted to identify regions where the difference between the two groups is statistically significant.
CHAPTER 4: RESULTS

4.1 Seasonal Trends and Relationships

As covered in the literature, there are several ongoing statistically significant trends in the regional Antarctic climate and SH modes of climate variability. Interestingly, depending on the location and particular climate mode, the trends vary by season. In order to decide which season(s) and time period(s) are best suited for focus within this study, linear regression, linear congruency, and correlation are performed between the key climate variables highlighted in the literature to be changing and the dominant SH modes of climate variability (i.e., ENSO and SAM).

To examine trends in the regional Antarctic climate, monthly and seasonal least-squares linear regression coefficients are calculated over time (trends) for the following: station temperature data on the Antarctic Peninsula (Fig. 4.1), Bromwich et al. (2013) Byrd reconstruction temperature data, ERA-Interim 2-meter temperature data over West Antarctica, and ERA-Interim ABSL magnitude and location data (Fig. 4.1; Fogt et al. 2012a). Figure 4.1 displays a map of the Antarctic Peninsula stations used for analysis and the ABSL region. Variations in the ABSL position and magnitude are investigated using the monthly minimum ERA-Interim sea level pressure value in the region 55°S-75°S, 180°-60°W (region shown in Fig. 4.1, as in Fogt et al. 2012a). West Antarctica ERA-Interim temperature data are investigated in three separate spatially area-averaged regions between 72°S-85.5°S:
all of West Antarctica (75°W-156°W), eastern West Antarctica (75°W-115.5°W), and western West Antarctica (115.5°W-156°W).

For trends in large-scale climate variability, monthly and seasonal linear trends are also calculated for the following: Marshall (2003) SAM index, SOI, Niño 3.4, 4, 3 and 1+2 SST anomalies, and Niño 3.4, 4 and 1+2 area-averaged OLR data (Table 4.1). The trends are calculated over two time periods: the full period of record for each variable and 1979-2012. The period 1979-2012 is chosen so that ERA-Interim data can be compared with other data that has longer periods of record. Upon examination of the monthly trends, it was decided to use only seasonally averaged data in order to filter out inter-monthly variability (essentially, reduce “noise” in the data) and to improve the robustness of the results. The seasonal linear regression coefficients (trends) and statistical significance are shown in Table 4.1. To avoid complications in “data overload,” the 95% confidence
intervals are not included in Table 4.1; however, this does not interfere with the key conclusions from the table, because the significance is still denoted. If any trends are referenced in the text, the 95% confidence interval is included.

From Table 4.1, several stories emerge, some of which were highlighted in the literature, and others whose existence and causality are unknown. Looking first at the temperature trends over the full period of record (reference sections 3.3.1 and 3.1.2 for a full list of data records), there are significant ($p<0.01$) warming trends observed across the northeast Antarctic Peninsula (i.e., Esperanza and Faraday) during austral summer (DJF), which coincide with significant ($p<0.01$) positive trends in the SAM index. The literature suggests these two trends are linked, with positive trends in the SAM index leading to warming along the northeast Peninsula, mainly through adiabatic warming of air parcels descending on the lee of the mountains across the Antarctic Peninsula (Marshall et al. 2006; Orr et al. 2008). The positive trends in the SAM index continue into austral fall (MAM), as do the positive temperature trends along the Peninsula, albeit not as significant over the northeast Peninsula as in DJF. Further, the positive SAM index trends and northeast Peninsula warming trends are also present over the 1979-2012 period. The other trends during DJF and MAM, both in large-scale climate variability and the local Antarctic climate, are not fully understood. Further, there are no significant trends in the ERA-Interim West Antarctic 2-meter temperatures or in the ABSL magnitude or location in these seasons.
TABLE 4.1: Seasonal trends for Marshall (2003) SAM index and SOI (units of standardized index/decade), tropical Pacific SSTs (units of °C/decade), tropical Pacific OLR (units of W m\(^{-2}\)/decade), Antarctic Peninsula station temperatures (red, units of °C/decade), Byrd reconstructed temperature and West Antarctic ERA-Interim 2-meter temperature (blue, units of °C/decade), and ABSL (green) central pressure (units in hPa/decade), longitude (units of °East/decade) and latitude (units of °latitude/decade). Trends are calculated for the full period of record (or 1957, whichever is later) ending at 2012 (first column), and over the period 1979-2012 (second column).

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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<th></th>
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<td>0.11</td>
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<td>-0.08</td>
<td>0.07</td>
<td>0.02</td>
<td>0.08</td>
<td>-0.04</td>
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<td>0.005</td>
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<td><strong>0.11</strong></td>
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<td>0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>SST 1+2</td>
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<td>-0.01</td>
<td>0.11</td>
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<td>2.26</td>
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<td>1.73</td>
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<td>1.98</td>
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<td>2.93</td>
</tr>
<tr>
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<td><strong>-1.06</strong></td>
<td><strong>-1.06</strong></td>
</tr>
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<td><strong>1.02</strong></td>
<td><strong>1.18</strong></td>
<td><strong>0.36</strong></td>
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<td><strong>0.35</strong></td>
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<td>0.36</td>
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<tr>
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<td>0.35</td>
<td>0.27</td>
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<td>0.41</td>
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<tr>
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<td>0.54</td>
<td><strong>0.69</strong></td>
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<td>-0.01</td>
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<td>0.43</td>
<td>0.31</td>
<td>0.31</td>
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<td>0.001</td>
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<td>0.02</td>
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<td><strong>0.63</strong></td>
<td><strong>0.63</strong></td>
</tr>
<tr>
<td>East W. Ant.</td>
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<td>-0.09</td>
<td>-0.05</td>
<td>-0.05</td>
<td>0.08</td>
<td>0.08</td>
<td><strong>-0.004</strong></td>
<td><strong>-0.004</strong></td>
</tr>
<tr>
<td>ABSL Pressure</td>
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<td>-0.93</td>
<td>-0.31</td>
<td>-0.31</td>
<td>0.2</td>
<td>0.2</td>
<td>-0.34</td>
<td>-0.34</td>
</tr>
<tr>
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<td>-3.18</td>
<td>-3.18</td>
<td>3.06</td>
<td>3.06</td>
<td>0.04</td>
<td>0.04</td>
<td>-3.15</td>
<td>-3.15</td>
</tr>
<tr>
<td>ABSL Latitude</td>
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<td>-0.01</td>
<td>-0.005</td>
<td>-0.005</td>
<td>0.25</td>
<td>0.25</td>
<td>0.23</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Boldface trends are significantly different from zero at \(p<0.10\); boldface, italicized, and underlined trends are significantly different from zero at \(p<0.05\), and trends significantly different from zero at \(p<0.01\) are denoted with an asterisk.
Turning to the austral winter (JJA) and spring (SON), the positive trends in
the SAM weaken and are no longer statistically significant; similarly the positive
temperature trends on the northeast Antarctic Peninsula weaken and are no longer
statistically significant. Meanwhile, statistically significant \((p<0.01)\) warming trends
are observed along the western Antarctic Peninsula (i.e., Faraday and Rothera)
during JJA and SON. In addition, the strongest warming at Byrd station is found
during these two seasons. From Table 4.1, the strongest warming trends on the
western Peninsula are observed during winter, while the strongest warming over
West Antarctica is observed during spring. Noteworthy, the warming over the
western Peninsula remains strong and statistically significant over both time
periods during JJA and SON, and actually increases in magnitude at Faraday from
1950-2012 to 1979-2012 and remains highly significant at \(p<0.01\). Meanwhile, the
strongest warming at Byrd station appears to be during the early part of the 1957-
2012 period of record, as the significance of the trends decreases during the 1979-
2012 period.

Other interesting trends are observed in Table 4.1 during JJA and SON,
especially during SON. Focusing on the Antarctic climate variables, significant
\((p<0.05)\) warming is observed over the western half of West Antarctica during SON.
Recall, because there are no complete station observation data over West Antarctica
(aside from the incomplete Byrd station data that was patched by Bromwich et al.
(2013)), ERA-Interim 2- meter temperature data are employed to represent West
Antarctic near-surface temperature trends. Since ERA-Interim data can only be used
post 1979, the absence of significant warming over all of West Antarctica (over the 1979-2012 period) during JJA and SON is consistent with the decrease in the warming trend at Byrd station post 1979. Therefore, significant warming over all of West Antarctica (O’Donnell et al. 2011; Steig et al. 2009) and the warming at Byrd (Bromwich et al. 2013) were likely strongest before 1979, and the more recent warming trends are not as strong and/or significant. However, it is interesting that significant warming is observed over the western half of West Antarctica post 1979, especially given that this area is geographically separated from the warming trends across the western Antarctic Peninsula, where significant warming is observed both before and after 1979 during SON.

Looking at trends in dominant climate modes during JJA and SON, statistically significant trends are also observed, especially during SON. First and foremost, the significant positive trends in the SAM index that was observed during DJF and MAM diminish and are not observed during JJA and SON. This suggests that the warming trends over the western Peninsula and western West Antarctica are likely a result of some different large-scale forcing mechanism. The literature suggested that the warming over West Antarctica is linked to the tropical Pacific through the generation of Rossby wavetrains from tropical convection that propagates to the high latitude South Pacific, and influences regional circulation and temperature advection patterns (Bromwich et al. 2013; Schneider et al. 2012a; Ding et al. 2011). For this reason, trends in the SOI and various regions of tropical Pacific SSTs during JJA and SON are of particular interest in Table 4.1. Looking first at the
SOI, there is no significant trend over the full period of record; however, a significant ($p<0.05$) positive trend emerges post 1979, indicating a more recent trend toward increased La Niña-like conditions. Studies showed that La Niña conditions produce a negative pressure and geopotential height anomaly in the high latitude South Pacific (Mo and Higgins 1998), essentially deepening the ABSL. As a result, an increase in La Niña conditions would likely drive an increase in warm air advection onto the western Peninsula, possibly explaining the warming trends there; however, it is unlikely that the positive SOI trends are explaining the warming trends across both the western Peninsula and western West Antarctica as there are no significant warming trends in the geographic region between these two locations (i.e. eastern West Antarctica). A significant ($p<0.05$) negative trend is also observed in OLR across the Niño 1+2 region, which is located in the far eastern tropical Pacific (see section 3.1.3). As discussed in section 3.1.2, negative OLR values are typically associated with increased convection in the tropical Pacific; however, rarely is deep tropical convection observed over the far eastern tropical Pacific (the location of the Niño 1+2 region) due to relatively cooler SSTs and higher static stability compared to tropical SSTs along and west of the dateline (Lachlan-Cope and Connelly 2006). Therefore, it is unlikely that an increase in cloud cover over the eastern tropical Pacific is driving Rossby wavetrains to the Antarctic region, as deep convection alters the upper level divergence and vorticity, generating the Rossby waves. Nevertheless, the negative Niño 1+2 OLR trend could be linked to the more expansive SOI trends. Recall from section 3.1.2 that OLR is first and foremost related
to temperature and is used only as a proxy for cloud cover/tropical convection. Since La Niña conditions (positive SOI values) are associated with below normal SSTs in the Niño 1+2 region, the negative OLR trend could also be a result of cooling SSTs in the Niño 1+2 region associated with increased La Niña conditions in the absence of cloud cover.

To investigate interannual relationships among the data, seasonal correlations between the major climate modes and the local Antarctic climate are provided in Table 4.2. To focus on the significant relationships between large-scale climate modes and the local Antarctic climate, only the SOI and SAM index are correlated with the Antarctic climate variables. Although not given in Table 4.2, correlations between Niño 3.4 SST anomalies and the local Antarctic climate were also calculated to check the robustness of the ENSO/high latitude relationships. As in Table 4.1, correlations over both the full period of record and over the period 1979-2012 are each listed separately so that ERA-Interim data can be analyzed comparatively with other climate data. At this point, the data are not detrended because the trends are an important component at deciding which season(s) to investigate, as they indicate other statistical underlying relationships within the data. Detrended correlations will be investigated later once the season(s) are selected.

Correlations for DJF and MAM are shown in Table 4.2a. Recall from Table 4.1 and the literature (Marshall 2007; Fogt et al. 2009), statistically significant positive trends in the SAM index are observed in these two seasons, which are related to the
TABLE 4.2a: Austral summer and autumn seasonal correlations of Antarctic temperatures and ABSL with the Marshall (2003) SAM index and SOI over the full period of record (as indicated in TABLE 4.1) and 1979-2012.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
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<td></td>
<td>DJF</td>
<td>MAM</td>
<td>DJF</td>
<td>MAM</td>
<td>DJF</td>
<td>MAM</td>
</tr>
<tr>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
</tr>
<tr>
<td>Faraday</td>
<td>0.10</td>
<td>0.00</td>
<td>-0.05</td>
<td>-0.28</td>
<td>0.04</td>
<td>0.30</td>
</tr>
<tr>
<td>Rothera</td>
<td>-0.03</td>
<td>-0.11</td>
<td>-0.11</td>
<td>-0.16</td>
<td>0.33</td>
<td>0.58*</td>
</tr>
<tr>
<td>Bellingshausen</td>
<td>0.06</td>
<td>0.36</td>
<td>0.03</td>
<td>0.23</td>
<td>0.15</td>
<td>0.60*</td>
</tr>
<tr>
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<td>0.12</td>
<td>0.57*</td>
<td>0.23</td>
<td>0.58*</td>
<td>0.01</td>
<td>0.46*</td>
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<td>Marambio</td>
<td>0.08</td>
<td>0.53*</td>
<td>0.19</td>
<td>0.54*</td>
<td>-0.08</td>
<td>0.55*</td>
</tr>
<tr>
<td>Byrd</td>
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<td>-0.07</td>
<td>-0.16</td>
<td>-0.09</td>
<td>-0.08</td>
<td>-0.29</td>
</tr>
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<td>All W. Ant.</td>
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<td>-0.24</td>
<td>-0.34</td>
<td>-0.24</td>
<td>-0.09</td>
<td>-0.56*</td>
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<td>-0.17</td>
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<td>-0.48*</td>
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<td>-0.49*</td>
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Colors and statistical significance of correlations is as denoted in TABLE 4.1.
TABLE 4.2b: Austral winter and spring seasonal correlations of Antarctic temperatures and ABSL with the Marshall (2003) SAM index and SOI over the full period of record (as indicated in TABLE 4.1) and 1979-2012.

<table>
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<tr>
<th></th>
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<th>1979-2012</th>
<th>SOI</th>
<th>SAM</th>
<th>1979-2012</th>
<th>SOI</th>
<th>SAM</th>
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<td>0.23</td>
<td>0.29</td>
<td>0.26</td>
<td>0.54*</td>
<td>-0.09</td>
<td>0.61*</td>
</tr>
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<td>0.35</td>
<td>0.39</td>
<td>0.39</td>
<td>0.54*</td>
<td>0.63*</td>
<td>0.31</td>
<td>0.61*</td>
</tr>
<tr>
<td>Bellingshausen</td>
<td>0.05</td>
<td>0.47*</td>
<td>1.13</td>
<td>0.54*</td>
<td>0.39*</td>
<td>0.30</td>
<td>0.34</td>
</tr>
<tr>
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<td>0.45*</td>
<td>0.12</td>
<td>0.46*</td>
<td>0.29</td>
<td>0.39*</td>
<td>0.32</td>
</tr>
<tr>
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<td>0.43*</td>
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<td>0.44*</td>
<td>0.20</td>
<td>0.52*</td>
<td>0.28</td>
</tr>
<tr>
<td>Byrd</td>
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<td>-0.12</td>
<td>-0.15</td>
<td>-0.28</td>
<td>0.04</td>
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<td>0.12</td>
</tr>
<tr>
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<td>-0.34</td>
<td>-0.03</td>
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<td>-0.08</td>
<td>0.18</td>
<td>-0.08</td>
<td>0.15</td>
<td>-0.17</td>
<td>0.15</td>
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<td>-0.71*</td>
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<td>-0.23</td>
<td>0.05</td>
<td>-0.21</td>
<td>0.05</td>
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</table>

Colors and statistical significance of correlations is as denoted in TABLE 4.1.
warming along the northeast Peninsula. Therefore, as demonstrated by the correlations in Table 4.2a, it is not surprising to see statistically significant positive correlations between the SAM index and the temperatures along the northeast Peninsula. For example, during DJF when the SAM index has the strongest positive trend, the SAM index is significantly positively correlated with temperatures at Esperanza and Marambio at $p<0.01$ over both the full period of record and 1979-2012. Significant negative correlations are also observed between the SAM index and the ABSL pressure and its latitudinal position during DJF. This is not surprising either, since the literature demonstrates that positive SAM index values are associated with negative pressure and geopotential height values in the vicinity of the ABSL and across interior Antarctica (Fogt et al. 2006; Fogt et al. 2012a; Hosking et al. 2013). Noteworthy, Table 4.1a also reveals significant negative correlations between the SOI and temperatures across all and eastern West Antarctica and with the ABSL pressure during DJF. This can be interpreted that positive SOI values (La Niña conditions) are associated with negative pressure anomalies in the ABSL (which is consistent with Fogt et al. 2011) and colder than normal conditions across West Antarctica. The latter is not fully understood, and it is unclear why La Niña conditions are associated with below normal temperature across portions of West Antarctica. Moving forward to MAM, it is readily apparent that the SAM is the dominant climate mode driving changes in local climate across the entire region. In fact, over both the full period of record and 1979-2012, nearly every climate variable is significantly correlated with the SAM index at $p<0.01$. 
From Table 4.2b, it is demonstrated that the SAM index correlation with the northeast Antarctic Peninsula temperatures remains strongly positive and statistically significant through JJA and SON. The negative correlation between the SAM index and the ABSL pressure also remains statistically significant at $p<0.01$ through JJA and SON. Noteworthy, the SAM index is negatively correlated with temperatures across western West Antarctica at $p<0.05$ during JJA, and with temperatures across all of West Antarctica, including Byrd, at a minimum of $p<0.05$ during SON. This is most likely a result of below normal temperatures dominating continental Antarctica during positive phases of the SAM, consistent with Thompson and Solomon (2002) and Marshall (2007). Most interesting from Table 4.2b is the sharp increase in magnitude and significance of the correlations between the SOI and temperatures along the western Antarctic Peninsula during SON. For instance, positive correlations between the SOI and temperatures at Faraday and Rothera emerge during SON and are significant at $p<0.01$ over both the full period of record and 1979-2012. Meanwhile, as previously mentioned, significantly positive correlations at $p<0.01$ are observed between the SAM index and temperatures along the northeast Peninsula over both time periods. It is rather interesting to see such strong discrepancies in relationships across such small geographical distance (i.e., the SOI correlation with western Peninsula temperatures and the SAM index correlation with northeast Peninsula temperatures).

Altogether, it is concluded from Tables 4.1 and 4.2 that the statistically significant positive trends in the SAM index during DJF are likely the cause of the
statistically significant positive temperature trends along the northeast Antarctic Peninsula during that season. This relationship was also covered fairly extensively in the literature, so it is not of high interest for this study. During MAM, it is clear that the SAM has the dominant influence on the local Antarctic climate given the highly significant ($p<0.01$) correlations between the SAM index and nearly the entire regional climate. Since this study seeks to better understand any tropical influence on the West Antarctic and Antarctic Peninsula climate, MAM is also not of high interest for the study. During JJA, the SAM index is significantly correlated with temperatures along the northeast Peninsula and over portions of West Antarctica. Statistically significant correlations at $p<0.05$ are also observed between the SOI and ABSL pressure and longitude during JJA; however, weaker correlations are observed between the SOI and regional temperatures. Since ENSO also tends to be weakest in austral winter, JJA is not of particular interest for this study, either, despite the strongest warming across the Peninsula being observed in JJA. Further, previous work has suggested that the JJA Peninsula warming is inherently tied to decreases in sea ice in the Amundsen and Bellingshausen Seas (Turner et al. 2012), and as such, the JJA warming has been investigated more perhaps than other seasons.

Moving to SON, a very interesting relationship between SAM, ENSO, and the Antarctic climate emerges. First, the SAM index is statistically significantly correlated at $p<0.01$ with the northeast Peninsula temperatures, while the SOI is statistically significantly correlated at $p<0.01$ with the western Peninsula temperatures. Additionally, the SOI has recently been trending positive at $p<0.05$
over the 1979-2012 period while the western Peninsula temperatures (i.e., Faraday and Rothera) are simultaneously experiencing warming trends at $p<0.01$. Recall also that OLR in the Niño 1+2 region is trending negative at $p<0.05$ in SON, suggesting that the ENSO trends are robust, and may be related to the western Peninsula temperature trends given the strong correlations between the SOI and western Peninsula temperatures. Given the remarkable discrepancy in correlations across the region, with the SAM index being significantly correlated with the northeast Peninsula and interior West Antarctic temperatures, and the SOI being significantly correlated with western Peninsula temperatures, SON is of high relevance to the overarching goal of this study, which is to better identify the influence of the tropics on the Antarctic climate and the combined role that ENSO and SAM have on the regional climate. In addition, according to the literature, very little is understood about the SAM and ENSO influence on Antarctic climate during SON. Therefore, this study will continue focusing on SON only.

4.2 SON Spatial Trends and Relationships

From Table 4.1, there is a statistically significant positive (negative) trend in the SOI (OLR 1+2) during SON over the period 1979-2012, indicating a trend toward increased La Niña-like conditions. In addition, statistically significant warming trends are observed across the western Antarctic Peninsula (Faraday and Rothera stations), Byrd station, and the western half of West Antarctica. To investigate these
FIG. 4.2: ERA-Interim SON trends for a) 500 hPa geopotential height, b) MSLP, c) 2-meter temperature, and d) 10-meter meridional wind (positive=southerly wind) over the period 1979-2012. Trend values are contoured and labeled on the map, trend units are labeled in the titles, and statistical significance is shaded.
SON trends further, spatial trends in the atmospheric circulation and near-surface temperatures over the period 1979-2012 are plotted in Fig. 4.2.

From Figs. 4.2a-b, there are two consistent trends in 500 hPa geopotential height and MSLP in the vicinity of West Antarctica and the Antarctic Peninsula. First, there is a region of statistically significant ($p<0.05$) decreases in 500 hPa geopotential height and MSLP in the eastern Ross Sea. This negative trend would be associated with a deepening of the ABSL in this region, which is consistent with Fogt et al. (2012a) identifying a statistically significant deepening of cyclones in the Ross Sea. Second, further east toward the Antarctic Peninsula, a region of strong positive trends in 500 hPa geopotential height and MSLP is located to the northeast of the Antarctic Peninsula, significant at $p<0.05$ for 500 hPa geopotential height and $p<0.01$ for MSLP. The increasing geopotential height and MSLP in this region is consistent with the PSA-1/La Niña pattern (Mo and Higgins 1998), and also consistent with the trend toward increased La Niña conditions. This is also consistent with the positive SON SST trends in the Niño 4 region (Table 4.1), which is located in the western tropical Pacific where anomalously warm SSTs are typically observed during La Niña events (positive and statistically significant over the 1950-2012 period; positive but not significant over the 1979-2012 period).

Across the eastern and central tropical Pacific, Fig. 4.2b shows a tongue of positive MSLP trends significant at $p<0.01$, mainly in the Niño 1+2 region. This is also consistent with the negative SON SST trends in the Niño 1+2 region over the 1979-
2012 period (Table 4.1), as cooling SSTs would lead to cooler near-surface ambient air temperatures in this region and higher surface pressure.

Spatial trends in 2-meter temperature and meridional wind are plotted in Figs. 4.2c-d. From Fig. 4.2c, statistically significant negative temperature trends \((p<0.01)\) are observed across the Niño 1+2 region, which coincides with the region of positive MSLP trends. Below normal temperatures and above normal MSLP in this region is associated with La Niña conditions (Trenberth 1997), and is consistent with the SOI and OLR 1+2 trends in Table 4.1. Moving poleward to the high latitude South Pacific and West Antarctic/Antarctic Peninsula region, statistically significant positive temperature trends are observed along the western Antarctic Peninsula and across the western half of West Antarctica, also consistent with the trends in Table 4.1. A closer geographic look at these temperature changes near Antarctica will be given later.

In the vicinity of the negative 500 hPa geopotential height/MSLP trends in the eastern Ross Sea and the positive 500 hPa geopotential height/MSLP trends to the northeast of the Antarctic Peninsula, there are also statistically significant trends in the meridional circulation (Fig. 4.2d). First, statistically significant positive meridional wind trends (increased southerly flow or decreased northerly flow) are observed over the Ross Sea, which is located on the western side of the negative 500 hPa geopotential height/MSLP trends. Assuming geostrophic flow, these trends are directly in line with the increased clockwise flow around the center of greatest pressure/geopotential height decrease in the Ross Sea. This increased southerly
flow also aligns with statistically significant cooling trends (Fig. 4.2c) and the increases in sea ice extent and sea ice season length in the Ross Sea region as noted by Stammerjohn et al. (2008, 2012). Increased counterclockwise flow is observed around the positive pressure trends to the northeast of the Antarctic Peninsula, with increased northerly flow across the southern tip of South America and extreme northern tip of the Antarctic Peninsula.

Due to the focus of this thesis, a closer geographic look at the trends across the high latitude South Pacific region is warranted, and is plotted in Fig. 4.3. In particular, Fig. 4.3 allows for a more detailed look at the magnitude and significance of the trends in the vicinity of West Antarctica and the Antarctic Peninsula, especially for temperature and meridional wind, which were difficult to interpret from Fig. 4.2. From Figs. 4.3a-b, the negative 500 hPa geopotential height and MSLP trends are observed to be -12 meters and -1.2 hPa per decade, respectively, while the positive 500 hPa geopotential height and MSLP trends to the northeast of the Peninsula are 15 meters and 1.6 hPa per decade, respectively. The warming along the western Peninsula is approximately 0.6°C per decade (significant at $p<0.01$; Fig. 4.3c), consistent with the observed warming trends of 0.76°C per decade and 0.61°C per decade at Faraday and Rothera, respectively (Table 4.1). The warming across western West Antarctica is approximately 1.2°C per decade (significant at $p<0.01$; Fig. 4.3c), which is much stronger but still consistent with the ERA-Interim western West Antarctic area-averaged warming trend in Table 4.1. Figure 4.3 suggests that the warming in western West Antarctica is confined mainly to extreme western
FIG. 4.3: As in Fig. 4.2, except for the West Antarctic/Antarctic Peninsula region only.
West Antarctica, which would explain the relatively weaker warming trends for the entire area-averaged western half of West Antarctica in Table 4.1.

Looking at the meridional circulation trends in Fig. 4.3d, there are negative meridional wind trends (increased northerly flow) on the eastern side of the negative pressure/geopotential height trends in the Ross Sea from around 135°W-120°W. Although statistically insignificant, the increased northerly flow could partially explain the positive temperature trends offshore of western West Antarctica (Fig. 4.3c) through geostrophic warm air advection. Interestingly, the warming trend across interior western West Antarctica (Fig. 4.3c) align with positive meridional wind trends, or increased southerly flow from interior West Antarctica, which may or may not be linked to the deepening pressure/geopotential height trends in the Ross Sea. In contrast, the warming along the western flank of the Peninsula aligns with negative meridional wind trends, although these trends are also not statistically significant. The negative meridional wind trends imply increased northerly flow, which appear to be generated by the altered regional pressure gradient, in particular the strengthening counterclockwise flow around the positive pressure/geopotential height trends to the northeast of the Peninsula.

The spatial trends presented in Figs. 4.2 and 4.3 are consistent with the SON trends provided in Table 4.1 and provide insight into possible mechanisms driving the trends. Starting first with the tropics, the positive MSLP trends and negative near surface temperature trends in the eastern and central tropical Pacific (Fig. 4.2b-c) provides evidence that the positive trends in the SOI and negative trends in
OLR 1+2 (Table 4.1) are robust, and there likely exists an SON trend toward increased La Niña conditions over the period 1979-2012. From Mo and Higgins (1998), La Niña events are typically associated with a negative pressure/geopotential height anomaly in the high latitude South Pacific, and a positive pressure/geopotential height anomaly to the northeast of the Peninsula. Therefore, the positive trend in MSLP and 500 hPa geopotential height to the northeast of the Peninsula (Figs. 4.2a-b and 4.3a-b) is consistent with the trends in the tropics, and this regional pressure trend and increased northerly flow along the western Peninsula (Fig. 4.3d) could be linked to the warming trends along the western Peninsula through increased geostrophic warm air advection (Fig. 4.3c; Table 4.1). This will be examined later by use of teleconnection maps. Across the ABSL region, the negative MSLP and 500 hPa geopotential height trends in the Ross Sea (Figs. 4.2a-b and 4.3a-b) are consistent with results from Fogt et al. (2012a), and the deepening pressure in this region appears to be associated with the warming trends across western West Antarctic through increased northerly flow (Fig. 4.3d) and resultant geostrophic warm air advection.

Although there are many consistent relationships between the trends plotted in Figs. 4.2 and 4.3, it is yet unclear exactly what is causing the circulation changes in the first place. Before investigating possible mechanisms, it is necessary to better understand the relationships various climate patterns have with the Antarctic climate in austral spring. This is perhaps best done first by using teleconnection maps, whereby an index representing a given pattern is correlated with various
parameters from the atmospheric reanalysis at every grid point. Based on Table 4.1, statistically significant trends in the SOI and OLR 1+2 are observed in SON; therefore, teleconnection maps from these climate modes / parameters will be examined first.

The spatial relationships between ENSO and the various atmospheric parameters used above are examined below in Figs. 4.4 and 4.5. Here, detrended teleconnection maps are produced between the SOI and OLR 1+2 (respectively) and 500 hPa geopotential height, MSLP, and 2-meter temperature. For each panel, the ERA-Interim reanalysis dataset is correlated with the SOI and OLR 1+2 values at each grid point over the period 1979-2012. All values are detrended before performing the correlations to remove any influence that trends in the data may have on the strength and significance of the correlation coefficients; the effects of trends on these relationships will be examined later through a linear congruency analysis.

Figure 4.4 displays the detrended SOI teleconnection maps with the key climate variables. Immediately apparent from Figs. 4.4a-b is the alternating correlation coefficient signs between the SOI and geopotential height/pressure following a great circle trajectory from the western tropical Pacific through the ABSL region, ending in the region to the northeast of the Antarctic Peninsula. Recall that positive SOI values are representative of La Niña conditions; therefore, the highly significant ($p<0.01$) region of negative correlation in the high latitude South Pacific represents a deeper (weaker) than normal ABSL during La Niña (El Niño)
FIG. 4.4: SON Detrended teleconnection maps between the SOI and ERA-Interim a) 500 hPa geopotential height, b) MSLP, and c) 2-meter temperature. Correlation coefficient values are contoured and labeled on the map, and the significance of the correlations is shaded.
conditions, and the significant positive correlation to the northeast of the Antarctic Peninsula represents above (below) normal high pressure in this region during La Niña (El Niño) conditions. This result is consistent with the work of Turner (2004) and Mo and Higgins (1998), and highlights the PSA-1 Rossby wavetrain which propagates from the tropics to the high latitude south Pacific Ocean during strong ENSO events. The near-surface temperatures (Fig. 4.4c) are positively correlated with the SOI along the west coast of the Antarctic Peninsula, significant at $p<0.01$, and negatively correlated at $p<0.01$ across the Ross Sea region.

Although based on grid point correlations with a time series, Fig. 4.4 clearly demonstrates the important role that the tropics play in modulating temperature variability across the high latitude South Pacific and western Antarctic Peninsula. These temperature variations are tied to ENSO by the regional pressure/geopotential height anomalies across the high latitude South Pacific manifested in the PSA-1 pattern. For example, from Fig. 4.4, La Niña (SOI > 0) conditions are associated with a series of high-low-high pressure/geopotential height anomalies from west ($180^\circ$) to east ($60^\circ$W) across the ABSL region. The anomalous pressure patterns strengthen the regional pressure gradients, which in turn drive a stronger than normal poleward transport of relatively warm, moist air along the western Antarctic Peninsula and a stronger than normal equatorward transport of relatively cold, dry air across the Ross Sea region.

These expected circulation/climate impacts can then be further linked to overall trends observed in Figs. 4.2 and 4.3. First, the statistically significant
increases in 500 hPa geopotential height and MSLP are occurring to the northeast of the Antarctic Peninsula (Figs. 4.2 and 4.3). According to Fig. 4.4, La Niña conditions (positive SOI values) are associated with above normal pressure in this region and above normal temperatures along the western Antarctic Peninsula. Therefore, the trend in increased La Niña conditions, as demonstrated in Table 4.1 through both the SOI and OLR trends, could be linked to the warming across the western Antarctic Peninsula through a strengthening of the high pressure to the northeast of the Peninsula and a resultant increased pressure gradient and warm northerly flow. Again, this will be demonstrated more quantitatively later through the use of a statistical technique called linear congruency analysis.

Although this connection described above is fairly straightforward, other trends noted in Figs. 4.2 and 4.3 are not as easily linked to changes in ENSO. With regards to the deepening of the ABSL in the Ross Sea region, there is no clear expected relationship between ENSO and pressure/geopotential height in the Ross Sea. Instead, Fig. 4.4 demonstrates that ENSO variability is most strongly correlated with pressure/geopotential height in the Amundsen Sea region, not the Ross Sea. Therefore, it is unclear what role, if any, the positive SOI trends have on the deepening of the ABSL in the Ross Sea sector. In a similar vein, it is unclear if there is any relationship between the SOI and the warming trends across western West Antarctica.

Figure 4.5 displays detrended teleconnection maps between the same atmospheric variables and OLR 1+2. Recall from the previous section (section 4.1)
FIG. 4.5: As in Fig. 4.4, except for OLR in Niño 1+2 region.
that below normal OLR values in the Niño 1+2 region are associated with La Niña conditions as a result of below normal SST/near-surface temperature in the far eastern tropical Pacific. Therefore, not surprisingly, the sign of the 500 hPa geopotential height and MSLP correlation with OLR 1+2 is opposite sign in the high latitude South Pacific and across the northeast Antarctic Peninsula than that observed in the SOI (Figs. 4.5a-b). Interestingly, despite weaker and less significant correlations between OLR 1+2 and pressure/geopotential height compared to the SOI, the location of the greatest correlation magnitude and statistical significance is shifted further west across the high latitude South Pacific. For example, the center of statistically significant ($p<0.05$) OLR 1+2 and pressure/geopotential height correlation in the ABSL region is located much further west in the Ross Sea. Given the positive correlation, below normal OLR 1+2 values would be associated with below normal pressure/geopotential height in the Ross Sea region.

Turning to Fig. 4.5c, OLR 1+2 is significantly negatively correlated with near-surface temperatures across the entire region stretching from the western Antarctic Peninsula across almost all of West Antarctica. Because OLR 1+2 is trending negative, the expected relationships in Fig. 4.5c can be inverted to link OLR 1+2 changes to temperature changes. In so doing, FIG. 4.5c suggests that the OLR 1+2 is significantly ($p<0.01$) related to the warming across interior West Antarctica, including Byrd station and western West Antarctica. Further, given the statistically significant relationship between OLR 1+2 and pressure/geopotential height in the Ross Sea region, the negative trend in OLR 1+2 could be playing a role in the
strengthening of the ABSL in the Ross Sea region (Figs. 4.2 and 4.3), which in turn could be related to the warming across interior West Antarctica, and possibly even along the western Antarctic Peninsula by geostrophic temperature advection. Again, these connections can only be speculated at this stage, but will be examined in greater detail throughout this chapter.

Although not an index of a climate parameter/mode, the methods employed in generating the teleconnection maps in Figs. 4.4 and 4.5 can be extended to investigate the possible mechanisms driving the warming across interior West Antarctica by using the Byrd station temperatures as the time series. This is a useful approach because it reveals atmospheric circulation features associated with interior West Antarctic temperature variability that are independent of the SOI and OLR 1+2 (or even other climate modes not discussed here).

Plotted in Fig. 4.6 are teleconnection maps for Byrd station temperatures. Despite the highly significant correlation between interior West Antarctic temperatures (i.e., in the vicinity of Byrd station) and OLR 1+2, it is very apparent from Fig. 4.6 that the temperatures at Byrd station have little to no association with geopotential height, MSLP, and near-surface temperatures in the OLR 1+2 region. Instead, Byrd station temperatures are most strongly associated with above normal 500 hPa geopotential height and MSLP across the Antarctic Peninsula and interior West Antarctica (Figs. 4.6a-b). There is a small region of statistically significant negative correlation in the extreme northwest ABSL region, but the overarching pressure/geopotential height pattern associated with temperature variability at
FIG. 4.6: As in Fig. 4.5, except for Byrd station temperatures.
Byrd station appears to be more negative SAM-like conditions rather than anything tropically generated, or even changes in the ABSL for that matter. Moreover, the above normal pressure across eastern West Antarctica and the Antarctic Peninsula that is highly correlated with Byrd station temperatures appears to play the dominant role in governing temperature variability at Byrd station and interior West Antarctica, and the mechanisms responsible for anomalous high pressure in this region (i.e., ENSO or SAM forcing) are not clear.

4.3 SON Linear Congruency

To more precisely detail the role that trends in the SOI and OLR 1+2 play in the Antarctic regional climate trends, linear congruency is calculated between the SOI and OLR 1+2 (respectively) and the West Antarctic/Antarctic Peninsula temperature records. Recall from section 3.2.2 that linear congruency is only useful when two variables are trending together across the same independent variable (i.e., time). Therefore, linear congruency is only calculated for the climate parameters with significant trends (SOI and OLR 1+2) and the temperature records with significant trends (Faraday, Rothera, Byrd, western West Antarctica). To analyze the linear congruency comparatively for all temperature records, linear congruency is only calculated for the period 1979-2012. The SON decadal temperature trends (from Table 4.1), the congruent component (portion of the temperature trend that is linearly congruent, or linearly related to/expected from changes in the SOI or OLR 1+2 trend), and the residual (portion of the temperature
TABLE 4.3: SON temperature trends (units of °C/decade; as in Table 4.1) and linear congruency with SOI and OLR 1+2. The temperature trends are located in columns 1 and 3. The linearly congruent portion of the temperature trends (congruent) with respect to the SOI and OLR 1+2 trends is located in columns 2 and 5, respectively. The linearly independent portion of the temperature trends (residual) with respect to the SOI and OLR 1+2 trends is located in columns 3 and 6, respectively.

<table>
<thead>
<tr>
<th></th>
<th>SOI trend</th>
<th>SOI congruent</th>
<th>SOI residual</th>
<th>OLR 1+2 trend</th>
<th>OLR 1+2 congruent</th>
<th>OLR 1+2 residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faraday</td>
<td>0.76</td>
<td>0.32</td>
<td>0.44</td>
<td>0.76</td>
<td>0.21</td>
<td>0.55</td>
</tr>
<tr>
<td>Rothera</td>
<td>0.61</td>
<td>0.35</td>
<td>0.27</td>
<td>0.61</td>
<td>0.18</td>
<td>0.44</td>
</tr>
<tr>
<td>Byrd</td>
<td>0.59</td>
<td>0.09</td>
<td>0.50</td>
<td>0.59</td>
<td>0.28</td>
<td>0.31</td>
</tr>
<tr>
<td>West W. Ant.</td>
<td>0.63</td>
<td>-0.02</td>
<td>0.64</td>
<td>0.63</td>
<td>0.24</td>
<td>0.39</td>
</tr>
</tbody>
</table>

A trend that is linearly independent of changes in the SOI/OLR 1+2) are displayed in Table 4.3.

From Table 4.2b and Fig. 4.4, there exists a significant relationship between temperatures on the western Antarctic Peninsula and the SOI (i.e., ENSO). This relationship is more explicitly quantified through linear congruency analysis. From Table 4.3, it is revealed that nearly half of the warming trend at Faraday is linearly congruent with the positive trend in the SOI, and more than half of the warming trend at Rothera is linearly congruent with the SOI trend. This implies that nearly 50% or more of the warming occurring at Rothera and Faraday is associated with or expected from the observed changes in the SOI. Further inland across interior West Antarctica, this relationship is not present, as little to no portion of the warming trends at Byrd and western West Antarctica are linearly congruent with the positive SOI trend. In fact, from Table 4.3, the positive trend in the SOI is actually associated with slight cooling across western West Antarctica, demonstrating the complex
relationship between ENSO and temperatures across the region; the ENSO signal affects temperatures along the western Peninsula differently than interior West Antarctica. This dichotomy will be examined further in the following section.

Together, Figs. 4.2 and 4.3 demonstrated that the local pressure decreases in the Ross Sea could be enhancing the poleward transport of warm, maritime air onto western West Antarctica through assumed geostrophic temperature advection. Further, Fig. 4.5 suggested that OLR variability in the Niño 1+2 region is significantly correlated with pressure in the Ross Sea region as well as temperatures across nearly all of interior West Antarctica. Therefore, changes in the OLR 1+2 could potentially be related to warming across interior West Antarctica through its relationship with pressure variability in the Ross Sea region. Table 4.3 suggests that this is a likely scenario. Although not quite as strong as the linear congruent portions between the SOI and western Peninsula temperatures, approximately half of the warming at Byrd station is linearly congruent with the negative trends in OLR 1+2, and more than one-third of the warming across western West Antarctica is linearly congruent with the OLR 1+2 trend. Again, this implies that a substantial portion of the warming within this large geographic region is consistent or perhaps associated with the changes in eastern tropical Pacific near-surface temperatures reflected in the OLR 1+2 variability. Across the western Peninsula, approximately one-fourth of the warming at Faraday and Rothera is linearly congruent with the OLR 1+2 trend, suggesting that trends in OLR 1+2 have a more spatially-uniform
influence on temperatures across the region, which was also suggested by the OLR 1+2 teleconnection map in Fig. 4.5.

Despite approximately half or more of the warming trends at Faraday, Rothera, Byrd, and western West Antarctica not being explained by the trends in the SOI and OLR 1+2, in some cases half of the warming is explained by the observed changes in these two climate parameters. Therefore, the results from Table 4.3 suggest that if it were not for the trends in the SOI and OLR 1+2, the warming trends across the region may not be statistically significant or as large. As such, the changes in the atmospheric circulation (Figs. 4.4 and 4.5) due to changes measured by the SOI and OLR 1+2 (Table 4.1) are likely a major component or contributor to the observed warming across the region (Figs. 4.2 and 4.3).

A potential weakness in linear congruency is that it does not explain the physical mechanisms driving the congruent portions of the temperature trends; rather, it is a statistical measure that shows how trends in two variables are related. However, the possible (or expected) physical mechanisms, in terms of atmospheric circulation changes, can be inferred from the mean impacts each climate parameter has on the atmosphere from the teleconnection maps in Figs. 4.4 and 4.5. Some of these relationships were alluded to earlier, but through linear congruency, they are perhaps better quantified and easier to envision with this statistical connection determined. For example, the positive trend in the SOI (Table 4.1) is linked to a significant portion of the warming along the western Peninsula (Table 4.1; Fig. 4.3) through the ENSO-related pressure/geopotential height response in the Amundsen
and Bellingshausen Seas and possibly to the northeast of the Peninsula, as seen in
the teleconnection map in Fig. 4.4. As the SOI becomes more positive, the overall
patterns in the teleconnection map amplify, or strengthen, in time. In turn, the
pressure/geopotential height deepens (increases) in the ABSL vicinity (to the
northeast of the Peninsula), leading to increased warm air advection onto the
western Peninsula, and leading to a significant portion of the warming there. This
relationship is demonstrated to be true from the spatial trends in Figs. 4.2 and 4.3.

In a similar fashion, the negative trend in OLR 1+2 (Table 4.1) is likely linked
to the warming both across interior West Antarctica and along the western
Peninsula (Fig. 4.3) through the pressure/geopotential height response in the Ross
Sea region as seen in Fig. 4.5. Here, the patterns in Fig. 4.5 can be inverted (since the
OLR is trending negative), leading to below normal pressure/geopotential height
and increased warm air advection onto West Antarctica. For the western Peninsula,
the negative OLR 1+2 trend also suggests an increase in the normal pressure/
geopotential height to the northeast of the Peninsula, which would similarly
increase the warm air advection onto the western Peninsula. It thus appears that
tropical variability, and particular changes in this variability (measured by trends in
both the SOI and OLR 1+2), alters the atmospheric circulation in such a way to
enhance warm air advection onto western West Antarctica and/or the Antarctic
Peninsula. These coupled changes (tropical variability and the regional circulation
changes) explain from as little as 33% to over 50% of the ongoing warming. Other
factors, perhaps even more local in nature (such as sea ice changes, cloud cover or
water vapor changes, or diabatic effects) likely can account for the remaining portion of the temperature trends. Nevertheless, the region is clearly being strongly influenced by remote forcing from the tropics.

4.4 SON Time-Varying Relationships

Linear congruency provides excellent insight into the statistical relationship between linear trends, but it doesn’t provide complete insight into the actual physical influence that the major climate modes have on the regional climate. Similarly, the dichotomy between temperature trends from the western to northeastern Antarctic Peninsula, and their changing relationships with ENSO and SAM, has not been yet been addressed. As a first means to better document the influence that the SOI, OLR 1+2, and the dominant SH climate mode, the SAM, have on the regional climate, detrended linear regression coefficients are calculated between each of the major climate modes (respectively) and the local temperature and ABSL minimum pressure data over the period 1979-2012. In Table 4.1, linear regression coefficients were calculated with respect to time to determine if there were long-term trends. Here, linear regression coefficients are calculated between the local climate variables and the major climate parameters in order to investigate how the local climate responds with respect to changes in the climate parameters. Because the data are detrended, the influence that the trends have on the various is removed, which will aid in identifying underlying, fundamental relationships among the data by separating out external variability. These detrended regression
TABLE 4.4: SON detrended regression coefficients and 95% confidence intervals for Antarctic temperature data and ABSL minimum pressure, and SOI, OLR 1+2, and Marshall (2003) SAM index over the period 1979-2012. Units are °C/standardized index for temperature data and hPa/standardized index for ABSL pressure data.

<table>
<thead>
<tr>
<th></th>
<th>SOI</th>
<th>OLR 1+2</th>
<th>SAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faraday</td>
<td>0.54 ± 0.31</td>
<td>-0.12 ± 0.16</td>
<td>0.15 ± 0.39</td>
</tr>
<tr>
<td>Rothera</td>
<td>0.64 ± 0.35</td>
<td>-0.11 ± 0.19</td>
<td>0.55 ± 0.40</td>
</tr>
<tr>
<td>Bellingshausen</td>
<td>0.22 ± 0.25</td>
<td>-0.03 ± 0.12</td>
<td>0.38 ± 0.24</td>
</tr>
<tr>
<td>Esperanza</td>
<td>0.35 ± 0.46</td>
<td>-0.07 ± 0.22</td>
<td>0.88 ± 0.39</td>
</tr>
<tr>
<td>Marambio</td>
<td>0.36 ± 0.54</td>
<td>-0.10 ± 0.26</td>
<td>0.92 ± 0.50</td>
</tr>
<tr>
<td>Byrd</td>
<td>0.03 ± 0.54</td>
<td>-0.23 ± 0.24</td>
<td>-0.60 ± 0.54</td>
</tr>
<tr>
<td>West W. Ant.</td>
<td>-0.22 ± 0.43</td>
<td>-0.17 ± 0.19</td>
<td>-0.75 ± 0.38</td>
</tr>
<tr>
<td>ABSL Pressure</td>
<td>-0.60 ± 0.99</td>
<td>0.28 ± 0.46</td>
<td>-2.43 ± 0.64</td>
</tr>
</tbody>
</table>

Boldface regression coefficients are significantly different from zero at $p<0.05$; boldface, italicized, and underlined regression coefficients are significantly different from zero at $p<0.01$. Colors are denoted as in TABLE 4.1 and 4.2.

coefficients are similar to the correlations presented in Table 4.2, but explicitly remove the impact of the time changes (trends) noted in each variable.

The linear regression coefficients and 95% confident intervals between the climate modes and regional Antarctic climate variables are displayed in Table 4.4. Immediately apparent is the statistically significant SOI regression coefficients with the Peninsula. It is clear that ENSO has a statistically significant relationship only with temperatures along the western Antarctic Peninsula, and its influence across the rest of the Peninsula, interior West Antarctica, and on the ABSL pressure is much weaker and not statistically significant at $p<0.05$. Further, the OLR 1+2 regression coefficients with regional climate are not significant at $p<0.05$ for any local climate variable. However, although not denoted in Table 4.4, the OLR 1+2
regression coefficients with Byrd and western West Antarctica temperatures are significant at $p<0.10$ (expected from the correlations in Table 4.2b, the OLR 1+2 teleconnection map in Fig. 4.5, and the linear congruency values in Table 4.3).

Noteworthy, the OLR 1+2 regression coefficient with the ABSL pressure is not statistically significant at $p<0.10$. On the other hand, Table 4.4 demonstrates that the SAM has a dominant, statistically significant relationship (mostly at $p<0.01$) with all local climate variables except temperature at Faraday along the western Peninsula. The regression coefficients in Table 4.4 between the SAM and temperatures across the northeast Peninsula (significantly positive) and with the ABSL pressure (significantly negative) are consistent with previous results that are well documented in the literature (Lefebvre et al. 2004; Marshall 2007; Fogt et al. 2012b). And, despite not precisely demonstrated in the literature, several studies (i.e., Marshall 2007) have noted that there is a negative relationship between the SAM and interior Antarctic temperatures. This relationship arises through the more zonal (meridional) pattern of the polar front jet when the SAM is in its positive (negative) phase, resulting in decreased (increased) warm air intrusions across the continent. From the literature, less is understood about the relationship between the SAM and western Antarctic Peninsula temperatures and the SOI and Antarctic Peninsula temperatures altogether.

Up until this point, all relationships investigated in this study have been analyzed over the full period of record, or 1979-2012. However, there may exist time-varying relationships that would go unnoticed when only analyzing the data
over long timescales. These time-varying relationships may play an important role in governing regional circulation variability, which in turn could have major impacts on the local climate including long-term trends and relationships. Further, investigating the time variations in the relationships might help to better understand why SOI has a significant relationship only with the western Antarctic Peninsula, while the SAM influence is most marked in the northeastern Antarctic Peninsula in SON.

Fogt and Bromwich (2006) demonstrated that the ENSO-SAM phase relationship varies on decadal timescales, which plays a major role at influencing the high latitude South Pacific ENSO teleconnection and the resultant circulation in the ABSL region and associated temperature advection patterns. For instance, Fogt and Bromwich (2006) showed that during the 1980s, the SOI and SAM index were negatively correlated (out of phase), and the ENSO teleconnection to the ABSL region was significantly weaker than during the 1990s when the SOI and SAM index were positively correlated (in phase). Therefore, this time-varying ENSO-SAM relationship significantly alters the circulation in the ABSL region. Their study stopped at the year 2001, so the ENSO-SAM decadal relationship up until 2012 is unknown, and the combined role that ENSO and SAM have on the local climate through changes in the ABSL regional circulation is also unknown.

As noted by Fogt and Bromwich (2006), the variability of the ENSO teleconnection to the high latitude South Pacific fluctuates in time. Therefore, significant correlations between the major climate modes and the local climate may exist on
shorter timescales. To investigate these time dependencies, 10-year running correlations between the SOI and SAM index are calculated over the period 1957-2012 (Fig. 4.7; solid black line). As alluded to previously, the influence of ENSO and SAM on the Peninsula during SON appears most complex (i.e., SOI is significantly correlated through time with western Antarctic Peninsula temperatures, and the SAM is significantly correlated through time with northeastern Antarctic Peninsula temperatures; Table 4.2b). More specifically, it is unknown whether or not there are time-varying relationships between the SOI and SAM and the Peninsula temperatures and if the ENSO and SAM influence across the Peninsula varies in time and space. To investigate what role, if any, ENSO and SAM have on the western and northeastern Peninsula temperatures on shorter time scales, 10-year running correlations between the SOI and SAM index, respectively, and the western and northeastern Antarctic Peninsula temperatures are also calculated and plotted in Fig. 4.7 (over the full period of record, indicated in Table 3.1) in addition to the SOI-SAM index 10-year running correlations.

Based on the analysis in Table 4.4, it is expected that a persistent correlation exists between the SAM index and temperatures along the northeastern Peninsula (Marambio and Esperanza) and the SOI and temperatures along the western Peninsula (Faraday and Rothera). These running correlations are plotted separately in Fig. 4.7a. Although small fluctuations exist depending on the 10-year period, the correlation sign and magnitude between the SOI and western Peninsula temperatures and the SAM and northeastern Peninsula temperatures remain nearly
FIG. 4.7: Running SON decadal correlation (i.e., 1980 represents the 1980-1989 10-year correlation) for a) persistent correlations between the SOI and the SAM index and Antarctic Peninsula temperatures and b) time-varying correlations between the SOI and the SAM index with Antarctic Peninsula temperatures. In both Figs. 2a and 2b, the running SON decadal correlation between the SOI and the SAM index is plotted as a solid black line.

the same over the full period of record at each station. The only exception in Esperanza, where the SAM-temperature correlation starts out negative, but quickly switches to a positive correlation after 1970 and remains positive through 2012. Therefore, Figure 4.7a reveals that the long-term statistically significant correlations during SON (Table 4.2b) are composed of persistent correlations on decadal timescales as well.
From Table 4.2b, the SOI and SAM correlations with western and northeastern Peninsula temperatures that were not statistically significant at $p<0.10$ over the full period of record and 1979-2012 show marked changes in the sign and magnitude of the 10-year running correlations (Fig. 4.7b). In most cases, the correlations are of one sign during much of the 1970s, switch sign during the 1980s, and then reverse sign again during the 1990s-2000s. While this relationship weakens slightly at Faraday during the 1990s, it is observed to be strong for all other decades over its period of record. Most interesting from Fig. 4.7b is that the temporal changes in correlation between the SAM index and western Peninsula temperatures and the SOI and northeastern Peninsula temperatures temperature nearly trace the changes in the SOI-SAM index correlation (solid black line). In other words, the time-varying SAM relationship with western Peninsula temperatures and the time-varying ENSO relationship with northeastern Peninsula temperatures are related to the ENSO-SAM relationship. These temporally varying correlations that follow the SOI-SAM index correlation in Fig. 4.7b are in stark contrast with the persistent correlations in Fig. 4.7a, which are persistent in time and unrelated to the ENSO-SAM relationship. This demonstrates that the ENSO-related and SAM-related impacts on Antarctic Peninsula temperatures vary spatially.

Also noteworthy from Fig. 4.7 is that the 1960s and the 1980s are dominated by negative SOI-SAM index correlations, while the 1970s (briefly) and the 1990s and 2000s are dominated by positive SOI-SAM index correlations. To test the robustness of these 10-year running correlations and their sensitivity to outliers, 15-year
running correlations are also calculated (not shown); albeit weaker in magnitude, similar correlation sign changes are observed during 1957-2012 period. While Fogt and Bromwich (2006) noted the change in the SOI-SAM index correlation between the 1980s and 1990s, their study only covered the period 1979-2001; the persistence of the “in phase” relationship through 2002-2012 and other previous correlation sign switches prior to 1979 extends their work. The correspondence of the temporally varying correlations in Fig. 4.7b with the SOI-SAM index correlation changes is robust, as not only are changes in the sign of these correlations reflected by the SOI-SAM index correlation, but the magnitude of the correlations is also nearly the same throughout the 50+ year records.

The SAM index-temperature relationship is particularly strong at Faraday, and the brief break in its relationship with the SOI-SAM index correlation in the 1990s is strongly overshadowed by the otherwise tracing of the correlations during all other decades. For Esperanza, the switch in behavior of the SAM index-temperature correlation before and after 1970 alluded to earlier (Fig. 4.7a) is also observed in its decadal correlations with the SOI (Fig. 4.7b). Before 1970, the SOI-Esperanza temperature correlation mirrored the SOI-SAM index correlation, while the SAM-Esperanza temperature correlation traced the SOI-SAM index correlation. After 1970, the correlations switch, and the SOI and SAM index correlations with Esperanza (with respect to the SOI-SAM index correlation) behave the same as Marambio, described previously.
Altogether, Fig. 4.7 suggests that the influence of the SAM on the western Peninsula climate and that of ENSO on the northeastern Peninsula climate are strongly modulated by the phase relationship between ENSO and SAM, including temporal fluctuations in this relationship. Furthermore, other climate parameters (not shown), such as wind speed, meridional wind, and MSLP, also show a strong linear relationship that varies in time in accordance with the SOI-SAM index correlation.

Why are there differences between the relationship of ENSO and SAM on the northeastern and western Peninsula climate? Figure 4.7 suggests that the temperature impacts across the Peninsula are at least partly driven by the temporally changing relationship between ENSO and SAM. As noted previously, Fogt and Bromwich (2006) found that the variations in the South Pacific ENSO teleconnection between the 1980s and 1990s during SON are strongly influenced by ENSO-SAM relationship. The influence of the ENSO-SAM relationship on the ENSO teleconnection to the ABSL region is examined in Fig. 4.8. Here, 10-year running correlations between the SOI (dashed line) and SAM index (dotted line), respectively, and the ABSL minimum pressure are plotted alongside the 10-year running SOI-SAM index correlation (solid line). Despite an overall weak correlation between the SOI and the ABSL pressure (Table 4.2b) over the full period of record, Fig. 4.8 reveals that there exists periods of strong SOI-ABSL pressure correlations on shorter timescales. Further, it is readily apparent that there is a strong linear relationship between the running SOI-SAM index correlation and the SOI-ABSL
pressure running correlation; the SOI-ABSL pressure and SOI-SAM index running correlations nearly mirror each other from 1979 onward. For example, during La Niña events (SOI>0), the positive SOI-ABSL pressure correlation implies above normal (weaker) ABSL central pressures (as in the 1980s when the SOI-SAM index correlation is negative; ENSO and SAM are out of phase), and below normal (stronger) ABSL central pressures when the SOI-ABSL pressure correlation is negative (as in the 1990s and 2000s when the SOI-SAM index correlation is positive; ENSO and SAM are in phase). Similar connections can be made to the Antarctic
Peninsula temperatures presented in Fig. 4.7b. The fact that the running correlations mirror each other in Fig. 4.8 strongly suggests that the ENSO influence on the ABSL is related to the phase of the SAM (i.e., the ENSO-SAM phase relationship), implying that the location and/or strength of the ABSL changes during times when ENSO events act in isolation compared to times when they occur with SAM events. In stark contrast, the SAM-ABSL pressure running correlations are persistently negative over time and show no linear relationship with the running SOI-SAM index correlations. For example, positive SAM events always deepen the pressure somewhere within the ABSL region.

Together, Figs. 4.7 and 4.8 demonstrate both persistent (in time) significant correlations across the ABSL to the Antarctic Peninsula and time-varying correlations (generally weak and statistically insignificant over the full period of record) that fluctuate temporally with the ENSO-SAM relationship. Apparently, it is changes in the atmospheric circulation arising from the varying ENSO-SAM relationship that drive these time-varying influences across the Antarctic Peninsula. Further, it is apparent from Fig. 4.8 that the varying influences of ENSO and SAM on the Peninsula climate are a result of changes in the strength (and possibly position) of the ABSL, given that the ABSL is the dominant and most persistent circulation feature of the region (Fogt et al. 2012a; Turner et al. 2013; Hosking et al. 2013).
4.5 SON Atmospheric Circulation Composites

To investigate these atmospheric circulation changes and their impacts on the Antarctic Peninsula, anomaly composites are used in two independent approaches. Since the time-varying influence of SAM on the western Peninsula and ENSO on the northeastern Peninsula is linked to the relationship between ENSO and SAM, circulation anomalies associated with in-phase events (when a La Niña (El Niño) event occurs with a positive (negative) SAM event; positive SOI-SAM index correlation) are examined first and plotted in Fig. 4.9. This approach is similar to that performed by Fogt et al. (2011), where they examined pressure and vertical circulation anomalies associated with anomalous ENSO-SAM combinations. The events chosen for compositing in Fig. 4.9 are based on years when both the SOI (and Niño 3.4 SST anomalies) and the SAM index occur together and each exceed the 70th (fall below the 30th) percentile for both La Niña/SAM+ (El Niño/SAM-) over the period 1979-2012. These percentile thresholds were chosen to increase the sample size to four in-phase years in each composite and preserve a dataset-independent match with the SOI and Niño 3.4 SST anomalies (both the SOI and Niño 3.4 SST anomalies exceed the 70th (fall below the 30th) percentile for each respective La Niña (El Niño) event). In all cases, anomaly composites are presented and the statistical significance compared to the 1981-2010 climatological average is shaded. While Fogt et al. (2011) presented composites across various ENSO and SAM events, this study focuses only on SON and over a much smaller sample size, thereby highlighting the influence of the strongest events.
FIG. 4.9: Anomaly composites of top simultaneous strong (top 70th percentile) in-phase ENSO and SAM austral spring events based on the ERA-Interim reanalysis compared to the 1981-2010 climatology. Composites are for a) La Niña / SAM+ MSLP; b) El Niño / SAM- MSLP; c) La Niña / SAM+ meridional wind; d) El Niño / SAM- meridional wind. Shading indicates anomalies statistically different from zero at $p<0.10$, $p<0.05$, and $p<0.01$.

In-phase composites for ERA-Interim MSLP are shown in Figs. 4.9a-b and for ERA-Interim meridional wind in Figs. 4.9c-d. Readily apparent in the MSLP composites is the tropical ENSO signature, manifested as an east-west pressure difference across the tropical Pacific reminiscent of the Southern Oscillation (Figs. 4.9a-b). Despite the simultaneous occurrence of SAM events, the only persistently marked circulation anomaly in the high southern latitudes is in the ABSL region. During La Niña/SAM+ combinations, the ABSL is more than 4 hPa below the
climatological average (Fig. 4.9a; significant at $p<0.05$). The influence is especially marked for El Niño/SAM- cases (Fig. 4.9b), with pressure deviations more than 6 hPa above the climatological average and significant at $p<0.01$. As noted by Fogt et al. (2011), the simultaneous occurrence of in-phase ENSO and SAM events not only amplifies the typical ENSO signal in the high latitude South Pacific, but also broadens its spatial extent. In particular, the broadening of the ABSL creates an influence on the meridional wind that extends from the western Peninsula to the northeast Peninsula (Figs. 4.9c-d). Thus, the amplification and expansion of the ABSL anomalies, most marked during simultaneous in-phase ENSO and SAM events, allows for ENSO to have a pronounced influence on the northeastern Peninsula. The ENSO influence on this region is relatively weak and inconsistent otherwise (see Fogt et al. 2011, Figs. 5-8), thereby explaining the overall weak SOI-northeast Peninsula temperature correlations in Table 4.2b and the time-varying SOI-northeast Peninsula temperature correlations in Fig. 4.7b.

ENSO teleconnections to the South Pacific are typically always observed during times of weak or neutral SAM events (Fogt et al. 2011), which explains the persistent and statistically significant SOI-western Peninsula temperature correlations. In each of these cases (with or without SAM events), the flow around the anomalous circulation in the ABSL drives changes in the meridional wind that almost always extends across the western Peninsula. On the other hand, SAM events, which have a persistent and statistically significant influence on temperatures across the northeast Peninsula (Table 4.2b and Fig. 4.7a) through
Föhn effects (Marshall et al. 2006; Orr et al. 2008), have a weaker and time-varying influence across the western Peninsula in SON. Similar to above, the broadening and spatial extent of the ABSL in observed during in-phase SAM/ENSO events only; when SAM events occur without influence from ENSO, the response in the vicinity of the ABSL is often more zonally symmetric and confined much closer to the Antarctic continent (Fogt et al. 2011, 2012b). Although the SAM correlation with the ABSL minimum pressure remains persistent in time (Fig. 4.8), the reduced spatial response in this region during SAM-only events (as compared to ENSO-only or in-phase events) produces flow that is not only weaker in magnitude but also more zonal, with a less persistent impact on the temperatures across the western Peninsula. As a result, SAM index-temperature relationships across the western Peninsula vary in time, quite similarly as SOI-temperature correlations across the northeastern Peninsula vary in time. It can thus be inferred from Figs. 4.7b, 4.8, and 4.9 that these two time-varying relationships are strongly governed by the relationship between ENSO and SAM through variations in both the intensity and spatial extent of the ABSL.

Although La Niña conditions often occur with SAM positive events, and El Niño conditions with SAM negative events (Gong et al. 2010, 2013), thereby creating the circulation anomalies described in Fig. 4.9, all phases of the SAM (including its neutral state) have been observed during austral spring ENSO events since 1957. In light of this, and to provide further evidence that the SAM-ENSO relationship plays a leading role in explaining temperature variations across the Peninsula, anomaly
FIG. 4.10: As in Fig. 4.9, but for ERA-Interim MSLP anomalies vs. the 1981-2010 climatology during the top five highest (Warm) and lowest (Cold) spring temperatures across the Antarctic Peninsula. The western Peninsula (W, Figs. 5a,c) consists of Rothera and Faraday stations, while the northeast Peninsula (NE; Figs. 5b,d) consists of Esperanza and Marambio stations (see Table 3.1 for reference and Fig. 4.1 for locations).

composites based on Peninsula temperatures are presented in Fig. 4.10. This approach provides an independent investigation of the atmospheric conditions driving temperatures variations across Peninsula because the years included in these composites are derived solely from observed temperature records on the western and northeastern Peninsula rather than from a climate pattern. For each case, the top five warmest and coldest SON years (approximately the 85th and 15th percentiles, respectively) of the averaged temperature records post 1979 were selected for compositing the circulation patterns. The years chosen for compositing
TABLE 4.5: SON years (in rank order) used to create the anomaly composites for Fig. 4.10. The phases are based on when the climate index (SAM index and either the SOI or Niño 3.4 SSTs) is above or below the 70th or 30th percentile, respectively. LN = La Niña, EN = El Niño.

<table>
<thead>
<tr>
<th>West Peninsula</th>
<th>Northeast Peninsula</th>
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<tbody>
<tr>
<td></td>
<td>Warm ENSO / SAM Phase</td>
</tr>
<tr>
<td>Warm 2008</td>
<td>LN / SAM+</td>
</tr>
<tr>
<td>2010</td>
<td>LN / SAM+</td>
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<tr>
<td>1989</td>
<td>neutral</td>
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<tr>
<td>1985</td>
<td>SAM+</td>
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in Fig. 4.10 and the associated ENSO and SAM conditions are provided in Table 4.5. Consistent with the previous discussion, none of the warmest (coldest) years on the western Peninsula are El Niño (La Niña) events, and none of the warmest (coldest) years on northeastern Peninsula are SAM- (SAM+). In addition, for the northeastern Peninsula, the majority of the ENSO influence during warm and cold years occurs during in-phase events, suggesting that these conditions have the dominant influence on temperatures across the region as outlined in Fig. 4.9; otherwise, more than half of the years included in Figs. 4.9 and 4.10 are different.

Figure 4.10 shows the marked circulation differences between the western and northeastern Peninsula during warm and cold events. For the western Peninsula (Figs. 4.10a and 4.10c), much of the anomalous circulation resembles a propagating Rossby wave emanating from the tropical Pacific, reminiscent of the Pacific-South American pattern (Karoly 1989; Mo and Higgins 1998; Mo and Paegle
2001) commonly observed during ENSO years. For the warm events (Fig. 4.10a), below normal pressure anomalies ($p<0.05$) are observed in the ABSL region, resulting in increased northerly flow across the western Peninsula generating anomalously warm conditions. During cold years (Fig. 4.10c), the juxtaposition of the above normal pressure anomalies in the ABSL region and the below normal pressure anomalies ($p<0.05$) in the Weddell Sea drive a colder, southerly flow along the western Peninsula, again strongly resembling a tropical wave train pressure pattern and little resemblance to a typical SAM pattern. This is consistent with the more persistent ENSO influence on the western Peninsula described in Table 4.2b and Fig. 4.7a. Across the northeastern Peninsula (Figs. 4.10b and 4.10d), there is a less marked tropical component to the circulation anomalies; instead, the anomalous circulation is more related to the SAM, with pressure anomalies significant at $p<0.05$ observed inland across the Antarctic continent and within the ABSL region. This is consistent with a more persistent SAM influence on temperatures across the northeast Peninsula described in Table 4.2b and Fig. 4.7a and on the ABSL in Fig. 4.8. However, given that these temperatures are the most extreme cases, a slight tropical component to regional circulation is still noted in the northeast Peninsula temperature composites, but this is expected given that it would further enhance the meridional flow across the region generating more extreme temperature anomalies.
4.6 The 1988 SON La Niña/SAM Negative Event

The directly preceding analyses detailing shifts in the ENSO-SAM relationship and the relationship these climate modes have with the Antarctic Peninsula climate have been based on running 10-year correlations. Due to the small sample size, 10-year correlations can be strongly influenced by the presence of outliers. As mentioned previously, similar (albeit weaker) shifts in the correlations are obtained using 15-year running windows; however, to further test the sensitivity of the shorter-term running correlations, individual SON years for the SOI and SAM index were removed and the correlations recalculated. In performing these tests, it was noted that only the removal of the year 1988 had any significant influence on the running SOI-SAM index correlation signs; the correlations and their temporal changes remain robust otherwise.

The 1988 SON was characterized by strong out of phase conditions: a strong La Niña (SOI = +2.7) and a very strong negative SAM event (SAM index = -2.32). The SOI-SAM index 10-year running correlation when 1988 is removed is depicted below in Fig. 4.11. Notably, with the removal of this event, the SOI-SAM index running correlations remain positive after the mid-1970s. In regard to Fig. 4.7, the removal of 1988 does not significantly affect the conclusions made from the running correlations: although subtle differences are noted, in general, the persistent relationships observed in Fig. 4.7a remain whether or not 1988 is included, while the time-varying relationships in Fig. 4.7b still continue to trace the (revised) SOI-SAM index running correlations presented in Fig. 4.11. Additionally, the removal of
1988 does not significantly alter the correlation/regression between the SOI and the SAM index over the full 1957-2012 period (not shown); the SOI and SAM index relationship during SON remains weak and statistically insignificant, primarily due to the negative correlation prior to 1970 that reverses and remains positive after 1990 (Figs. 4.7, 4.8, and 4.11).

Given that 1988 produces a strong shift in the SON SOI-SAM index running correlations in the 1980s, it is prudent to examine the uniqueness of the circulation anomalies during this year. The 1988 SON conditions are displayed in Figs. 4.12a-d,
FIG. 4.12: ERA-Interim 1988 SON La Niña/SAM event compared to La Niña years (left column; La Niña conditions contoured, 1988 anomalies shaded) and the 1981-2010 climatology (right column; anomalies contoured and standard deviations from climatology shaded) for a-d) SON; e-f) October 1988 only. a-b;e-f) 500 hPa height; c-d) 2 m temperature. Nine La Niña events during SON identified by the CPC (1983, 1984, 1988, 1995, 1998, 1999, 2000, 2007, 2010) were used in creating the composites for the right column.

with comparisons made to La Niña events (including the 1988 La Niña event) in the left column and the 1981-2010 climatological average in the right column. Figure 4.12a depicts the 500 hPa geopotential height composite average La Niña conditions during SON (contours) and the 1988 differences from the La Niña average (shaded);
similar results are obtained using MSLP or other pressure levels in the troposphere. Typically, in a La Niña event (contours in Fig. 4.12a), positive height anomalies of \( \sim 10 \text{ geopotential meters (gpm)} \) exist over the Weddell Sea, while negative height anomalies of \( \sim -20 \text{ gpm} \) are present in the Amundsen and Bellingshausen Seas and broader South Pacific region. However, during the 1988 La Niña/SAM negative event, the positive height anomalies in the Weddell Sea are on the order of 10-12 gpm higher than typical La Niña conditions (shading in Fig. 4.12a), giving rise to a positive geopotential height anomaly that is nearly double that observed during normal La Niña events. In contrast, in the South Pacific, the typical region of negative height anomalies normally seen during La Niña events is characterized by above (La Niña) average geopotential heights near the Antarctic Peninsula and ABSL region, and below (La Niña) average height to the northwest of this region. Effectively, this implies a substantial reduction in the spatial extent of the high southern latitude ENSO teleconnection during the 1988 La Niña/SAM negative event, as the teleconnection is shifted westward and northward away from the ABSL region toward the south central South Pacific Ocean.

These circulation changes are also depicted in Fig. 4.12b: compared to the 1981-2010 climatological average, the most negative height anomalies are found near \( 60^\circ \text{S}, 150^\circ \text{W} \), which is much farther north and west than they are typically observed during La Niña conditions (contours in Fig. 4.12a, near \( 65^\circ \text{S}, 120^\circ \text{W} \)). Moreover, the above average geopotential heights in the Weddell Sea, which exceed 3 standard deviations from the climatological mean (shading in Fig. 4.12b), are a
significant difference between this La Niña event and others during SON. These above normal geopotential heights are associated with both the negative SAM event and the northwestward displacement of the ENSO teleconnection in the high latitude South Pacific. As discussed in earlier studies (L’Heureux and Thompson 2006; Gong et al. 2010; Fogt et al. 2011), it is the equatorward eddy momentum fluxes associated with the negative SAM event that oppose the poleward eddy momentum fluxes associated with La Niña events, disrupting the ENSO signal propagation to the high southern latitudes and displacing the teleconnection equatorward.

The displacement of the ENSO teleconnection during SON 1988 is also clearly evident by the circulation changes and resulting temperature advection (through implied geostrophy). During typical La Niña events, above average temperatures are noted along coastal West Antarctica and the western Antarctic Peninsula (contours in Fig. 4.12c). However, during the 1988 La Niña/SAM negative event, above (La Niña) normal temperatures, indicated by the yellow and orange shading in Fig. 4.12c, are located farther west and inland across interior West Antarctica (centered near ~80°S, 115°W). Further, compared to other La Niña events, the positive temperature anomalies (>1 standard deviation from the climatological mean, Fig. 4.12d) are displaced westward from the Antarctic Peninsula, which greatly reduces the ENSO impact across the northeast Peninsula, consistent with the change in correlation between the SOI and northeast Peninsula temperatures in Fig. 4.7b. The negative SAM event, which is typically marked with higher pressure in the
Amundsen and Bellingshausen Seas, shows no discernable impact in this region due to the La Niña event. As such, the negative SAM influence on temperature across the western Antarctic Peninsula is not as marked as it is across the northeast Peninsula, consistent with the change in this correlation observed in Fig. 4.7b.

A month-by-month investigation of the circulation anomalies associated with the 1988 La Niña/SAM negative event in SON reveals that the majority of the anomalous patterns depicted in Figs. 4.12a-d are a result of the conditions during October. During October 1988, the SAM reached an October record negative value (SAM index = -6.03; record for all Octobers over the period 1957-2012 based on the Marshall (2003) index) in conjunction with a moderately strong La Niña (SOI = +2.3). The October 1988 500 hPa geopotential height anomalies (shown in Figs. 4.12e-f) are consistent with those depicted in Figs. 4.12a-b, except that the above normal geopotential height anomalies in the Weddell Sea are even greater, while the ENSO teleconnection in the South Pacific is altogether absent. From Fig. 4.12f, the Weddell Sea geopotential height anomalies exceed 3 standard deviations from the climatological average over a much larger region than Fig. 4.12b. The circulation anomalies in Fig. 4.12f clearly depict the strong SAM negative event, while there is little indication of a La Niña pattern.

Despite the unique event in the 1980s, it is evident, simply based on the sign of the correlations presented in Fig. 4.7, that the SAM (ENSO) relationship with western (northeastern) Antarctic Peninsula climate is dependent on the relationship between ENSO and SAM, especially since other negative SOI-SAM index
correlations are observed prior to 1970. The in-phase combinations broaden the impacts of the ABSL, making the circulation anomalies (in particular, the meridional component to the circulation) extend across both the western and northeastern Peninsula. Otherwise, SAM events typically (but not necessarily always) influence only the northeast Peninsula, while ENSO events typically influence only the western Peninsula.

4.7 Chapter Summary

4.7.1 Why spring?

The majority of this study focuses on the austral spring season, or SON. From Table 4.1, there are statistically significant trends in the SOI (positive) and OLR 1+2 (negative) during SON over the period 1979-2012, indicating a recent trend toward increased La Niña conditions in this season. This is the only season where significant trends in the tropics are observed during this period, which was a major area of interest for this study. Further, from Table 4.1, statistically significant warming is observed across the western Antarctic Peninsula and over western West Antarctica during SON over the same time period (1979-2012). Finally, from Table 4.2b, a statistically significant correlation is observed between the SOI and western Antarctic Peninsula temperatures and the SAM and northeastern Antarctic Peninsula temperatures. Despite significant trends and relationships in other seasons, spring is the only season where the tropics are experiencing significant trends along with the Antarctic climate, and the marked discrepancy in relationship
between the SOI and SAM across the Peninsula is not understood. Further, the
trends and relationships in other seasons are better documented in the literature,
especially in austral summer.

4.7.2 Regional circulation changes

Sections 4.2 and 4.3 investigated spatial trends in temperature and
atmospheric circulation during SON (Figs. 4.2 and 4.3), as well as spatial
relationships during SON (Figs. 4.4 and 4.5). Upon investigation of the spatial trends,
it was observed that statistically significant deepening of the ABSL is occurring in
the Ross Sea region, which is consistent with the results of the Fogt et al. (2012a).
Further, positive pressure and geopotential height trends are observed to the
northeast of the Antarctic Peninsula indicating strengthening high pressure. The
effect of these high latitude pressure trends is illustrated through a schematic in Fig.
4.13. From the high latitude trends in pressure and associated meridional
geostrophic wind, it is inferred that the regional pressure gradients across the high
latitude South Pacific have strengthened in response to the deepening pressure in
the Ross Sea and increasing pressure to the northeast of the Peninsula, which has
produced an increased poleward transport of relatively warm, moist air from the
middle latitudes to the west coast of the Antarctic Peninsula and over western West
Antarctica. Therefore, it is likely that the regional pressure trends are a key player in
the observed warming across the Antarctic Peninsula and West Antarctica.
FIG. 4.13: Schematic showing the SON warming across West Antarctica and the Antarctic Peninsula (red shading), the pressure trends (red L=negative pressure trends; blue H=positive pressure trends), and associated warm, northerly wind trends (red arrows). Modified from Fogt et al. (2012a).

From the teleconnection maps in Figs. 4.4 and 4.5, it is also apparent that the regional circulation trends in Fig. 4.13 (the L and H regions) are of tropical origin. For example, the SOI is significantly negatively correlated with pressure/geopotential height in the high latitude South Pacific and positively correlated with pressure/geopotential height to the northeast of the Peninsula. Further, OLR 1+2 is
significantly positively correlated with pressure/geopotential height in the Ross Sea region and negatively correlated with pressure/geopotential height to the northeast of the Peninsula. Therefore, the pressure trends across the region that are associated with the observed warming are strongly tied to the tropics, and are consistent with the trends toward increased La Niña conditions identified earlier.

4.7.3 Combined Role of ENSO and SAM on Antarctic Peninsula Climate

An investigation of time varying relationships revealed that the influence that ENSO has on northeast Antarctic Peninsula temperatures and the influence that SAM has on western Antarctic Peninsula temperatures is strongly modulated by the ENSO/SAM phase relationship. This is a result of the respective ENSO and SAM related response in the Amundsen and Bellingshausen Seas region, which is strongly influenced by the ENSO/SAM phase relationship, and also varies in time. For example, ENSO is only able to influence northeast Antarctic Peninsula temperatures when ENSO and SAM are in phase and the ENSO-related response in the high latitude South Pacific is stronger than normal and covers a greater spatial extent (i.e., the ENSO-related circulation reaches the northeast Peninsula). The same is true for the SAM and western Antarctic Peninsula temperatures. Otherwise, the ENSO influence on temperatures on the western Antarctic Peninsula and SAM influence on temperatures on the northeast Antarctic Peninsula is persistent in time and not affected as significantly by the ENSO/SAM phase relationship, hence explaining the significant correlations observed in Table 4.2.
CHAPTER 5: SUMMARY AND CONCLUSIONS

This thesis focused on identifying what role, separately and collectively, tropical teleconnections arising from ENSO and large-scale forcing from the SAM play in modulating the climate of West Antarctica and the Antarctic Peninsula through changes in the regional circulation, including changes in the ABSL. In particular, this study sought to understand how ENSO and SAM are related to the ongoing statistically significant changes in the high latitude South Pacific regional circulation and the warming across West Antarctica and the Antarctic Peninsula. Using a combination of atmospheric reanalysis data and surface observations, it was found that statistically significant ($p<0.05$) warming was occurring along the western flank of the Antarctic Peninsula (Faraday and Rothera) and over the western half of West Antarctica during SON over the period 1979-2012. The warming at Faraday and Rothera during SON has actually increased post 1979 compared to the rate of warming observed prior to 1979. Warming was also observed at Byrd station during SON, but, in contrast to the western Peninsula, the significance of the warming trend decreased from $p<0.01$ over the period 1957-2012 to $p<0.10$ for the period 1979-2012. Interestingly, statistically significant trends ($p<0.05$) were also observed in the SOI and OLR 1+2 during SON over the 1979-2012 period.

To investigate the role that tropical forcing may be playing on the regional warming trends during SON, spatial trends and detrended teleconnection maps
were produced. The spatial trends revealed statistically significant ($p<0.05$) negative trends in 500 hPa geopotential height and MSLP in the Ross Sea region of the high latitude South Pacific, and statistically significant positive trends in 500 hPa geopotential height and MSLP ($p<0.05$ and $p<0.01$, respectively) to the northeast of the Antarctic Peninsula. Fogt et al. (2012a) identified a statistically significant trend toward strengthening cyclones in the Ross Sea region during SON, which is consistent with the negative pressure/geopotential height trend found in this region. Statistically significant trends in 2-meter temperatures and 10-meter meridional wind were also observed across the region; it is therefore inferred that the deepening pressure/geopotential height in the Ross Sea region and increasing pressure/geopotential height to the northeast of the Peninsula have collectively strengthened the regional pressure gradients across the high latitude South Pacific, and in turn have strengthened the poleward transport of relatively warm, moist air to the coastal regions of western West Antarctica and along the western Antarctica Peninsula.

The role that tropical forcing may have on the observed trends, both in terms of the regional circulation and temperatures, was investigated using detrended teleconnection maps for the two SON trending tropical climate parameters: the SOI and OLR 1+2. Upon examination of the SOI teleconnection map, it was found that the SOI has a statistically significant ($p<0.01$) positive relationship with near-surface temperatures across the western Antarctica Peninsula, and a negative relationship with near-surface temperatures across the Ross Sea region. For example, La Niña
conditions (SOI>0) are associated with above normal temperatures along the western Antarctica Peninsula, and below normal temperatures across the Ross Sea region. This relationship exists due to the strong relationship that ENSO has with the regional circulation (i.e., 500 hPa geopotential height and MSLP) across the high latitude South Pacific and extreme southwestern South Atlantic (to the northeast of the Peninsula) associated with the PSA-1 pattern (Mo and Higgins 1998): during ENSO events, a Rossby wavetrain propagates from the tropics to the high latitude South Pacific producing a series of alternating pressure/geopotential height anomalies. These circulation anomalies associated with ENSO strongly influence the regional circulation across the high latitude South Pacific, including a deeper than normal ABL during La Niña events, and in turn influence the regional temperature advection patterns. As a result, the significant correlations between the SOI and temperatures are found on the western and eastern side of the ABL where the meridional flow strongly influences temperature variability.

To further investigate the role of ENSO on the temperature trends across the Peninsula, long-term correlations between the SOI and Peninsula temperatures were calculated as well as linear congruency between the SOI and temperatures that are statistically changing. The SOI-Peninsula temperature correlations revealed that the SOI has a statistically significant ($p<0.01$) relationship with temperatures at Faraday and Rothera over the period 1979-2012. Much weaker correlations are observed between the SOI and temperatures across the northeast Peninsula (i.e., Esperanza and Marambio). Further, it was found that nearly half of the warming at
Faraday and more than half of the warming at Rothera is linearly congruent with the positive trend in the SOI. This implies that 50% or more of the warming trends at Faraday and Rothera are associated with or expected from the observed positive trends in the SOI, through the circulation changes described above. The SOI relationship with temperatures across interior West Antarctica is drastically different, with little to no part of the SOI trend being linearly congruent with the warming here.

As for OLR 1+2, the teleconnection maps revealed that OLR variability in the Niño 1+2 region is significantly correlated (at least $p<0.05$) with 500 hPa geopotential height and MSLP in the Ross Sea region and along/to the north of the Antarctic Peninsula. Further, it was also found that OLR 1+2 is significantly correlated ($p<0.01$) with temperatures across both the western Antarctic Peninsula and interior West Antarctica. Linear congruency revealed that approximately 33%-50% of the warming across interior West Antarctica (i.e., Byrd station and western West Antarctica) is associated with or expected from the observed negative trends in OLR 1+2. However, due to the location of the Niño 1+2 region in the far eastern tropical Pacific away from the deep tropical convection that drives the high latitude ENSO teleconnection, the OLR data were only used as a proxy for SSTs/near-surface temperatures. Therefore, the statistically significant negative trend in OLR 1+2 is likely a reflection of the positive SOI trends, as increased La Niña events would be associated with negative SST/near-surface temperature trends in the far eastern tropical Pacific. As a result, for this study, the OLR 1+2 relationship with the regional
circulation and temperatures is assumed to be a result of the same processes discussed with the SOI, and the physical relationship between OLR 1+2 and the regional circulation/(West) Antarctic temperature variability is not fully understood. This is especially true for the OLR 1+2 relationship with pressure/geopotential height in the Ross Sea region; future research should consider the dynamical mechanism associated with this OLR 1+2 teleconnection.

Due to the complicated nature of the interior West Antarctic temperature relationship with regional circulation, a teleconnection map for Byrd temperatures was also created. From this approach, it was observed that negative SAM-like conditions are the leading cause of above normal temperatures across interior West Antarctica. More importantly, it is high pressure over eastern West Antarctica and the Antarctic Peninsula that drives above normal temperatures at Byrd stations. This is likely a result of both increased warm air advection on the western side of the high pressure, and also increases in solar insolation accompanied with adiabatic compressional warming.

To investigate the physical role that the large-scale climate modes have on the local Antarctic climate, including the role of the SAM and the combined role of ENSO and SAM, detrended regressions and time varying correlations were calculated. Regression analysis revealed that the SOI has a statistically significant ($p<0.01$) relationship with temperatures along the western Antarctic Peninsula (Faraday and Rothera), while the SAM has a statistically significant relationship ($p<0.01$) with nearly all temperatures across the region except Faraday, including
the northern and northeast Antarctic Peninsula (Belingshausen, Esperanza, and Marambio), Byrd station, and western West Antarctica. The OLR 1+2 regression coefficients with regional temperatures are much weaker and less statistically significant.

An analysis of 10-year running correlations between the SOI and SAM index, respectively, and the Antarctic Peninsula temperatures revealed that the ENSO relationship with western Peninsula temperatures is persistent in time, and the SAM relationship with temperatures on the northeastern Peninsula is persistent in time. Interestingly, the ENSO-northeast Peninsula temperature relationship and the SAM-western Peninsula temperature relationship varies considerably in time, and fluctuates in response to changes in the SOI-SAM relationship. Further investigation using 10-year running correlations found that the temporally varying ENSO relationship with temperatures on the northeast Peninsula and the temporally varying SAM relationship with temperatures across the western Peninsula is related to the degree to which ENSO and SAM are “in phase”, as this strongly affects the degree to which the ENSO teleconnection influences the magnitude and spatial extent of the ABSL. For example, when the SOI-SAM index are positively correlated, or in-phase, the ENSO teleconnection to the ABSL region is stronger than normal and has a much larger spatial extent across the high latitude South Pacific. However, when the SOI-SAM index are negatively correlated, or out of phase, the ENSO teleconnection to the ABSL region is significantly weaker and/or altogether absent. Therefore, during SON, it is found that the ENSO relationship with the ABSL is
linearly related to the SOI-SAM index correlation. In turn, changes in the SOI-SAM index relationship, through their impacts on the ABSL and/or overall ENSO teleconnection, modulate the degree and sign of the ENSO influence on the northeastern Antarctic Peninsula climate and the SAM influence on the western Antarctic Peninsula climate.

In using the 10-year running correlations, there appears to be a sudden shift in the SOI-SAM index correlation, as noted by Fogt and Bromwich (2006), from the 1980s to the 1990s. This study finds that this correlation shift is more likely a statistical artifact, influenced by the presence of a strong La Niña/SAM negative event in SON 1988. During this event, an unusually high (greater than 3 standard deviations from the climatological mean) pressure/geopotential height anomaly in the Weddell Sea, associated with the SAM negative event, hindered the propagation of the La Niña signal to the Amundsen-Bellingshausen Seas, displacing it farther north and west. This altered the SON atmospheric circulation impacts across the Antarctic Peninsula and West Antarctica. It is thus apparent that ENSO’s influence across West Antarctica and the Antarctic Peninsula, and therefore any influence it has on the warming in this region, is tied to the strength and phase of the SAM. Similarly, SAM-related impacts across the western Peninsula primarily depend on the phase of ENSO.

While this study has undoubtedly increased the understanding of SON temperature changes across the Antarctic Peninsula and West Antarctica, there are still many unanswered questions. Future work should investigate the physical
relationship between SSTs/near-surface temperatures in the OLR 1+2 region and the regional circulation across the South Pacific, especially with regards to the OLR 1+2 relationship with deepening pressure across the Ross Sea region. In addition, future work should investigate the causes of anomalous high pressure over the Antarctic Peninsula region, as it is demonstrated in this study to play a major role at producing anomalously warm SON conditions across interior West Antarctica. Future work should also investigate the role of the position and intensity of tropical convection in generating variations in the ENSO-related Rossby waves and not only how this influences the overall ENSO teleconnection (as in Lachlan-Cope and Connolley (2006)), but also how this might influence the SAM phase (Gong et al. 2010, 2013; Ding et al. 2012). Sea ice conditions, including their long-term trends, also deserve further investigation, as they may play a role in the ENSO and SAM signatures in the Amundsen-Bellingshausen Seas through changes in surface latent and sensible heat fluxes, which in turn could influence the strength of the underlying synoptic activity that comprises the ABSL.
REFERENCES


