Understanding 20th Century Antarctic Pressure Variability and Change in Multiple Climate Model Simulations

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Master of Science

Hallie E. Dusselier

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This thesis titled
Understanding 20th Century Antarctic Pressure Variability and Change in Multiple
Climate Model Simulations

by

HALLIE E. DUSSELIER

has been approved for
the Department of Geography
and the College of Arts and Sciences by

Ryan L. Fogt
Associate Professor of Meteorology

Robert Frank
Dean, College of Arts and Sciences
ABSTRACT

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Understanding 20th Century Antarctic Pressure Variability and Change in Multiple Climate Model Simulations

Director of Thesis: Ryan L. Fogt

The CAM5 non-coupled Community Atmospheric model version 5 (CAM5) is used to study the role that natural and anthropogenic forcings (ozone forcing, radiative forcing, tropical forcing) play in the Antarctic pressure pattern in the last century. Seasonal pressure reconstructions at key Antarctic stations through the 20th century are employed as the best estimates of Antarctic pressure variability since 1905, especially as it is shown here that pressure reanalyses are unreliable in the early 20th century. Three experiments are conducted with the CAM5 model; the first of these experiments allows radiative forcings to vary in time with prescribed, time-varying tropical sea surface temperatures, with the goal being to isolate the role of radiative forcings on the pressure pattern over the continent (when compared with another simulation), and to act as the control, as this is most like the real world. The second experiment that is performed with the model has time varying ozone forcing and climatological sea surface temperatures. The goal of this experiment is to isolate the role of ozone forcing on the Antarctic pressure pattern. The final experiment has fixed radiative forcing at 1990 values, but time-varying prescribed tropical sea surface temperatures. The goal of this experiment is to isolate the role of tropical sea surface temperature variability, or aid in isolating the role of radiative forcing when compared with the first experiment.
While each of the simulations of the model results contained interannual variability as expected, the results of the model in each experiment were well within the range of the pressure reconstructions, demonstrating reliability. Additionally, when smoothed, similarities between experiment trends and reconstructions trends were clearly identifiable. Model trends showed that tropical sea surface temperatures have a marked influence on the negative pressure trends in Antarctica, particularly near the Peninsula and West Antarctica and near the Amundsen and Bellingshausen Seas. It is also seen that tropical forcing has the most significant impact during MAM, JJA, and SON during the 20th century. During DJF, a stronger influence from ozone is seen, particularly after 1957. In this season, ozone influenced the negative trends across the continent more uniformly, with more positive trends seen in the southern midlatitudes in DJF after 1957.
DEDICATION

To one of my best friends,

Megan Greving Henn:

for being my guardian angel this past month as I finished this thesis,

which has been most difficult without you here.
ACKNOWLEDGMENTS

I cannot begin to thank all the people who deserve it and who were there for me through the good times and the difficult times in this process over the last two years. First and foremost, thank you to Ryan Fogt. A thank you is certainly not enough because I would not even be at Ohio University without him. Thank you Ryan for never failing to support me academically and personally. Writing a thesis has been anything but easy, but you have been there through every step of the way, pushing me to keep moving and challenging me find my full potential. Ryan, you have been more than an excellent advisor, but I am also so grateful to call you my friend. Not only have you been there for me academically as my advisor, but you’ve also had an enormous impact in both my personal and faith life.

I would also like to thank my Scalia family. To Nate McGinnis and Doug Schuster, thank you for your constant support, for always being there during the difficult times, and for never failing to make me laugh hysterically just when I needed it most. Thank you for keeping me sane (or insane) the last two years and for being the brothers I never had. I also would not have made it through the last two years without the “Antarctica kids”, Chad Goergens and Megan Jones. Thank you for all of your support, whether it be helping me with programs or teaching me something new. Thank you also for the many bizarre conversations that always give me a great laugh and all of the “summer jams” which I will never forget.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Abstract</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedication</td>
<td>5</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>6</td>
</tr>
<tr>
<td>List of Tables</td>
<td>10</td>
</tr>
<tr>
<td>List of Figures</td>
<td>12</td>
</tr>
<tr>
<td>Chapter 1: Introduction</td>
<td>18</td>
</tr>
<tr>
<td>Chapter 2: Literature Review</td>
<td>24</td>
</tr>
<tr>
<td>2.1 Antarctic temperature changes review</td>
<td>24</td>
</tr>
<tr>
<td>2.2 Antarctica pressure change</td>
<td>31</td>
</tr>
<tr>
<td>2.3 Large-scale atmospheric circulation variability</td>
<td>32</td>
</tr>
<tr>
<td>2.4 Ozone</td>
<td>42</td>
</tr>
<tr>
<td>2.5 Chapter summary</td>
<td>49</td>
</tr>
<tr>
<td>Chapter 3: Data and Methods</td>
<td>51</td>
</tr>
<tr>
<td>3.1 Observations</td>
<td>51</td>
</tr>
<tr>
<td>3.1.1 Reanalysis data</td>
<td>53</td>
</tr>
<tr>
<td>3.1.2 Era-Interim</td>
<td>54</td>
</tr>
<tr>
<td>3.1.3 CFSR</td>
<td>55</td>
</tr>
<tr>
<td>3.1.4 20CR</td>
<td>56</td>
</tr>
<tr>
<td>3.1.5 Era-20C</td>
<td>56</td>
</tr>
<tr>
<td>3.1.6 Reconstructions</td>
<td>58</td>
</tr>
<tr>
<td>3.2 Climate modeling data</td>
<td>63</td>
</tr>
<tr>
<td>3.3 Methods</td>
<td>66</td>
</tr>
<tr>
<td>3.3.1 Statistical analysis</td>
<td>67</td>
</tr>
<tr>
<td>3.3.2 Correlation</td>
<td>67</td>
</tr>
<tr>
<td>3.3.3 Trend analysis</td>
<td>68</td>
</tr>
<tr>
<td>Chapter 4: Antarctic 20th Century Pressure Trends from Observations, Reanalyses, and Reconstructions</td>
<td>71</td>
</tr>
</tbody>
</table>
4.1 Introduction ................................................................. 71
4.2 Observation trends .................................................... 72
4.3 Reconstructions ......................................................... 79
4.4 Assessment of reanalyses .............................................. 90
4.5 Full century comparisons ............................................ 97
4.6 Spatial trends of reanalyses .......................................... 109
4.7 Antarctic station pressure trend summary ....................... 118
4.8 Chapter summary ....................................................... 125

Chapter 5: Modeling Results .............................................. 129
  5.1 Introduction ............................................................ 129
  5.2 Spatial trends .......................................................... 130
  5.3 Trends with error bars ............................................... 140
  5.4 Time series ............................................................. 147
       5.4.1 Antarctic averaged time series .............................. 147
       5.4.2 Regional time series .......................................... 151
  5.5 Running trends ....................................................... 155
  5.6 Chapter summary .................................................... 158

Chapter 6: Conclusions .................................................. 163
References ........................................................................ 173
Appendix: Reanalyses MSLP trends.................................... 182
LIST OF TABLES

Table 2.1  Temperatures change seasonally across Antarctica and significance levels. Table extracted from Turner et al. (2005).

Table 3.1  Observational pressure data from the READER archive. Marsh/O’Higgins*: Latitude and longitude and year are for O’Higgins. Marsh station is located near Bellingshausen. McMurdo/Scott Base+: Elevations from McMurdo and start year from McMurdo.

Table 3.2  Each reanalyses and years of data used.

Table 3.3  Listing of CAM5 experiments used in this thesis.

Table 4.1  Observed trends (hPa per decade) by season and station from 1957-2014 with 95% confidence interval. Significant trends \((p < 0.05)\) indicated by (*).

Table 4.2  Observed trends (hPa per decade) by season and station from 1979-2014 with the 95% confidence interval. Significant trends at \((p < 0.05)\) indicated by (*).

Table 4.3  Trends in hPa per decade with 95% confidence interval for all reanalyses, observations, and reconstructions over different time periods for MAM. Significant trends at \((p < 0.05)\) indicated by (*).

Table 4.4  Trends in hPa per decade with 95% confidence interval for all reanalyses, observations, and reconstructions over different time periods for JJA. Significant trends at \((p < 0.05)\) indicated by (*).
Table 4.5  Trends in hPa per decade with 95% confidence interval for all reanalyses, observations, and reconstructions over different time periods for SON. Significant trends at \((p < 0.05)\) indicated by (*)

Table 4.6  Trends in hPa per decade with 95% confidence interval for all reanalyses, observations, and reconstructions over different time periods for DJF. Significant trends at \((p < 0.05)\) indicated by (*).

Table 5.1  Interpretation of significant trends from each experiment.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Map of Antarctica with specific focus regions identified. Figure extracted from Turner et al. 2004.</td>
<td>19</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Temperature changes by season using different methodologies. Extracted from O’Donnell et al. (2011).</td>
<td>28</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Figure 2.2. CFSR reconstructions 1958-2012 seasonally. Solid lines indicate significance $p &lt; 0.05$. NS shows areas with no significance. Figure extracted from Nicolas and Bromwich (2014).</td>
<td>29</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Pressure from 1971-2000 by season with significance level at each station. Figure extracted from Turner et al. (2005).</td>
<td>32</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Elevation of Antarctica (lighter colors higher, darker colors closer to sea level) as well as location of Amundsen and Bellingshausen Seas. Station locations indicated by red dots. Figure extracted from Nicolas and Bromwich (2014).</td>
<td>34</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Figure 2.5a. Geopotential height anomalies in the positive phase of the SAM. Figure 2.5b. Temperature anomalies in the positive phase of the SAM. Figure 2.5a and 2.5b extracted from IPCC report 2007 3.6.5 The Southern Hemisphere and Southern Annular Mode. Figure 2.5c. SAM index time series from 1957-2015. Figure 2.5c adapted from IPCC report 2007 3.6.5 The Southern Hemisphere and Southern Annular Mode. (Update version of 2007 figure).</td>
<td>36</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>Depiction of the warm phase (El Niño) of ENSO with temperature characteristics and jet patterns. Fig. extracted from Yuan (2004).</td>
<td>40</td>
</tr>
</tbody>
</table>
Collectively, El Niño and La Niña events during the 1990s and ice changes during that time. Figure 2.7a. Two El Niño years. Figure 2.7b. Three La Niña years. Figure extracted from Stammerjohn et al. (2008).

Decrease in ozone from 1957-1984. Figure adapted from Farman et al. (1985).

Variation in ozone at Halley by season, 1956-1959. Figure extracted from Rowland (2006).

Figure 2.10a. Prescribed ozone 1979-1997 model with geopotential height chance by season. Figure 2.10b. Observed ozone changes and geopotential height changes as 30-year linear trends from 1969 to 1998. Figure extracted from Gillett and Thompson (2003).

Ozone hole recovery timeline. Figure extracted from Newman et al. (2006).

Location of stations used in this research with the exception of Byrd station is West Antarctica, which is excluded from this thesis. Figure extracted from Fogt et al. (2016a).

Predictor stations for reconstructions. Extracted from Fogt et al. (2016a).

Trends with 95% confidence intervals for the observations in black. Reconstructions indicated by the red line from 1957-2013. Figure extracted from Fogt et al. (2016a).

Scatterplot of cross-correlations between stations grouped geographically from 1957-2013. The x-axis shows the correlations between the stations grouped geographically with the observed data. The y-axis shows the correlations in the reconstructions and observations. Figure extracted from Fogt et al. (2016a).
Figure 4.1a  Observed MSLP trends in hPa per decade 1957-2014 by season for DJF and MAM by station. Significant trends at $p < 0.05$ indicated by (*) after station name.

Figure 4.1b  Observed MSLP trends in hPa per decade 1957-2014 by season for JJA and SON by station. Significant trends at $p < 0.05$ indicated by (*) after station name.

Figure 4.2a  Observed MSLP trends in hPa per decade 1979-2014 by season for DJF and MAM by station. Significant trends at $p < 0.05$ indicated by (*) after station name.

Figure 4.2b  Observed MSLP trends in hPa per decade 1979-2014 by season for JJA and SON by station. Significant trends at $p < 0.05$ indicated by (*) after station name.

Figure 4.3  Surface pressure time series at Amundsen-Scott for reconstructions and observations from 1905-2010 by season.

Figure 4.4  MSLP time series at Bellingshausen for reconstructions and observations from 1905-2010 by season.

Figure 4.5  MSLP time series at Casey for reconstructions and observations from 1905-2010 by season.

Figure 4.6  30-year running trends in hPa per decade at Amundsen-Scott by season for reconstructions and observations. X-axis is starting year of 30-year period.

Figure 4.7  30-year running trends in hPa per decade at Bellingshausen by season for reconstructions and observations. X-axis is starting year of 30-year period.

Figure 4.8  30-year running trends in hPa per decade at Casey by season for reconstructions and observations. X-axis is starting year of 30-year period.
Figure 4.9  Correlations, biases, and root mean square errors by season and by station for each of the reanalyses. The period of comparison with observations is 1979-2013 for Era-Interim, 1979-2000 for CFSR, 1975-2011 for 20CR, and 1957-2010 for Era-20C.

Figure 4.10  Time series of pressure from 1957-2010 at Amundsen-Scott for 20CR compared to observations by season.

Figure 4.11  Time series of surface pressure from 1979-2013 at Vostok for Era-Interim, 20CR, and Era-20C compared to observations by season.

Figure 4.12  Surface pressure time series at Amundsen-Scott from 1905-2010 by season. (20CR excluded because of errors at Amundsen-Scott station).

Figure 4.13  MSLP time series at Bellingshausen from 1905-2010 by season.

Figure 4.14  MSLP time series at Casey from 1905-2010 by season.

Figure 4.15  30-year running trends in hPa per decade at Amundsen-Scott by season. (20CR is excluded because of errors at Amundsen-Scott stations). X-axis is starting year of 30-year period.

Figure 4.16  30-year running trends in hPa per decade at Bellingshausen by season. X-axis is starting year of 30-year period.

Figure 4.17  30-year running trends in hPa per decade at Casey by season. X-axis is starting year of 30-year period.

Figure 4.18  Era-Interim MSLP trends by decade 1979-2014 by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).
Figure 4.19  CFSR MSLP trends by decade 1979-2000 by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).

Figure 4.20  Era-20C MSLP trends by decade 1979-2010 by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).

Figure 4.21  Era-20C MSLP trends by decade 1957-2010 by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).

Figure 4.22  20CR MSLP trends by decade 1979-2011 by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).

Figure 4.23  20CR MSLP trends by decade 1957-2011 by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).

Figure 5.1  Trends (1905-2014) by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$). The first, second, and third columns show trends per decade from No Rad, Ozone, and All Rad experiments respectively.

Figure 5.2  As in Fig. 5.1, but for 1905-1956.

Figure 5.3  As in Fig. 5.1, but for 1957-2014.

Figure 5.4  As in Fig. 5.1, but for 1979-2014.

Figure 5.5  Trends per decade from each experiment and the reconstructions are displayed for MAM and JJA and for 1905-2010, 1905-1956, 1957-2010, and 1979-2010. The 95% confidence intervals are also displayed with the trends.
Figure 5.6  Trends per decade from each experiment and the reconstructions are displayed for SON and DJF and for 1905-2010, 1905-1956, 1957-2010, and 1979-2010. The 95% confidence intervals are also displayed with the trends.

Figure 5.7  Time series of trend in hPa per decade of pressure anomalies for the reconstructions and for the Ozone, All Rad, and No Rad experiments seasonally through the 20th century.

Figure 5.8  Six regions of Antarctica with each station labeled in appropriate regions. Figure extracted from Fogt et al. (2016b).

Figure 5.9  Trends in hPa per decade of pressure anomalies for DJF for reconstructions, Ozone, All Rad, and No Rad experiments for each region.

Figure 5.10  30-year running pressure anomaly trends by season for reconstructions, Ozone, All Rad, and No Rad experiments averaged over the continent. X-axis is starting year of 30-year period.

Figure A.1  Era-Interim MSLP trends in hPa per decade 1979-2014 by season and by station. Significant trends at $p < 0.05$ indicated by (*) after station name.

Figure A.2.  20CR MSLP trends in hPa per decade 1957-2011 by season and by station. Significant trends at $p < 0.05$ indicated by (*) after station name.

Figure A.3.  CFSR MSLP trends in hPa per decade 1979-2000 by season and by station. Significant trends at $p < 0.05$ indicated by (*) after station name.

Figure A.4.  Era-20C MSLP trends in hPa per decade 1957-2010 by season and by station. Significant trends at $p < 0.05$ indicated by (*) after station name.
CHAPTER 1: INTRODUCTION

Significant changes in the Antarctic climate have been documented in the past several decades. In particular, changes have been noted in the temperature pattern (e.g., Steig et al. 2009; Bromwich et al. 2013; Nicolas and Bromwich 2014) as well as changes in the pressure pattern (Turner et al. 2005) across the continent. Interestingly, these changes have not been occurring uniformly over Antarctica, with key differences between East and West Antarctica, as well as across the Antarctic Peninsula; all of these changes have global implications through ice loss and sea level rise. While trends in the atmospheric circulation have been clearly linked to these changes, relatively little is known about how unique the circulation changes are over the full 20th century, and therefore how historically unique these temperature changes are, or their causality.

Because of the unique changes mentioned above, the area of study that will be focused on for this thesis is the continent of Antarctica and surrounding Southern Ocean (90° - 50°S). Antarctica comprises the largest landmass in the Southern Hemisphere and is unique because of several features across the continent and its shape, which influence how atmospheric patterns interact with the continent. The eastern part of the continent is more symmetric and nearly circular, extending between 70° and 65° S latitude seen in Fig. 1.1. This part of the continent is referred to as East Antarctica, and has several bases/stations located around the coast. The Antarctic Interior is also located in this area near and around the South Pole and only has two stations located in the large region. East Antarctica and the Antarctic Interior are unique because they are much higher in elevation (4500m) compared to West Antarctica and the Antarctic Peninsula, which are
separated by the Transantarctic Mountains. West Antarctica (seen Fig. 1.1) is much closer to sea level and only has one station. Additionally, the Peninsula is mountainous and has several stations, 6, with meteorological records over 30 years. This asymmetric shape to the continent influences how atmospheric patterns impact the continent, which will be discussed further in later chapters. Several other regions seen in Fig. 1.1 are important and will be discussed throughout this thesis. These regions include the Weddell Sea located to the east of the Antarctic Peninsula, the Bellingshausen Sea, located to the west of the Antarctic Peninsula, the Amundsen Sea, located off the coast of West Antarctica, and the Ross Sea located west of the Amundsen Sea. Finally, the Southern Ocean surrounds the entire continent.

Figure 1.1. Map of Antarctica with specific focus regions identified. Figure extracted from Turner et al. (2004).
In several recent studies, western and northern parts of the Antarctic Peninsula have been documented with the most significant warming across the continent (Turner et al. 2005; Steig et al. 2009; Nicolas and Bromwich 2014). While these regions of Antarctica have been found to be warming in recent years, other areas, such as the Antarctic Interior and large portions of coastal East Antarctica have been cooling slightly (although at a statistically insignificant rate) over the last 50 years.

Other robust changes have been noted across the continent, including changes in the atmospheric pressure pattern, which induce changes that have been consistent with the warming trends regionally. Variations in the sea level pressure are key in understanding changes in the general atmospheric circulation, since this drives the wind pattern and can have other impacts on temperature and sea ice conditions. Other key factors also play a potential role in atmospheric and oceanic circulation variability including remote forcing from changes in the tropics, stratospheric ozone depletion, and increase in greenhouse gasses. Variations in these forcing mechanisms are associated with the uneven changes across the continent and will be discussed in subsequent chapters (Turner et al. 2009; Schneider et al. 2012).

While there has been much research focused on the changing global mean temperature, relatively little is understood about the regional changes and their specific impact and causality, especially in the high southern latitudes prior to the late 1950s. This thesis focuses on pressure changes across the Antarctic continent as a whole, and changes in atmospheric circulations and forcing mechanisms over the last century. This is done in order to identify relationships between climate variations across the
continent and circulation patterns, with the intent of understanding Antarctic climate variability and the potential forcing mechanisms for regional atmospheric circulation changes throughout the 20th century. The following chapters will aim to gain a further understanding of these pressure changes and their influence on large-scale atmospheric circulation patterns. While some processes such as ozone depletion have been considered as factors in these changes (Miller et al. 2006; Polvani et al. 2011b), other radiative forcings and tropical sea surface temperature variability are also assessed.

To gain an understanding of these processes, climate models are used. For this particular study, a climate model is helpful in understanding how each of the forcing mechanisms influence the changes in the climate over time, as forcing mechanisms can be isolated in specific modeling experiments. The climate model that will be used in this thesis is the Community Atmosphere Model, version 5 (CAM5), developed in the United States by the National Center for Atmospheric Research (NCAR). This model is the atmospheric component of the coupled Community Earth System Model version 1 (CESM1).

One major issue with analyzing these changes in the past century is the lack of complete and reliable atmospheric observational datasets in Antarctica. Pressure datasets extend back to the International Geophysical Year (1957-1958) with a semi-complete record, though some data must still be patched within this timeframe. However, most surface pressure datasets do not extend before this date. To compensate for this, available pressure datasets will be evaluated and discussed in a separate component, and recently developed reconstructed seasonal pressure will be used in order to gain a full
understanding of these changes as a comparison to model results through the entire century; reconstructions have been created in a companion projection to this work (Fogt et al. 2016a,b).

In light of these challenges, this research aims to answer several questions about the changes occurring across the Antarctic continent. The project will rely heavily on reconstructed pressure across Antarctica as mentioned previously, and will employ modeling techniques in order to answer these questions listed here:

• How well can a state-of-the-art non-coupled climate model accurately depict the Antarctic atmospheric variability and changes when directly compared to reconstructions?

• What are the relative roles of natural / internal climate variability (sea surface temperature changes and circulation patterns) and external forcing mechanisms (such as ozone depletion and greenhouse gas changes) on Antarctic pressure changes during the 20th century from a climate model framework and pressure reconstructions?

• How do these processes influence the asymmetry of changes in East and West Antarctica?

This thesis seeks to answer the questions listed above and is organized as follows: Chapter 2 will be a literature review of temperature and pressure changes across Antarctica and climate patterns that affect atmospheric circulations. Chapter 3 will outline the data, which include observational data, as well as reanalysis, reconstruction, and model data, used in this work. In addition, Chapter 3 will outline the methods used
to analyze this data. Chapter 4 assesses atmospheric pressure trends from observations and reanalyses and compares them with seasonal Antarctic station based reconstructions over the 20th century. Chapter 5 is the heart of the work, where results from the model are assessed and the relative role of the various forcing mechanisms on Antarctic pressure trends over the 20th century is determined. Finally, a summary and conclusion of the work is provided in Chapter 6.
CHAPTER 2: LITERATURE REVIEW

2.1 Antarctic temperature changes review

Surface warming across the continent of Antarctica is estimated to be 0.34 ± 0.10°C per decade, which is similar to surface warming occurring in other locations on the globe (Bracegirdle et al. 2008). However, there have been key differences in temperature changes in different areas of the continent, as well as in different seasons (Turner et al. 2005). Strong warming trends have been noted over much of the Antarctic Peninsula, while cooling trends have been noted across the interior of the continent (Steig et al. 2009). Warming across the western and northern parts of the Antarctic Peninsula have been the most significant, with warming trends of +0.56°C per decade at \( p < 0.05 \) for the period of 1951-2000 at Faraday station annually (Turner et al. 2005). Turner et al. (2005) also noted that the overall warming trend over the Antarctic Peninsula is greatest during the winter months of June, July, and August (JJA). Most notably, Turner et al. (2005) show warming of 1.09°C at \( p < 0.05 \) per decade from 1951-2000 in the winter at Faraday station, located on the Peninsula. Turner et al. (2005) also document observed warming of +0.24°C at \( p < 0.01 \) per decade at Faraday during austral summer (December, January, February [DJF]), located on the Peninsula (Table 2.1). Bellingshausen (also located on the Peninsula) also has shown rapid warming of +0.3°C at \( p < 0.01 \) per decade during the summer (Table 2.1) according to Turner et al. (2005). The Antarctic Peninsula is warming more rapidly than any other location, based on spatial temperature reconstructions by Steig et al. (2009).
Table 2.1. Temperatures change seasonally across Antarctica and significance levels. Table extracted from Turner et al. (2005).

<table>
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<th>Station</th>
<th>Temperature trend (°C decade⁻¹)</th>
<th>Period</th>
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<tbody>
<tr>
<td></td>
<td>Annual</td>
<td>Spring</td>
<td>Summer</td>
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<td>Novolazarevskaya</td>
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<td>+0.19 ± 0.34</td>
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<tr>
<td>Syowa</td>
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<td>+0.01 ± 0.48</td>
<td>-0.01 ± 0.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molodezhnaya</td>
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<td>-0.18 ± 0.50</td>
<td>-0.14 ± 0.32</td>
</tr>
<tr>
<td>Mawson</td>
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<td>-0.04 ± 0.33</td>
<td>-0.09 ± 0.26</td>
</tr>
<tr>
<td>Davis</td>
<td>+0.03 ± 0.35</td>
<td>+0.05 ± 0.50</td>
<td>+0.05 ± 0.30</td>
</tr>
<tr>
<td>Mirny</td>
<td>-0.01 ± 0.26</td>
<td>+0.09 ± 0.46</td>
<td>-0.14 ± 0.30</td>
</tr>
<tr>
<td>Vostok</td>
<td>-0.02 ± 0.34</td>
<td>-0.11 ± 0.51</td>
<td>+0.13 ± 0.42</td>
</tr>
<tr>
<td>Casey</td>
<td>+0.01 ± 0.40</td>
<td>+0.13 ± 0.50</td>
<td>-0.09 ± 0.30</td>
</tr>
<tr>
<td>Dumont d’Urville</td>
<td>+0.02 ± 0.27</td>
<td>+0.23 ± 0.45</td>
<td>0.00 ± 0.31</td>
</tr>
<tr>
<td>Scott Base</td>
<td>+0.29 ± 0.36</td>
<td>+0.34 ± 0.68</td>
<td>+0.05 ± 0.38</td>
</tr>
<tr>
<td>Rothera</td>
<td>+1.01 ± 1.42</td>
<td>+1.06 ± 1.53</td>
<td>+0.36 ± 0.37</td>
</tr>
<tr>
<td>Faraday/Vernadsky</td>
<td>+0.56 ± 0.43</td>
<td>+0.25 ± 0.44</td>
<td>+0.24 ± 0.17</td>
</tr>
<tr>
<td>Bellingshausen</td>
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<td>-0.10 ± 0.47</td>
<td>+0.30 ± 0.20</td>
</tr>
<tr>
<td>Esperanza</td>
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<td>-0.07 ± 0.57</td>
<td>+0.43 ± 0.34</td>
</tr>
<tr>
<td>Marambio</td>
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<td>-0.8 ± 10.5</td>
<td>&lt;90%</td>
</tr>
<tr>
<td>Orcadas</td>
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<td>+0.15 ± 0.14</td>
<td>+0.15 ± 0.06</td>
</tr>
<tr>
<td>Halley</td>
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<td>0.00 ± 0.53</td>
<td>+0.12 ± 0.28</td>
</tr>
<tr>
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<td>-0.01 ± 1.69</td>
<td>-0.02 ± 1.25</td>
</tr>
<tr>
<td>Amundsen–Scott</td>
<td>-0.17 ± 0.21</td>
<td>-0.12 ± 0.63</td>
<td>-0.21 ± 0.49</td>
</tr>
</tbody>
</table>
Steig et al. (2009) used reconstructed temperatures over the continent because it has been shown that reanalyses are not as reliable (Bromwich et al. 2007). Steig et al. (2009) also mentions that there may be some problems with reconstructions which use interpolation techniques due to large spatial gaps. In this case, however, because of great spatial consistencies in the temperature pattern regionally, an interpolation technique may be reliable (Steig et al. 2009; King and Comiso 2003). Steig et al. (2009) make similar conclusions to the observations using temperature reconstructions over the continent in the last 50 years, and show the greatest warming to be occurring during austral spring (September, October, November [SON]) and winter (JJA) over West Antarctica. Steig et al. (2009) also discussed that while cooling has occurred over much of East Antarctica in recent decades, the temperature decrease was strongest in more recent trends (1969-2002; though still comparatively insignificant). It should be noted that while some cooling trends may be considered meaningful, scarcity of station data and record availability make it impossible to determine the significance of the cooling trend of East Antarctica and the Antarctic interior within a longer timescale (Turner et al. 2005).

In a study by Bromwich et al. (2013), it was determined that for the period between 1958-2010, there was warming of 0.47°C per decade at $p < 0.01$ at Byrd station in West Antarctica, using a temperature reconstruction, observations, and reanalysis where data are missing. Bromwich et al. (2013) found that temperatures at Byrd are correlated well with temperatures across all of West Antarctica. The findings are nearly in agreement with results presented by Turner et al. (2005) and Steig et al. (2009) with temperature changes that are similar to warming at Faraday (Bromwich et al. 2013).
Another study by O’Donnell et al. (2011), makes similar conclusions using different reconstruction techniques. In that study it was found that the Peninsula is warming most rapidly in the winter (Fig. 2.1). Figure 2.1 compares the findings from Steig et al. (2009) with two other reconstruction methods by O’Donnell et al. (2011). While both the RLS (regular least squares), and the E-W (eigenvector-weighted) method agree well, there are some differences in results seen with the method used by Steig et al. (2009). Here it can be seen that there is no significant temperature change across all seasons in East Antarctic according to Steig et al. (2009). However, an important finding by Turner et al. (2005) is that there have been no significant changes in temperature trends at Syowa station, located on coastal East Antarctica. This is in contrast with findings at the Novolazarevskaya station (located 100km from Syowa), which has seen +0.25°C of warming ($p < 0.10$) (Table 2.1) in the past decade (Turner et al. 2005).
Nicolas and Bromwich (2014) also studied the temperature pattern across Antarctica, however in their study, reconstructions are extended back to 1957-1958 using the available temperature records that extend back to this period, as well as reconstructed temperature records at Byrd station in West Antarctic from Bromwich et al. (2013). They use spatial interpolation methods for 15 stations using several reanalysis datasets, including CFSR reanalysis, which yielded the highest skill (Nicolas and Bromwich
Nicolas and Bromwich (2014) found that warming in West Antarctica is similar to the warming on the Peninsula. Warming on the Antarctic Peninsula is significant ($p < 0.05$) in each season and annually, while West Antarctica shows significance in SON and JJA and annually. East Antarctica is shown to have significant warming during only SON during this period. Seasonal temperature trends from the Nicolas and Bromwich (2014) reconstruction are shown in Fig. 2.2. Figure 2.2 also highlights significant trends, which are seen across West Antarctica and the Peninsula annually.

Figure 2.2. CFSR reconstructions 1958-2012 seasonally. Solid lines indicate significance ($p < 0.05$). NS shows areas with no significance. Figure extracted from Nicolas and Bromwich (2014).
One major impact of the temperature changes across the continent can be seen in the sea ice extent. Because of the rapid warming, it is projected that sea ice will be reduced nearly 25% ($2.6 \pm 0.73 \times 10^6$ km$^2$) by the end of the 21st century (Arzel et al. 2006; Bracegirdle et al. 2008). While there is a direct relationship with temperature changes and sea ice, atmospheric circulations may indirectly influence sea ice by impacting the variability of temperatures. A study by Lefebvre et al. (2004) shows that average wind directions have a role in the formation of sea ice. When the winds are more northerly, there tends to be more warming and therefore a decrease in sea ice. On the other hand, when winds are more southerly, surface temperatures tend to cool and sea ice will grow. This relationship will be discussed further in subsequent sections.

Based on the studies and findings discussed above, previous research indicates that there have been significant temperature variations and asymmetric changes over the continent. The temperature asymmetry suggests there is a link between the changing temperatures and atmospheric circulation changes, perhaps tied to large-scale patterns of climate variability, which may have influenced the significant temperature trends in certain parts of the continent. Past research has focused on the relationship between these temperature changes and atmospheric circulations tied to patterns of climate variability, however the specific cause or direct forcing mechanism for the atmospheric circulation trends are not fully understood.
2.2 Antarctica pressure change

Turner et al. (2005), conducted a study which assessed pressure changes at 19 stations across Antarctica. In that study, mean sea level pressures were used primarily from 1961-2000 from the READER archive. Looking at the 1971-2000 range (period when most stations had consistent data), Turner et al. (2005) found there has been a decrease in MSLP across the continent, especially at Molodezhnaya station which showed a decrease of 1.63 hPa per decade at $p < 0.01$ in the summer, and a decrease of 0.98 hPa per decade at $p < 0.01$ annually. Mirny station also had some of the greatest changes during this time period with a decrease of 0.95 hPa per decade at $p < 0.01$ (Turner et al. 2005). Both of these stations are located near the coast in East Antarctica. All of the stations used in the Turner et al. (2005) study are shown in Fig. 2.3, with pressure changes seen across all season. The largest and most significant pressure changes can be seen in East Antarctica during the summer, with a secondary minimum occurring in the winter at some stations (Turner et al. 2005). In the Turner et al. (2005) study, the decreases in pressure that have been occurring over the past several decades can be attributed to changes in atmospheric circulations which will be discussed in the following section.
2.3 Large-scale atmospheric circulation variability

Large-scale (i.e., continental scale and larger) climate patterns play a major role in Antarctic climate variability (Bracegirdle et al. 2008). Not surprisingly, the warming trends noted at several locations across the continent are likely linked to changes in hemispheric and regional atmospheric circulation patterns, rather than changes in the
global atmospheric circulation (in particular, any circulation changes in the Northern Hemisphere).

Time-mean flow in the Southern Hemisphere is more zonal than the Northern Hemisphere. This is because most of the features surrounding Antarctica and the Southern Hemisphere are more uniform due to a majority of it being ice and ocean. Topographically, Antarctica is asymmetric, with a high plateau in East Antarctica that reaches more than 3500+ meters high (Lachlan-Cope 2001). The Transantarctic Mountains separate the continent, with lower elevations in West Antarctica, and higher terrain across the Peninsula. The continent’s shape and topography influences the time-mean flow and is related to the existence of the semi-permanent low pressure in the Amundsen Sea known as the Amundsen Sea Low (ASL; Lachlan-Cope 2001). Synoptic scale cyclones are common in this region and lead to frequent sustained northwesterly flow across the western part of the Antarctic Peninsula, contributing to the anomalous low pressure in the Amundsen Sea (Fogt et al. 2012a). Figure 2.4 shows the elevation of Antarctica and surrounding sea. It is clear that West Antarctica is much lower while the East is very high (up to 4000m) and divided by the Transantarctic mountain range (Nicolas and Bromwich 2014).
With frequent cyclones and northwesterly flow near the Peninsula, there is a direct relationship with the asymmetric nature of temperature changes across the continent. For temperatures, changes can occur based on the strength of the ASL. When the ASL is stronger than usual, there is increased northerly flow near the Peninsula, which acts to warm temperatures in this location (Stammerjohn et al. 2008). On the other hand, when the ASL is weak, the atmospheric flow acts opposite, and leads to cooler than normal temperature across the Peninsula (Stammerjohn et al. 2008). The nature of the ASL also has a significant impact on the extent and formation of ice in these regions. As discussed previously, the direction of the wind and the strength play a significant role in
sea ice change. When the ASL is stronger, there is typically a decrease in ice extent near the Peninsula. This is made clear in a study by Lefebvre et al. (2004), which concludes that when the ASL is strong, the northerly flow causes a decrease in the sea ice. Additionally, another study by Holland and Kwok (2012) concluded that not only does the northerly flow advect warmer temperatures toward the Peninsula and decrease sea ice, but the direction of the wind also causes the ice to converge closer to the coastline, decreasing the extent and coverage of the ice. In the opposite scenario, weaker wind would allow for ice to push farther away from the coast.

In addition to regional circulations, large-scale climate patterns also have an important impact. One of these patterns that has a known significant impact on conditions across the Antarctic is the Southern Annular Mode. The Southern Annular Mode (SAM) is a mode of atmospheric circulation variability that measures the strength of the meridional pressure gradient between the middle and high latitudes of the Southern Hemisphere (Thompson et al. 2000). The meridional pressure gradient can alter the strength of the circumpolar zonal winds (Thompson et al. 2000). The SAM plays a significant role with changes in the Antarctic climate, and is said to make up roughly 35% of all climate variability in the extratropical Southern Hemisphere (Marshall 2007), making it important to know how it will change through time.

The SAM has two phases, which are described based on pressure patterns and the strength of the circumpolar jet. In the positive polarity, SAM is characterized with lower than average sea level pressures across Antarctica and higher than average pressures in the southern midlatitudes, around ∼45°S. The positive phase can be seen in Fig. 2.5a,
showing lower than average geopotential heights over the Pole and higher geopotential heights at the midlatitudes. This pressure pattern induces stronger than average circumpolar westerly flow, due to the greater meridional pressure gradient (Fogt et al. 2012b). In contrast, when SAM is in its negative phase, sea level pressures across Antarctica will be higher than average, with lower than average pressures in the southern midlatitudes, and a general weakening of the jet (Marshall 2007; Thompson et al. 2000).

Figure 2.5a (top left). Geopotential height anomalies in the positive phase of the SAM. Figure 2.5b (top right). Temperature anomalies in the positive phase of the SAM. Figure 2.5a and 2.5b extracted from IPCC report 2007 3.6.5 The Southern Hemisphere and Southern Annular Mode. Figure 2.5c (bottom). SAM index time series from 1957-2015. Figure 2.5c adapted from IPCC report 2007 3.6.5 The Southern Hemisphere and Southern Annular Mode. (Update version of 2007 figure).
The sign / phase of SAM has a notable relationship with the temperatures across the continent. When SAM is in its positive phase, East Antarctica exhibits cooler than average temperatures, while the Antarctic Peninsula displays warmer than normal temperatures (Marshall 2007). This is because the stronger circumpolar flow characterizing the positive SAM phase prohibits meridional transfer around much of Antarctica, locking the cold air in place over the polar cap. For reasons that will be discussed further in future section, in the past two decades there have been more frequent positive phases of the SAM. Figure 2.5c shows the more frequent positive SAM indices through the mid 90s and 2000s. Based on this, it would be expected that the temperature pattern in the past few decades would reflect this trend, with primarily cooler temperatures seen over the continent of Antarctica due to the colder air being locked in place by the strong jet. Referring back to section 2.1 however, this is not necessarily the case. While there have been some cooling temperatures, there has also be rapid warming across Western Antarctica and the Antarctic Peninsula (Turner et al. 2005; Steig et al. 2009; O’Donnell et al. 2011). The warming temperatures cannot be directly attributed to the positive phase of the SAM; however, they can be attributed to the existence of the Amundsen Sea Low. In the positive phase of the SAM this low pressure system is stronger (Fogt et al. 2012a). Zonal asymmetry at this location is associated with relatively warm northerly flow on its eastern flank, leading to a local warming across much of the Antarctic Peninsula during the positive phase of SAM (cooling in its negative phase; Fogt et al. 2012b). The temperature pattern can be seen in Fig. 2.5b, showing the spatial temperature pattern from 1982-2004, which is in agreement with the
temperature changes discussed in previous sections. This aligns well with the expected temperature pattern in the positive phase of the SAM.

Another important factor that is impacted by changes in temperature due to the SAM are wind-driven changes in the sea ice extent and ice shelf stability surrounding Antarctica. In the positive phase of SAM, the warming across the Antarctic Peninsula has been linked to decreasing the ice shelf area (particularly the Larsen B Ice Shelf) on the eastern side (Orr et al. 2006). In general, there has been a documented overall increase in sea ice coverage around Antarctica over the past decades (Zwally et al. 2002; Holland and Kwok 2012). However, in studies by Holland and Kwok (2012), it is shown that there is a much more significant decrease in sea ice coverage in some sectors (i.e., the Amundsen and Bellingshausen Seas). These changes have generally been linked to possible changes in the SAM that drive zonal changes in wind and temperatures (Holland and Kwok 2012; Stammerjohn et al. 2008).

In addition to the SAM, the El Niño-Southern Oscillation (ENSO) has an impact on the Antarctic climate. The Southern Oscillation is described by the sea level pressure differences from the central equatorial Pacific (Tahiti, French Polynesia) and the Western Pacific (Darwin, Australia). El Niño is defined by above average sea surface temperatures across the equatorial Pacific. Pressure and sea surface temperatures vary together, and collectively, these variations make up ENSO. This circulation is very important to the climate of Antarctica because it is the largest climate cycle and it influences the high southern latitudes on decadal time scales (Turner 2004). The ENSO circulation originates in the tropical Pacific, due to changes in the sea surface temperatures and
easterly trade winds. While there is currently no universal metric identifying El Niño events, it is suggested by Trenberth (1997) that for El Niño events to occur, sea surface temperatures must be greater than 0.4°C above average for 5 consecutive overlapping 3-month seasons. Based on this definition, an El Niño event would occur 31% of the time (Turner 2004).

The positive or warm (El Niño) phase of ENSO is associated with lower pressure over the central Pacific (Tahiti), while high pressure anomalies exist in the western Pacific (Darwin). This is characterized by a negative sign for the Southern Oscillation Index (SOI), which is measured by the pressure difference between Tahiti and Darwin, Australia. The greater the difference in pressure, the greater the absolute value of the index will be. In this warm phase, the equatorial trade winds are reduced and upwelling decreases, which allows for warming of sea surface temperatures off the coast of South America. These warmer sea surface temperatures are what define El Niño conditions. In the opposite, or negative (cold, La Niña) phase of ENSO, conditions are reversed: higher pressure anomalies exist over the central Pacific with lower pressure anomalies over Darwin. In addition, the Southern Oscillation Index will be positive based on the pressure difference between the two locations. The trade winds increase across the equatorial Pacific, leading to increased upwelling and cooler than average sea surface temperatures off the coast of South America.

Turner (2004) notes that during the positive phase of ENSO (warm events, or El Niño events), positive geopotential height / pressure anomalies are found over the Amundsen-Bellingshausen Sea region due to the formation of a Rossby wave train in the
Pacific Ocean, essentially connecting the tropics to the high southern latitudes. A schematic of the El Niño or warm event is shown in Fig. 2.6. Here, higher pressure anomalies are seen over the Amundsen Sea region, weakening the ASL (Fogt et al. 2012a). During the La Niña phase however, there is a deepening of the ASL. There is also a noted connection between the phase of the SAM and the phase of ENSO. Specifically, ENSO teleconnections are amplified when the SAM is positively correlated with the SOI (Fogt and Bromwich 2006). For example, when SAM is in the positive phase and La Niña conditions occur, anomalous low pressure exists in the Amundsen-Bellingshausen Seas region and teleconnections are amplified (Fogt et al. 2011).

![Figure 2.6](image)

Figure 2.6. Depiction of the warm phase (El Niño) of ENSO with temperature characteristics and jet patterns. Figure extracted from Yuan (2004).

The phase of ENSO has also been shown to have a relationship with the extent of ice surrounding Antarctica (Yuan 2004). With the development of the stationary wave train in the warm phase (El Niño), high pressure in the Amundsen and Bellingshausen
Seas bring flow from the north on the western side, bringing warmer temperatures and a decrease in ice (Fig. 2.7a; Stammerjohn et al. 2008). On the eastern side of the high pressure, however, flow is directed from the south, bringing colder temperatures and an increase in ice extent (Fig. 2.7a). On the other hand, when a La Niña is occurring, anomalous low pressure is located to the west of the Antarctic Peninsula (Stammerjohn et al. 2008). This brings flow from the north on the eastern side of the Peninsula, warmer temperatures, decreasing sea ice, and compacting the ice as flow is directed toward the continent. On the western side of the low, flow is from the south bringing colder temperature and an increase in sea ice which can be seen in Fig. 2.7b.

Figure 2.7. Collectively, El Niño and La Niña events during the 1990s and ice changes during that time. Figure 2.7a (left). Two El Niño years. Figure 2.7b (right). Three La Niña years. Figure extracted from Stammerjohn et al. (2008).
2.4 Ozone

Stratospheric ozone loss has a significant impact on the SAM, especially with the shift of the SAM into the positive phase. Since 1985 the stratosphere has cooled approximately 10K during October and November in the polar region (Thompson and Solomon 2002). This ozone loss has been studied through the later decades of the 20th century and has been linked to the emission of synthetic materials (Rowland 2006). These synthetic materials, known as chlorofluorocarbons (CFCs), cause major destruction to ozone (Rowland 2006). While the decrease in ozone has been seen across many latitudes, it has been most notable over the Antarctic, specifically during the springtime (September, October, November [SON]) (Solomon et al. 1986).

The decrease in ozone over Antarctica has significant seasonal variability, and the most rapid decrease has been documented to occur during the springtime (SON; Solomon et al. 1986). The seasonal cycle of ozone concentration came in a discovery made at Halley station. This discovery was in contrast to a hypothesized finding of a maximum value of ozone at the end of spring, as found in northern latitudes (Rowland 2006). After the International Geophysical Year, ozone measurements were taken at Halley station. During the early period, ozone concentrations remained fairly steady, however soon after, a rapid decline was noted (Fig. 2.8) (Rowland 2006).
It was also discovered that the springtime decrease could be attributed to the blocking pattern caused by the polar vortex. The existence of the winter time polar vortex in the high southern latitudes is related to the decrease in solar radiation during the dark period through the winter months (June, July, August [JJA]) causing a thermal gradient between the pole and midlatitudes (Solomon 1999). Because of this, the strong westerly jet develops, known as the polar vortex, and acts to essentially isolate the pole from the midlatitudes (Solomon 1999). During the winter, there is also a decrease in the destruction of ozone, due to photochemical processes that require the sun. Therefore, the
most rapid destruction of ozone occurs during the spring, as light begins to return, and the polar vortex has not weakened yet (Solomon 1999). This phenomenon can be seen in Fig. 2.9, showing the variability of ozone at Halley station by season. It can be seen that with the return of the sunlight during the spring, ozone concentration begins to decrease rapidly, but remains fairly constant through the dark winter months when the polar jet is strong. Additionally, another process occurs during winter, setting up for the strong decrease in ozone in the spring because of a colder stratosphere and a stronger winter polar jet.

![Figure 2.9. Variation in ozone at Halley by season, 1956-1959. Figure extracted from Rowland (2006).](image)
The decrease in ozone during the last several decades has led to a significant impact on the temperatures within the stratosphere. Decreasing the ozone leads to less UV absorption in the stratosphere and therefore causing cooling within the stratosphere. When the stratosphere is colder, the tropopause remains lower over the polar cap, causing the temperature gradient between the midlatitudes and the poles to remain strong; therefore, the winter polar vortex is strong. Because of this recent change, the winter polar vortex is much slower to breakdown during the spring season (Perlwitz et al. 2008). The polar vortex is strongest through the winter season in the stratosphere when temperatures are at a minimum, and is expected to break down and eventually become easterly at the end of the winter season as the temperatures begin to warm (Thompson and Solomon 2002). With the rapid ozone depletion occurring during this time, however, the polar vortex breakdown occurs more slowly. The slower breakdown of the polar vortex has implications on the SAM. During the spring season the SAM is becoming more active, relating to the polar jet breakdown. For several reasons, including a cooler stratosphere and a decrease in the stratospheric jet, the stratosphere is susceptible to wave interactions between the troposphere and the stratosphere during the spring (Thompson and Wallace 2000). When the stratosphere and troposphere interact, SAM becomes active, which can be linked to the decrease in ozone (Thompson and Wallace 2000). During the time when SAM is active, the stratosphere and troposphere are strongly coupled, therefore, as springtime ozone loss begins with the return of light and a weakening in the polar vortex, these processes extend into the tropospheric circulation. The coupling between the stratosphere and the troposphere along with the slower
breakdown of the polar vortex show that there is a strong connection with the more frequent positive SAMs in recent decades (Fig. 2.5c; SAM index time series) and ozone loss, however it does not show a direct relationship.

The direct impact that ozone has had on the phase of the SAM is demonstrated through modeling studies. Gillett and Thompson (2003) conducted a study in which they use a state-of-the-art atmospheric model with a mixed-layer ocean, prescribing ozone depletion in the stratosphere in the spring months. Prescribed ozone trends were based on observations from 1979 to 1997. They found that when modeled, changes in the stratosphere and troposphere match very well with observations during this time. This is shown in Fig. 2.10 with observed changes in geopotential height shown in Fig. 2.10b and the results of the modeling study by Gillett and Thompson (2003) on the left in Fig. 2.10a. As discussed previously, the stratosphere and troposphere may be linked during the springtime, which can be seen clearly in both Fig 2.10a and Fig. 2.10b with low height anomalies in the stratosphere connecting to the troposphere (Gillett and Thompson 2003). Additionally, not only is this connection between the stratosphere, troposphere, and ozone depletion seen to be occurring through the springtime, but it is also continuing on through the summer months with the delay in the breakdown of the jet. Based on the lowering heights that occur as a result of ozone depletions, the SAM becomes more positive, and can account for more frequent positive SAMs in recent decades.
With the relationship between the stratosphere and troposphere and the strengthening of the jet, these changes are in agreement with more positive SAMs and cooling over interior Antarctica and warming over the Peninsula (Perlwitz et al. 2008).

The impacts of ozone depletion causing a slower breakdown of the polar vortex and more frequent positive SAMs may not have a lasting effect into the future. Once it was discovered that the emission of these harmful substances in CFCs caused rapid depletion of the ozone, their use was completely banned in 1996 by the Montreal Protocol (D’Souza 1995). A study by Newman et al. (2004) discusses that the amount of ozone depleting substances in the stratosphere is no longer increasing. This suggests that the ozone has already begun to recover (Newman et al. 2006). Newman et al. (2006) also found that the ozone is expected to fully recover back to 1980 values by the year 2068.
Figure 2.11. Ozone hole recovery timeline. Figure extracted from Newman et al. (2006).

Other studies also show the gradual recovery of ozone over the next several decades. Because the decrease in ozone in the late 20\textsuperscript{th} century had a significant impact on atmospheric circulations (i.e., an increase in the positive phase of the SAM and changes in the polar vortex), shifts in these patterns may occur as the ozone begins to replenish. Using chemistry climate models (CCM), Perlwitz et al. (2008) suggest that as the ozone begins to increase again over the next several years, it is more likely that there will be a warming of the stratosphere during austral spring. Another possible impact is that there will be a general weakening of the tropospheric westerly winds during this time as well as in austral summer due to a smaller temperature gradient during the active phase of the SAM (Perlwitz et al. 2008). This causes some concern, as these changes will
induce a potential shift in the overall atmospheric circulation. The shift may lead to more significant changes in the Antarctic climate. One consequence is that the current positive phase of the SAM index will decrease significantly during the summer (Perlwitz et al. 2008). The shifts in the SAM may oppose the impact that the expected increased greenhouse gases will have in the future.

Increasing the greenhouse gases in the troposphere acts to warm the troposphere, therefore further increasing the temperature gradient (Perlwitz et al. 2008). Like the ozone depletion, increasing greenhouse gases lead to a more positive SAM. As ozone begins to recover, the impact of greenhouse gas increases and ozone will begin to oppose each other. In the Perlwitz et al. (2008) modeling study, results indicate that ozone recovery during the 21st century has a strong impact on tropospheric circulations, which outweighs the influence of the increasing greenhouse gases. Because of this, there is a significant impact on the strength of the SAM, which decreases significantly during the summer (Perlwitz et al. 2008). The change in ozone concentration is therefore seen as one of the major forcing mechanisms that lead to changes in the general circulation.

2.5 Chapter summary

Studies have shown that trends in warming and pressure are likely linked to changes within atmospheric circulation patterns. As with studies focusing on the SAM’s or ENSO’s impacts on the Antarctic climate, the underlying issue with much of the past research in this area is the brevity of observations that are available. Observations for much of the continent date back only a few decades, most starting around 1957. Long-
term trends have been difficult to determine, as well as the historical context for these changes in the Antarctic circulation. Because of these challenges, reconstructed data must be used and better modeling techniques must be implemented to have a more complete understanding of Antarctic climate variability. With known connections between changes in the climate and atmospheric circulations on a shorter time scale, a broader scope will need to be assessed in order to understand how these changes are unique within a century long time scale. Understanding this is the basis of this thesis.
CHAPTER 3: DATA AND METHODS

In this thesis, several datasets are used in order to assess pressure changes across the continent. Seasonal averages of pressure at each of the station are used. For this research, much of the data is available freely and downloaded to the Scalia Lab data servers at Ohio University. Additionally, pressure reconstruction data were made available by Dr. Ryan Fogt through an ongoing companion project to this work.

3.1 Observations

The data that are used for this study include observational datasets from the Reference Antarctic Data for Environmental Research (READER). These data are comprised of near-surface climate data such as temperature, surface pressure, sea level pressure, and wind speeds (Turner et al. 2004). The READER database includes this information in the form of monthly averages at each station across the continent (Turner et al. 2004). Seasonal averages of these observations at each station are used. Several stations are assessed specifically from this dataset that are listed in Table 3.1, along with the length of the record, their location (Fig. 3.1), and elevation.

The READER dataset is important because it has been shown to be of high quality and the most complete set of observed data for the continent (Turner et al. 2004). This dataset extends back until around 1957 (with a few stations extending earlier), although some stations have much shorter records. Specifically, this research will be utilizing the pressure data available from the READER archive. The observational pressure data from stations in Fig. 3.1 will be used to analyze the skill of
other data used in this research, as well as to understand importance and likely causality of the observed changes through the use of model simulations. The freely available data can be accessed at www.antarctica.ac.uk/met/READER.

Table 3.1. Observational pressure data from the READER archive. Marsh/O’Higgins*: Latitude and longitude and year are for O’Higgins. Marsh station is located near Bellingshausen. McMurdo/Scott Base+: Elevations from McMurdo and start year from McMurdo.

<table>
<thead>
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<th>Station</th>
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<th>Longitude</th>
<th>Elevation</th>
<th>Starting year</th>
</tr>
</thead>
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<td>0.0</td>
<td>2835m</td>
<td>1957</td>
</tr>
<tr>
<td>Bellingshausen</td>
<td>62.2S</td>
<td>58.9W</td>
<td>16m</td>
<td>1968</td>
</tr>
<tr>
<td>Casey</td>
<td>66.3S</td>
<td>110.5E</td>
<td>42m</td>
<td>1960</td>
</tr>
<tr>
<td>Davis</td>
<td>68.6S</td>
<td>78.0E</td>
<td>13m</td>
<td>1957</td>
</tr>
<tr>
<td>Dumont d'Urville</td>
<td>66.7S</td>
<td>140.0E</td>
<td>43m</td>
<td>1956</td>
</tr>
<tr>
<td>Esperanza</td>
<td>63.4S</td>
<td>57.0W</td>
<td>13m</td>
<td>1945</td>
</tr>
<tr>
<td>Faraday</td>
<td>65.3S</td>
<td>64.3W</td>
<td>11m</td>
<td>1947</td>
</tr>
<tr>
<td>Halley</td>
<td>75.5S</td>
<td>26.7W</td>
<td>30m</td>
<td>1957</td>
</tr>
<tr>
<td>Marambio</td>
<td>64.2S</td>
<td>56.7W</td>
<td>189m</td>
<td>1970</td>
</tr>
<tr>
<td>Marsh/O’Higgins*</td>
<td>63.3S</td>
<td>57.9W</td>
<td>10m</td>
<td>1963</td>
</tr>
<tr>
<td>Mawson</td>
<td>67.6S</td>
<td>62.9E</td>
<td>16m</td>
<td>1954</td>
</tr>
<tr>
<td>McMurdo/Scott Base+</td>
<td>77.9S</td>
<td>166.8E</td>
<td>24m</td>
<td>1956</td>
</tr>
<tr>
<td>Mirny</td>
<td>66.6S</td>
<td>93.0E</td>
<td>30m</td>
<td>1956</td>
</tr>
<tr>
<td>Novolazarevskaya</td>
<td>70.8S</td>
<td>11.8E</td>
<td>119m</td>
<td>1961</td>
</tr>
<tr>
<td>Rothera</td>
<td>67.6S</td>
<td>68.1W</td>
<td>32m</td>
<td>1976</td>
</tr>
<tr>
<td>Syowa</td>
<td>69.0S</td>
<td>39.6E</td>
<td>21m</td>
<td>1957</td>
</tr>
<tr>
<td>Vostok</td>
<td>78.5S</td>
<td>106.9E</td>
<td>3490m</td>
<td>1958</td>
</tr>
</tbody>
</table>
One issue with the observations record described above is the length of the record and temporal inconsistencies. Some stations have periods of missing data, so it is difficult to make conclusions on a longer time scale. Because observations are incomplete, both spatially and temporally, reanalysis data will also be implemented in this research.

![Figure 3.1. Location of stations used in this research with the exception of Byrd station in West Antarctica, which is excluded from this thesis. Figure extracted from Fogt et al. (2016a).](image)

### 3.1.1 Reanalysis data

In order to compensate for the incompleteness of data collected across the continent, gridded reanalysis data are used. Reanalysis data are used to fill in missing observations globally and are very helpful in understanding processes that occur over the continent (Bracegirdle and Marshall 2012). Reanalysis data are often considered to be a true representation of the real world, since they are created using historical meteorological observations that are assimilated in the form of remote sensing and in situ observations. The information is collected for a specified timeframe and input into a
consistent model. The model performs a quality control on the observations, and then uses this data as a current state or snapshot of the atmosphere (i.e., a model analysis). Since these analyses are created with historical data, the atmospheric state has been re-analyzed. A key feature of the reanalysis is that it is a uniform dataset that is complete both spatially and temporally; however they are not purely observational as the model uses various approaches to filling in the gaps where observations do not exist, and therefore are not without error.

3.1.2 Era-Interim

While several reanalysis datasets exist, the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis is primarily employed. ECMWF Interim Reanalysis (Era-Interim) includes gridded data (at 1.5° x 1.5° longitude-latitude) between the periods of 1979 to present time (Dee et al. 2011). Era-Interim is comprised of several atmospheric variables including surface temperature, mean sea level pressure (MSLP), 10m wind speed and direction, as well as geopotential heights. Era-Interim replaced the previous Era-40, which was found to be one of the most skilled pressure reanalyses in a study by Bromwich et al. (2007). Bromwich et al. (2011) concluded that of all the different reanalysis data, Era-Interim has been the most reliable with mean sea level pressure specifically. This is in agreement with Bracegirdle and Marshall (2012), who found that Era-Interim is the most stable at all stations. Because of these findings, it will be used in this study more than other reanalysis datasets, and in general, be considered a representation of real-world data. The reanalysis data will be primarily
employed for model validation and for representing spatial atmospheric circulation trends and variability.

3.1.3 CFSR

Another reanalysis dataset that will be used to compare with Era-Interim, is the Climate Forecast System Reanalysis (CFSR). CFSR is a newer reanalysis with 0.5° x 0.5° grid spacing and spans the dates 1979-present. A study by Saha et al. (2010) shows that CFSR is more skillful than the previous reanalysis of the 1990s, especially in the Southern Hemisphere. Not surprisingly, Saha et al. (2010) also found that CFSR is more reliable with time due to the use of more satellite data. CFSR improves on earlier reanalyses by increasing spatial resolution, using more complete observations, and using a better representation of atmospheric processes (Bracegirdle and Marshall 2012). A study by Bracegirdle and Marshall (2012) assessed the reliability of CFSR in comparison to observations and found that the CFSR reanalysis has significantly fewer biases in orographic height because of the higher resolution. However, their study also showed that there are significant temperature biases in the winter months in the CFSR reanalysis. Additionally, large biases were found in CFSR in surface pressure, especially in 1979-1988 and 1999-2008 (Bracegirdle and Marshall 2012), hence why this reanalysis is not favored over Era-Interim for this particular study focusing on pressure.
3.1.4 20CR

The 20th Century Reanalysis (20CR) is a reanalysis with 2° x 2° spatial resolution and monthly means from 1871-2008. This reanalysis uses only surface observations and contains climatological data including surface pressure, surface temperature, and sea ice (Compo et al. 2011). The 20th century reanalysis has been shown to have some biases with surface temperature compared to other reanalyses, having a warm bias in the polar regions in the satellite era (Compo et al. 2011). Biases have also been seen with MSLP, which are likely due to elevation influence and a lower spatial resolution (Compo et al. 2011). While the 20CR reanalysis has been shown to be reliable in many areas of the world, greater biases are seen in the polar regions, especially in the earlier period, with less observational data, prior to 1957 (Compo et al. 2011). Nonetheless, it is used here as an estimate of pre-1979 pressure variation across Antarctica.

3.1.5 Era-20C

ERA-20C reanalysis (part of the Era-CLIM project) is similar to 20CR, with its focus being a full century long reanalysis. The goal of the Era-20C reanalysis is to improve quality and consistency of observations. Era-20C is especially useful for surface pressure and wind (Stickler et al. 2014). Era-20C is quite similar to 20CR as it aims to be a reanalysis across the entire century, however it does not have upper air or satellite observations (Poli et al. 2013). Like the previous reanalysis Era-20C also has difficulties in the early 20th century because of the lack of data across Antarctica (Poli et al. 2013).
Its primary use in this study, like 20CR, is to provide another estimate of early 20\textsuperscript{th} century pressure variability.

Table 3.2. Each reanalysis and years of data used.

<table>
<thead>
<tr>
<th>Reanalysis</th>
<th>Years used in current study</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA-Interim</td>
<td>1979-2014</td>
<td>0.7° x 0.7°</td>
</tr>
<tr>
<td>CFSR</td>
<td>1979-2000</td>
<td>0.5° x 0.5°</td>
</tr>
<tr>
<td>20CR</td>
<td>1905-2011</td>
<td>2° x 2°</td>
</tr>
<tr>
<td>ERA-20C</td>
<td>1905-2010</td>
<td>1.5° x 1.5°</td>
</tr>
</tbody>
</table>

As mentioned previously, Era-Interim has been shown to be the most reliable reanalysis when it comes to surface pressure. While, Era-Interim only extends back to 1979, other global reanalyses, which have a longer time frame (back until at least 1958) have been shown to be unreliable in the early period due to few observations in Antarctica. In a study by Bromwich et al. (2007), it is shown that reanalysis data pre-1979 may be much more unreliable compared to post 1979, especially outside of the summer months. While there are still many biases within each reanalysis, there are significantly fewer after 1979 as more satellite data became available in the Southern Hemisphere (Bromwich et al. 2007). Bromwich and Fogt (2004) also show that after 1979, reanalysis data had high skill in all seasons. In particular, high skill has been
shown in this time frame with the pressure over Antarctica with Era-Interim, which is used most frequently in this research.

3.1.6 Reconstructions

One major issue with existing data in reanalyses and observations, is that current observations do not extend far enough back in time (or may not be reliable) in order to make many significant conclusions, especially regarding the uniqueness of changes in the atmospheric circulation and/or their causality. In order to create a more complete and useful dataset, seasonal mean reconstructed pressure data will be utilized for the stations (in Table 3.1), dating back to 1905. These data are generated in a separate part of the broader project.

As discussed in Chapter 2, temperature reconstructions across the continent have been shown to be reliable back to 1957 (Steig et al. 2009; O’Donnell et al. 2011; Nicolas and Bromwich 2014), and have a connection with changes in atmospheric circulation. Although these changes are connected with the pressure pattern, it is difficult to assess any long-term trends with the brevity of the observations. In addition, the causes of these changes are unclear on such a short time scale.

Due to these issues discussed above, a century long pressure reconstruction will be implemented, seasonally and by station. The pressure reconstructions will date back to 1905 at 17 stations across Antarctica, and have been created in a companion project to this work. The reconstructions are created using several midlatitude predictor stations (Fig. 3.2) with pressure data dating back through the 20\textsuperscript{th} century. Midlatitude stations
are given weights, based on the relationship they share with the Antarctic station being reconstructed. The reconstructions are a weighted sum of the predictor stations. Validations tests were performed for each of the reconstructions to find that the reconstructions performed better than the climatological average.

Fig. 3.2. Predictor stations for reconstructions. Extracted from Fogt et al. (2016a).

The results of these reconstructions were assessed by Fogt et al. (2016a). Figure 3.3 shows the best reconstruction trends from each of the stations, along with the 95% confidence intervals. It is found by Fogt et al. (2016a) that the skill of the reconstructions are highest in the summer months. Additionally, the study finds that some regions performed better than others, specifically the Peninsula, due its locations and nearness to the predictor station Orcadas. In the spring months, the skill was lowest, especially in East Antarctica (Fogt et al. 2016a). When compared to the observed pressure trends since 1957, the reconstructions have high skill (Fogt et al. 2016a). The skill is seen to be the highest in all months with the exception of the spring.
The skill in the reconstructions is made clear in scatterplots of cross correlations shown in Fig. 3.4. Instead of by stations, Fig. 3.4 is separated by region, and correlations between stations in regions are shown on the x-axis. From Fogt et al. (2016a), the stations regions are: Western Antarctic Peninsula (Faraday, Rothera); Northern Antarctic Peninsula (Bellingshausen, Esperanza, O’Higgins / Marsh, Marambio); East Antarctica (Casey, Davis, Mawson, Mirny); Dronning Maud Land (Halley, Novolazarevskaya, Syowa); Ross Sea Region (Dumont d’Urville, McMurdo / Scott Base); Antarctic Plateau (Amundsen-Scott, Vostok). Additionally, the y-axis describes the correlations between the observations and the reconstructions, therefore the best reconstructions follow the line x=y in Fig. 3.4. DJF is clearly the season where the reconstructions perform the best, as most of the points fall very closely to the x=y line with high correlations. SON is the season with the least skill in the reconstructions. As discussed previously, locations on the Peninsula perform better (seen in Fig. 3.4) due to their nearness to Orcadas.
Figure 3.3. Trends per decade with 95% confidence intervals for the observations in black. Reconstructions indicated by the red line from 1957-2013. Figure extracted from Fogt et al. (2016a).
Figure 3.4. Scatterplot of cross-correlations between stations grouped geographically from 1957-2013. The x-axis shows the correlations between the stations grouped geographically with the observed data. The y-axis shows the correlations in the reconstructions and observations. Figure extracted from Fogt et al. (2016a).
3.2 Climate modeling data

Several non-coupled climate model simulations are used in order to examine possible forcing mechanisms for the circulation changes seen in the observations and pressure reconstructions. From Chapter 2, it is well known that there is a relationship between changes in sea surface temperatures in the tropics and changes in the general atmospheric circulation at high latitudes (Turner 2004; Fogt et al. 2011). Also, it has been previously shown that the changes in the circulation have been linked with stratospheric ozone depletion, which is also associated with changes in ENSO (Staten 2012). How exactly changes in the sea surface temperatures directly impact long-term forcing trends and how exactly these mechanisms symmetrically and asymmetrically (i.e., locally) impact circulation changes is an active area of research within the Antarctic climate community.

Several climate model experiments are investigated in this thesis research in order to understand how various mechanisms influence Antarctic atmospheric circulation over the 20th century. Each of these is listed in Table 3.3. The model that is used to accomplish this research is the newest version of the Community Atmosphere Model, version 5 (CAM5), developed in the United States by the National Center for Atmospheric Research (NCAR). The CAM5 model is the atmospheric component of the coupled Community Earth System Model version 1 (CESM1). The experiments have prescribed sea surface temperatures within the model, therefore this is a non-coupled, atmosphere only model configuration. In these CAM5 experiments, the ocean is represented as slab mixed layer with an added heat flux term to represent heat transport
within the ocean. The CAM5 model will run with a spatial resolution of $1^\circ \times 1^\circ$. Experiments are analyzed (Table 3.3) in order to isolate potential forcing mechanisms. Some of these variables include radiative forcing, ENSO, and changes in ozone concentration.

The first of the experiments uses the sea surface temperatures with radiative forcing (called All Rad). The ensemble has assigned sea surface temperatures that vary in time, located between $30^\circ$N and $35^\circ$S; the remaining sea surface temperatures and sea ice conditions are prescribed to a climatological repeating seasonal cycle. Radiative forcings also vary with time globally. Radiative forcings for this experiment include both natural and anthropogenic forcings, including CO$_2$ and CH$_4$, volcanic sulfate, solar variations, and anthropogenic aerosols (Neale et al. 2013).

The next experiment is the sea surface temperature only ensemble (called No Rad). In this run, there is fixed radiative forcings from the year 1990. This is similar to experiments by Deser and Philips (2009), which used sea surface temperatures and atmospheric chemical composition, forced by values from 1990. Like in the All Rad experiment, sea surface temperatures are prescribed between $30^\circ$N and $35^\circ$S and the remaining sea surface temperatures are prescribed to a climatological cycle. The only forcing in this experiment are the tropical sea surface temperatures.

The next experiment is called Ozone, where most radiative forcings (with the exception of ozone) is fixed at the 1990 values like in the No Rad experiment. This experiment uses climatological SSTs fixed at 1990 values and has set time-varying ozone calculated in a separate experiment (Marsh et al. 2013). While this experiment has been
done by others before (e.g. Polvani et al. 2011b), the simulations for this study made improvements to those by using the newest model configuration. Specifically, CAM5 now has fewer biases, especially in the location and intensity of the westerlies. Another major improvement is that the Ozone experiment for this research is run across a significantly longer time period (full 20th century) than past research. Past experiments have only investigated small time periods, and therefore are unable to obtain robust (or perhaps spurious) patterns of variability. The Ozone experiment is also useful because it is compared to the sea surface temperature only variation (No Rad). In comparing these two simulations directly, the role of fluctuating ozone levels can be isolated. Finally, the forcing data that are applied are among the most realistic in portraying the true changes in Antarctic ozone.

Table 3.3. Listing of CAM5 experiments used in this thesis.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Forcing</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Rad</td>
<td>SSTs 30°N-35°S + Radiative</td>
<td>1900 - 2014</td>
</tr>
<tr>
<td>(Sea surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperatures +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>radiative forcing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Rad</td>
<td>SSTs 30°N-35°S</td>
<td>1900 - 2014</td>
</tr>
<tr>
<td>(Sea surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperatures only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ozone</td>
<td>Climatological SSTs + WACCM O3</td>
<td>1900 - 2014</td>
</tr>
</tbody>
</table>
All of these simulations were completed at NCAR. Output from the experiments are accessed through an individual account on the NCAR computers, as well as through direct collaborations with several NCAR scientists, namely Drs. Clara Deser, David Schneider, and Adam Phillips.

3.3 Methods

To address the first scientific question, the CAM5 simulations are evaluated, in collaboration with the NCAR scientists identified above. The general performance of CAM5 is assessed to determine that there are no strong biases (differences from observations / reanalyses / reconstructions) that would compromise the integrity of the analysis and findings. Model data from the sea surface temperatures plus radiative forcing (All Rad) simulation (most comparable to the real world) are compared to the reconstructions to understand how well the model compares to reconstructions. It is expected that the model will perform well in capturing the timing, intensity, and global patterns associated with ENSO events, since these are largely dependent on correct ocean variability.

To answer the remaining two research questions, an investigation between the climate model simulations listed in Table 3.3 as well as the historical variability in the pressure reconstructions are performed. Because there is a known relationship between Antarctic circulation changes and temperature changes across the continent, it is important to look at how and why some of these changes might influence the climate variations across the continent. The three simulations are similar, except for the addition
or removal of certain forcing mechanisms. Because of this, comparing the simulations will help to determine how various mechanisms alter the atmospheric circulation.

### 3.3.1 Statistical analysis

To analyze the model simulations, many statistical methods are used in investigating Antarctic pressure variability. In general, climatological data, including temperature, heights, and pressure, have a normal distribution, with a higher concentration near the mean, and less, farther away from the mean. These statistical procedures are all parametric and based on the assumption that the pressure data are approximately normally distributed.

The $t$-test is used in order to understand and assess the significance of results between datasets. Because each year in the data is independent from one another, there are $(n-2)$ degrees of freedom. For the $t$-distribution significant differences between the simulations will be defined as $p < 0.05$ in general. Here, 0.05 will be the threshold in where the null hypothesis ($H_0$) is rejected, and the alternative hypothesis ($H_a$) is accepted. This will allow for meaningful differences between simulations to be highlighted. This type of test is useful as it draws attention of meaningful results, where significant areas in the model results are likely a result of physical relationships.

### 3.3.2 Correlation

For the purpose of this thesis, a two-tailed $t$-test is used to find the significance of correlations. The equation is as follows:
In equation 3.1, $t$ is the $t$-value with $(n-2)$ degrees of freedom, and $r$ is the correlation coefficient. Here it is assumed that ($r=0$) ($H_0$) and the alternative hypothesis ($H_a$) is that $r \neq 0$. This method is useful to analyze the relationship between results from model experiments and comparing them with reanalysis and observations. Additionally, this method is used in assessing the reanalysis, reconstructions, and observations.

3.3.3 Trend analysis

Linear regression techniques are also be used during this project, which assesses temporal changes within the dataset. Regression techniques are useful in assessing linear changes in the pressure pattern in time in years. This can be done through a linear regression, which calculates the slope of a line of best fit. First, the slope of the line is calculated as follows:

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

Equation 3.2
Here, \( x_i \) is the independent variable (time in years) and \( y_i \) is the dependent variable (pressure) and \( \bar{x} \) and \( \bar{y} \) are the sample averages. The slope of the line is \( b \). The following equation is used to calculate the error of the slope:

\[
S_b = \frac{S_y \sqrt{1 - r^2} \sqrt{\frac{n-1}{n-2}}}{S_x \sqrt{n-1}}
\]

*Equation 3.3*

In this equation, \( S_b \) is the error, \( S_y \) is the standard deviation of the dependent variable (\( y \)) and \( S_x \) is the standard deviation of the independent variable (\( x \)). In addition, \( r \) is the correlation coefficient (between time and pressure), and \( n \) is the number of points within the dataset. To find the statistical significance of the slope, the \( t \)-test is used:

\[
t_{n-2} \approx \frac{(b - b_0)}{S_b}
\]

*Equation 3.4*

As before, \( b \) is the slope, \( S_b \) is the error, and \( t_{n-2} \) is the \( t \)-test value with \((n-2)\) degrees of freedom. Additionally, \( b_0 \) is the hypothesized slope in this equation. In this equation, the hypothesized value of the slope \((H_0)\), is \( b_0 = 0 \). The alternative hypothesis \((H_a)\) is assumed to be \( b_0 \neq 0 \). As discussed previously, probability values will need to be assessed in order to determine the significance of the result. For the purpose of this thesis, levels of \( p < 0.05 \) or \( p < 0.01 \) show the probability that the trend is zero (i.e.,
that the null hypothesis is true). In order to find the range in which the 95% of the actual slopes are likely to occur, the confidence intervals are found with the following equitation:

$$CI = b \pm t_{n-2} \times S_b$$

*Equation 3.5*

In this equation, $CI$ is the confidence interval, $b$ is the slope, $t_{n-2}$ is the $t$-value with $(n-2)$ degrees of freedom and a two-tailed probability of $\alpha = 0.05$, and $S_b$ is the error of the slope. From this equation, the range in which each probability is valid is found. For a 95% confidence interval ($p < 0.05$), a range that would encompass 95% of the likely actual values of the slope, based on the estimated slope $b$ in the regression model.
CHAPTER 4: ANTARCTIC 20TH CENTURY PRESSURE TRENDS FROM OBSERVATIONS, REANALYSES, AND RECONSTRUCTIONS

4.1 Introduction

Observation data from the READER archive are examined first in order to gain a full understanding of the pressure trends across the continent in recent decades at the available stations. As discussed before, one issue with only using the observations is that they are over a very short time scale and are not complete spatially. Because of this problem, other sources of data (i.e., reanalyses and reconstructions) are examined for trends over a longer time scale and over the entire continent. Of these other data sources, reconstruction trends at each station are first examined over the course of the entire 20th century. Fogt et al. (2016) deemed these reconstructions (dating back to 1905) to be the best and most skillful at each of the stations. Additionally, reanalysis trends from Era-Interim, Era-20C, 20CR, and CFSR are also examined to have a more complete understanding of these trends spatially. Prior to investigating the pressure trends for each of the reanalyses, the skill of each is assessed in comparison with available observations. The assessment of the reanalyses is done by taking the latitude and longitude of each station and extracting seasonal pressure averages at each of the locations from the reanalyses and comparing these to the seasonal observations. This is done in order to gain a full understanding of how trustworthy the pressure trends from the reanalysis are.
4.2 Observation trends

Table 4.1 shows the observed trends from 1957-2014, which is the full period for the observations. Trends significantly different from zero at \( p < 0.05 \) over this period are indicated by the (*). Figure 4.1a and Fig. 4.1b also show observed trends at each station by season spatially. Similar to before, significant trends of \( p < 0.05 \) are indicated by an (*) after the station name.

Table 4.1. Observed trends (hPa per decade) by season and station from 1957-2014 with 95% confidence interval. Significant trends \( (p < 0.05) \) indicated by (*).

<table>
<thead>
<tr>
<th>Observations 1957-2014</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>DJF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellingshausen</td>
<td>0.34 ± 0.47</td>
<td>-0.27 ± 0.69</td>
<td>0.20 ± 0.51</td>
<td>-0.43 ± 0.44</td>
</tr>
<tr>
<td>Casey</td>
<td>-0.35 ± 0.49</td>
<td>-0.17 ± 0.66</td>
<td>0.32 ± 0.45</td>
<td>-0.68 ± 0.49*</td>
</tr>
<tr>
<td>Davis</td>
<td>-0.38 ± 0.41</td>
<td>-0.55 ± 0.58</td>
<td>0.11 ± 0.43</td>
<td>-0.55 ± 0.49*</td>
</tr>
<tr>
<td>Dumont</td>
<td>-0.09 ± 0.47</td>
<td>-0.20 ± 0.54</td>
<td>0.21 ± 0.42</td>
<td>-0.43 ± 0.45</td>
</tr>
<tr>
<td>Esperanza</td>
<td>0.23 ± 0.45</td>
<td>-0.15 ± 0.62</td>
<td>0.08 ± 0.61</td>
<td>-0.42 ± 0.52</td>
</tr>
<tr>
<td>Faraday</td>
<td>0.16 ± 0.50</td>
<td>-0.44 ± 0.60</td>
<td>0.11 ± 0.52</td>
<td>-0.61 ± 0.46*</td>
</tr>
<tr>
<td>Halley</td>
<td>-0.25 ± 0.42</td>
<td>-0.29 ± 0.49</td>
<td>0.18 ± 0.45</td>
<td>-0.86 ± 0.50*</td>
</tr>
<tr>
<td>Marambio</td>
<td>0.07 ± 0.69</td>
<td>-0.02 ± 0.83</td>
<td>0.16 ± 0.79</td>
<td>-0.89 ± 0.69*</td>
</tr>
<tr>
<td>Mawson</td>
<td>-0.37 ± 0.37</td>
<td>-0.26 ± 0.51</td>
<td>0.14 ± 0.39</td>
<td>-0.61 ± 0.45*</td>
</tr>
<tr>
<td>Scott Base</td>
<td>-0.67 ± 0.55*</td>
<td>-0.20 ± 0.68</td>
<td>0.02 ± 0.58</td>
<td>-0.63 ± 0.67</td>
</tr>
<tr>
<td>Mirny</td>
<td>-0.74 ± 0.41*</td>
<td>-0.80 ± 0.55*</td>
<td>-0.10 ± 0.41</td>
<td>-0.84 ± 0.44*</td>
</tr>
<tr>
<td>Novolazarevskaya</td>
<td>-0.59 ± 0.53*</td>
<td>-0.65 ± 0.59*</td>
<td>0.16 ± 0.48</td>
<td>-1.19 ± 0.54*</td>
</tr>
<tr>
<td>Rothera</td>
<td>-0.01 ± 0.62</td>
<td>-0.49 ± 0.66</td>
<td>0.18 ± 0.61</td>
<td>-0.78 ± 0.57*</td>
</tr>
<tr>
<td>Syowa</td>
<td>-0.32 ± 0.51</td>
<td>0.04 ± 0.59</td>
<td>0.35 ± 0.48</td>
<td>-0.74 ± 0.46*</td>
</tr>
<tr>
<td>O'Higgins</td>
<td>-0.18 ± 0.60</td>
<td>-0.23 ± 0.78</td>
<td>0.07 ± 0.73</td>
<td>-0.88 ± 0.54*</td>
</tr>
<tr>
<td>Amundsen-Scott</td>
<td>-0.35 ± 0.41</td>
<td>-0.04 ± 0.52</td>
<td>0.44 ± 0.40*</td>
<td>-0.45 ± 0.44*</td>
</tr>
<tr>
<td>Vostok</td>
<td>-0.28 ± 0.52</td>
<td>-0.07 ± 0.63</td>
<td>0.64 ± 0.46*</td>
<td>-0.34 ± 0.49</td>
</tr>
</tbody>
</table>
Figure 4.1a. Observed MSLP trends in hPa per decade 1957-2014 for DJF and MAM by station. Significant trends at $p < 0.05$ indicated by (*) after station name.
Figure 4.1b. Observed MSLP trends in hPa per decade 1957-2014 for JJA and SON by station. Significant trends at $p < 0.05$ indicated by (*) after station name.
The observed trends during DJF range from \(-1.19 \pm 0.54\) hPa per decade at Novolazarevskaya to \(-0.34 \pm 0.49\) hPa per decade at Vostok. Generally, observed trends are lower in East Antarctica in DJF. DJF is by far the season that has the most statistically significant trends (all of which are negative) for 1957-2014. During MAM, \(0.34 \pm 0.47\) hPa per decade is the highest trend at Bellingshausen, and although negative trends are still seen in this season, trends are weaker than DJF with fewer significant trends. Trends in MAM (March, April, May) are more positive across the Peninsula, however, trends are more negative across East Antarctica, made clear in Fig. 4.1a. For JJA, trends are generally more negative compared to MAM, however there are few significant trends with the exception of Mirny and Novolazarevskaya. Trends in SON are generally positive overall, which is in contrast to the other seasons; however, the only station which has a significant trend at \(p < 0.05\) is Vostok.

The trends during the later period of observations, from 1979-2014, are shown in Table 4.2 and significant trends of \(p < 0.05\) are indicated by an (*). This period is very similar to the full period, with one difference being in MAM, which shows negative trends at all stations during 1979-2014 compared to the longer time period. Another notable difference is that many of the trends switch signs in JJA; over the full period, they are mainly negative, but over the latter period, they are mainly positive. This suggests multi-decadal scale variability in the winter in Antarctic pressure, as noted by Fogt et al. (2016b). In contrast, the trends in DJF are significant across much of East Antarctica like in the full period of observed trends. For a spatial comparison, Fig. 4.2a
and Fig. 4.2b show observed trends at each station by season. Similar to before, significant trends of $p < 0.05$ are indicated by an (*) after the station name.

Table 4.2. Observed trends (hPa per decade) by season and station from 1979-2014 with the 95% confidence interval. Significant trends at ($p < 0.05$) indicated by (*).

<table>
<thead>
<tr>
<th>1979-2014 Observations</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>DJF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellingshausen</td>
<td>-0.80 ± 0.81</td>
<td>-0.26 ± 1.20</td>
<td>-0.12 ± 0.96</td>
<td>-0.77 ± 0.90</td>
</tr>
<tr>
<td>Casey</td>
<td>-0.28 ± 1.00</td>
<td>0.65 ± 1.22</td>
<td>0.95 ± 0.82*</td>
<td>-1.03 ± 0.87*</td>
</tr>
<tr>
<td>Davis</td>
<td>-0.28 ± 0.86</td>
<td>0.27 ± 1.12</td>
<td>0.70 ± 0.87</td>
<td>-1.13 ± 0.89*</td>
</tr>
<tr>
<td>Dumont</td>
<td>-0.03 ± 0.95</td>
<td>0.04 ± 1.22</td>
<td>0.92 ± 0.85*</td>
<td>-1.07 ± 0.80*</td>
</tr>
<tr>
<td>Esperanza</td>
<td>-0.15 ± 0.92</td>
<td>0.61 ± 1.25</td>
<td>0.30 ± 1.40</td>
<td>-0.34 ± 1.11</td>
</tr>
<tr>
<td>Faraday</td>
<td>-0.96 ± 0.99</td>
<td>-0.28 ± 1.35</td>
<td>-0.17 ± 1.12</td>
<td>-0.69 ± 1.01</td>
</tr>
<tr>
<td>Halley</td>
<td>-0.18 ± 0.95</td>
<td>0.24 ± 0.92</td>
<td>0.43 ± 1.00</td>
<td>-1.50 ± 1.03*</td>
</tr>
<tr>
<td>Marambio</td>
<td>-0.39 ± 0.87</td>
<td>0.41 ± 1.12</td>
<td>0.28 ± 1.20</td>
<td>-0.83 ± 1.03</td>
</tr>
<tr>
<td>Mawson</td>
<td>-0.37 ± 0.79</td>
<td>0.39 ± 1.15</td>
<td>0.83 ± 0.85</td>
<td>-0.94 ± 0.90*</td>
</tr>
<tr>
<td>Scott Base</td>
<td>-0.72 ± 1.00</td>
<td>0.30 ± 1.42</td>
<td>0.04 ± 1.09</td>
<td>-1.67 ± 1.22*</td>
</tr>
<tr>
<td>Mirny</td>
<td>-0.34 ± 0.91</td>
<td>0.38 ± 1.05</td>
<td>0.69 ± 0.88</td>
<td>-1.05 ± 0.87*</td>
</tr>
<tr>
<td>Novolazarevskaya</td>
<td>-0.72 ± 0.96</td>
<td>-0.47 ± 1.14</td>
<td>0.49 ± 0.96</td>
<td>-1.58 ± 0.92*</td>
</tr>
<tr>
<td>Rothera</td>
<td>-0.99 ± 1.14</td>
<td>-0.14 ± 1.47</td>
<td>-0.20 ± 1.29</td>
<td>-0.73 ± 1.09</td>
</tr>
<tr>
<td>Syowa</td>
<td>-0.32 ± 1.00</td>
<td>0.34 ± 1.18</td>
<td>0.81 ± 0.95</td>
<td>-1.20 ± 0.91*</td>
</tr>
<tr>
<td>O’Higgins</td>
<td>-1.06 ± 0.91*</td>
<td>-0.43 ± 1.40</td>
<td>-0.24 ± 1.24</td>
<td>-0.85 ± 0.96</td>
</tr>
<tr>
<td>Amundsen-Scott</td>
<td>-0.35 ± 0.82</td>
<td>0.55 ± 1.09</td>
<td>0.90 ± 0.83*</td>
<td>-0.81 ± 0.86</td>
</tr>
<tr>
<td>Vostok</td>
<td>-0.37 ± 1.01</td>
<td>0.18 ± 1.38</td>
<td>1.03 ± 0.98*</td>
<td>-0.88 ± 0.93</td>
</tr>
</tbody>
</table>
Figure 4.2a. Observed MSLP trends in hPa per decade 1979-2014 for DJF and MAM by station. Significant trends at $p < 0.05$ indicated by (*) after station name.
Figure 4.2b. Observed MSLP trends in hPa per decade 1979-2014 for JJA and SON by station. Significant trends at $p < 0.05$ indicated by (*) after station name.
From these two periods of observations, it is clear that the later period (1979-2014) has many more positive trends during SON and JJA and more negative trends during DJF and MAM in East Antarctica. Additionally, there are many consistencies between the two time periods. Significant trends during DJF are very similar throughout, with many more significant trends across East Antarctica. Also, while trends remain very much negative during both time periods during DJF, there is a notable difference between East Antarctica and the Peninsula, especially during the later period, with trends being somewhat less negative over the Peninsula compared to East Antarctica during this time.

4.3 Reconstructions

While the observed pressure trends discussed above are very important in the understanding of Antarctic pressure change, they provide somewhat limited information because of the shortness of the observation length. Because of this, both reanalyses and reconstructions are utilized to get a more complete understanding of pressure variability across the continent in the last century. While some discussion was given to the performance of the reconstructions in Chapter 3, a few stations will be examined in further detail here. Amundsen-Scott, Casey, and Bellingshausen will be examined because they are geographically distant from one another, and therefore represent different regional aspects of Antarctic pressure variability throughout the 20\textsuperscript{th} century. Each of the three chosen stations represents a different region of the continent. Amundsen-Scott is used to represent the Antarctic interior, while Casey represents East Antarctica, and Bellingshausen represents the Antarctic Peninsula.
Figure 4.3 shows the time series of pressure at Amundsen-Scott with the century long reconstruction and the observations. The reconstructions are very similar to the observations, especially during DJF. The other seasons are quite similar as well, with few distinct differences between the two. Before 1957, the reconstructions seem to match the later period reconstructions and the observations in pressure range and variability, showing consistency in pressure through time at this station. Pressure range is notable seasonally at this station, with pressure consistently higher in DJF and MAM than in JJA and SON. Additionally, there is less year to year pressure variability at Amundsen-Scott compared to the other two stations, reflecting its location in the interior of Antarctica, and therefore less influence by the oceans and passing cyclones.

Figure 4.4 shows the time series for Bellingshausen. Similar to Amundsen-Scott, DJF is the season which the reconstructions and the observations match the best. For Bellingshausen, SON stands out as the season that matches the least well. Interannual pressure variations at this station are different from Amundsen-Scott, with much more dramatic short-term variability seen in both the observations and the reconstructions through the entire century; there are a few notable years with dramatic change (e.g., DJF 1925-1926).
Figure 4.3. Surface pressure time series at Amundsen-Scott for reconstructions and observations from 1905-2010 by season.
Figure 4.4. MSLP time series at Bellingshausen for reconstructions and observations from 1905-2010 by season.
Finally, for Casey, the time series with reconstructions and observations are shown in Fig. 4.5. Once again, similar to the other stations, reconstructions in DJF perform the best at Casey. Unlike the other stations, MAM performs poorly at Casey, particularly during the 1990s. Similar to Bellingshausen, there is quite a bit of year to year variability at Casey in both the reconstructions and the observations; the winter season displays especially strong interannual variability in the observations, which is dampened in the reconstruction.

Running trends are assessed for each of these three stations. Running trends are important because they show how longer-term pressure trends are changing within the entire century. Thirty-year trends are used because this is the period that is long enough to smooth out interannual variability. From the running trends, the overall change through the century can be seen. As with the time series before, Amundsen-Scott, Bellingshausen, and Casey are assessed.
Figure 4.5. MSLP time series at Casey for reconstructions and observations from 1905-2010 by season.
Figure 4.6 shows the 30-year running trends per decade at Amundsen-Scott for the reconstructions and the observations. For Amundsen-Scott, the observed and reconstructed trends are quite similar for DJF, MAM, and JJA. SON is somewhat different with slightly higher positive observed trends through the 1970s. Looking at the overall changes in the trend magnitudes at Amundsen-Scott, there seems to be consistency in the 30-year trends in earlier years of the reconstructions for MAM, JJA, and SON, with increasing/more positive trends during the 1920s and 1930s and then falling/becoming more negative again. The exception is for DJF, which seems to have a more steady decline through the full period. For 30-year running trends in the later years at Amundsen-Scott, DJF and MAM have steadily falling trends, while trends in SON increase and trends in JJA remain fairly steady or increase slightly.

For, Bellingshausen, MAM is the season where the trends per decade of the reconstructions are the closest to the trends from the observations (Fig. 4.7). One thing to note at Bellingshausen is that for all other seasons, observed trends are somewhat more negative than the reconstructions, which differs from Amundsen-Scott (especially in DJF). For the full period trends at Bellingshausen, DJF and JJA (and SON with the exception of some negative trends in the 1930s and 1940s) are fairly steady until the running trends starting in later years. For MAM, trends increase sharply in the 1920s and quickly fall and become steadier during the 1930s and 1940s. During the later period, decreasing trends are seen during DJF and MAM, while increasing trends are seen during JJA and SON.
Figure 4.6. 30-year running trends in hPa per decade at Amundsen-Scott by season for reconstructions and observations. X-axis is starting year of 30-year period.
Figure 4.7. 30-year running trends in hPa per decade at Bellingshausen by season for reconstructions and observations. X-axis is starting year of 30-year period.
Figure 4.8 graphs the 30-year running trends per decade at Casey with the reconstructions and observations. When comparing the trends at Casey, results are quite similar to the trend comparison at Amundsen-Scott, with DJF being the season where the observed and reconstruction trends most closely match. Additionally, SON is the season where the trends are most different, with the observed trends being slightly more positive than the reconstructions. During DJF, running trends at Casey are relatively steady through the early period, and then begin to steadily decrease and become negative after 1950. For the other three seasons, there is a similar pattern in the trends at Casey compared to Amundsen-Scott. Trends increase and become more positive through the 1920s and 1930s then fall again. Trends in JJA and SON increase after the 1920s, while trends in MAM fall slightly at first, then begin to increase or become steadier toward the end of the period.

Based on the information presented at these three stations and discussed in previous chapters, it is clear that the reconstructions perform well through time, especially at representing the overall trends. DJF is the season that performs the best for the reconstructions, but other seasons also perform well, especially at Bellingshausen where the trends are best represented during MAM. Despite some differences in trends at each station, all three stations have trends that are becoming more strongly negative in the last few decades during DJF. Additionally, there seems to be trends that are becoming more positive at all three stations during JJA and SON, which reflects in particular the sign change in the trends in Tables 4.1 and 4.2 during JJA. MAM is more variable between the three stations with consistent decreasing trends at Bellingshausen
Figure 4.8. 30-year running trends in hPa per decade at Casey by season for reconstructions and observations. X-axis is starting year of 30-year period.
during MAM in recent decades, but more steady trends at Casey recently. Amundsen-Scott initially begins with deceasing pressures after 1950 but then begins to increase pressure again after the 1970s during MAM. In terms of the trends in the early 20th century, there is an increase and then decrease in trends in MAM, JJA, and SON at all three stations during the 1920s and 1930s. The highest trends during this period are at Casey during JJA.

4.4 Assessment of reanalyses

In addition to the reconstructions, the reanalyses are compared with the observations in order to find how similar each reanalysis is to the observations, and how they might therefore be interpreted to understand the spatial pattern of trends across Antarctica (i.e., at regions away from or in between the observations). Correlations, biases, and root mean square errors are examined for each reanalysis with the observations. To compare the reanalyses with the observations, the latitude and longitude of each station is used to find the nearest grid point within the model, which outputs the pressure data for each point by month. The pressures are then averaged to find the seasonal reanalysis average and then compared with the observed seasonal average. Figure 4.9 shows the comparison of the reanalyses with the observations.

In the first column of Fig. 4.9, correlations are shown seasonally for each of the reanalyses. From Fig. 4.9, it can be seen that in general, Era-Interim correlations (during 1979-2013) are relatively high throughout all the stations. There are a few exceptions however at several stations, specifically at Esperanza, O’Higgins, and Vostok, with
correlations as low as 0.80 at Esperanza during SON. In general, Era-Interim has higher
correlations than the other reanalyses in all four seasons and at all stations. DJF is by far
the best season for the correlations in all reanalyses, with SON exhibiting the worst
correlations, especially for Era-20C and 20CR. In general, correlation values are lower
for Era-20C and 20CR (which are compared to observations from 1957-2013), compared
to Era-Interim with several stations having correlations around 0.70 during SON. SON
has the worst correlations overall with the 20CR reanalysis, although the lowest
correlation (0.29) is during MAM at Amundsen-Scott. Amundsen-Scott and Vostok
stations exhibit similar problems in all reanalyses, which have very low
correlations. Correlations for CFSR are for the most part consistent throughout. Most
stations are over 0.90 with JJA at Novolazarevskaya being the only season and station
below 0.90. Correlation values for CFSR are much higher overall compared to 20CR and
Era-20C. Values are quite comparable to Era-Interim. One thing to note is that CFSR is
only compared from 1979-2000 and only MSLP is available for CFSR, therefore Vostok
and Amundsen-Scott will not be compared.

One major exception, however, is at Amundsen-Scott in the 20CR, which unlike
Vostok has very low correlations, but biases and RMSE values closer to zero. Given the
lower performance at Amundsen-Scott, a time series of pressure from 20CR is compared
with the observations in Fig. 4.10. Most notably, in DJF the observations are consistently
higher than the reanalysis, while in the three other seasons there is much more variability.
This extreme variability in the reanalysis is not consistent with observations, and it is
likely that there may be an error in 20CR reanalysis at this station specifically; however
further investigation would be required to confirm this inconsistency, and therefore 20CR data at Amundsen-Scott will not be used here.

Next, biases for each of the reanalyses are studied. Here, positive biases mean that the reanalysis average is higher than the average of the observation, and vice versa. Figure 4.9 shows that biases (middle column) are small and near zero at many stations Era-Interim. Like the correlations, biases are the best/lowest in DJF and the worst/highest in SON. Biases remain low and positive across most stations and most seasons, however 20CR consistently has larger biases than the other reanalyses at all stations. Vostok is the station that performs the worst in Era-Interim, 20CR, and Era-20C with higher positive biases in Era-20C and Era-Interim and very large negative biases in 20CR. These biases could be related to difference in model elevations discussed previously. The very high negative values at Vostok in 20CR indicate that the average of the observations are much higher than the average of 20CR. Because this station has much stronger biases than the rest, it is looked at more specifically in Fig. 4.11. The observations, 20CR, Era-Interim, and Era-20C are all shown as a time series, and large differences between datasets are noticeable. Differences in elevation in the model compared with the real world could account for the differences in pressure at these stations.
Figure 4.9. Correlations, biases, and root mean square errors by season and station for each of the reanalyses. The period of comparison with observations is 1979-2013 for Era-Interim, 1979-2000 for CFSR, 1975-2011 for 20CR, and 1957-2010 for Era-20C.
Figure 4.10. Time series of surface pressure from 1957-2010 at Amundsen-Scott for 20CR compared to observations by season.
Figure 4.11. Time series of surface pressure from 1979-2013 at Vostok for Era-Interim, 20CR, and Era-20C compared to observations by season.
Finally, root mean square error is examined for each of the reanalyses. Root mean square error (RMSE) is used to calculate how close values from the reanalysis are to observed values at each time and is the sum of square deviations which combines errors from both correlations and biases into a single statistic. Small numbers indicate that values are relatively close to observations and vice versa.

It can be seen in Fig. 4.9, that for the most part RMSE values for Era-Interim are low for each station with the exception of Vostok once again. In all seasons Vostok has much higher RMSE values than the other stations. RMSE for Era-20C is much higher than for Era-Interim. RMSE values for Era-20C are highest at Amundsen-Scott, which is likely related to the possible errors in model elevation discussed previously. RMSE for 20CR is the highest of all the reanalyses. Values reach as high as 15 hPa for Vostok, with Mawson being the next highest station around 5 hPa for 20CR. Overall, 20CR is the highest at most stations, especially at Vostok, which is much higher than the other stations. Finally, CFSR shows good RMSE values that are relatively low, with the highest station being Casey during MAM, which is even somewhat lower than Era-Interim. One thing to keep in mind about the CFSR reanalysis is that it only has MSLP and therefore does not have all the stations. Also in this comparison, CFSR only dates from 1979-2000, which is only 22 years, compared to Era-Interim, which is 35 years and Era-20C and 20C, which are a century long.
4.5 Full century comparisons

Because three datasets extend back through the 20\textsuperscript{th} century (reconstructions, 20CR, and Era-20C), they can be compared to one another, and trends can be discussed. The three stations that were examined for the reconstructions will also be compared here for all data over the century. Because of the problems discussed previously with Amundsen-Scott station in 20CR, this reanalysis will be left out of the comparison at Amundsen-Scott.

Figure 4.12 shows the time series at Amundsen-Scott, with the century long reanalyses (only Era-20C in this case), observations, and reconstructions. From Fig. 4.12, Era-20C is consistently lower than observations and reconstructions, and Era-20C is much more variable than the reconstructions, especially during the earlier period. Additionally, the surface pressure from Era-20C is much lower than the observations and reconstructions. This is probably due to a higher model elevation in Era-20C than in the real world, resulting in a low surface pressure bias (reflected in Fig. 4.9). At this station, Era-20C also appears to be more variable than the reconstructions from year to year, which may reflect the underestimation of the internal variability in the reconstruction or a problem with Era-20C.
Figure 4.12. Surface pressure time series at Amundsen-Scott from 1905-2010 by season. (20CR excluded because of errors at Amundsen-Scott station).
Figure 4.13 shows the time series for Bellingshausen. All reanalyses and reconstructions perform very well during the later period of the 20\textsuperscript{th} century, but are very different from one another during the earlier half. In the earlier period, Era-20C and 20CR are consistently higher than the reconstruction. Bellingshausen also has much more year to year variability in pressure compared to other stations, which is consistent in all datasets and through the entire century. There are also some notable differences between the reconstructions and the reanalyses in DJF during the 1920s when the reconstructions are approximately 10 hPa lower than the other reanalyses. Based on the reanalyses, MSLP was higher in the earlier period and is consistently lower in the later period in all seasons at this station. From the reconstructions, however, this is not the case, which shows consistency in pressure range throughout the period. For the reconstructions, MSLP ranges from 1005 hPa to 980 hPa and there is not much change in range between seasons. Given the high reconstruction performance at this station across all seasons, it is suspected that the changes in the pressure range in the reanalyses are an artifact of them converging to observations during the later part of the 20\textsuperscript{th} century; the similar pressure ranges in the reconstruction tell the more likely story of historical pressure variability at this site throughout the 20\textsuperscript{th} century.
Figure 4.13. MSLP time series at Bellingshausen from 1905-2010 by season.
The time series for Casey is shown in Fig. 4.14. In the later part of the 20th century, reconstructions are very similar to the observations. Additionally, the reanalyses, reconstructions, and observations are very similar to one another during DJF, but vary more in the other seasons. Like at Amundsen-Scott and Bellingshausen, Era-20C and 20CR are higher in all seasons than the reconstructions during both the early and late parts of the 20th century in MAM, JJA, and SON. The higher pressure in the reanalysis likely reflects the smoother topography in the models underlying reanalysis with lower surface elevations and hence higher pressure in the models than in reality. Casey has similar characteristics to Bellingshausen with sharp differences between the early period and the later period. In the early period reconstructions and reanalyses differ up to 10 hPa at times, like at Bellingshausen. Additionally, decreasing pressure values are seen in the reanalyses over the entire century, which is different from the reconstructions showing a more consistent pressure range. It is likely that this is an artificial trend in the reanalysis as well, commonly seen as they converge to observations when they become available (Bromwich and Fogt 2004; Bromwich et al. 2007).
Figure 4.14. MSLP time series at Casey from 1905-2010 by season.
Figures 4.15 – 4.17 show running trends per decade at each station for Era-20C, 20CR, and the reconstructions for each station individually. Figure 4.15 shows the trends at Amundsen-Scott. In all four seasons the observations, reconstructions, and Era-20C are very similar in the later period of the 20th century, however there are more differences in the early period. In general, trends tend to be negative and greater for Era-20C compared with the reconstructions in the early period. Running trends at Amundsen-Scott with the reanalyses tell a similar story to the discussion of the running trends with only the reconstructions. Differences, however, can be seen in the earlier period during DJF and MAM, which show a time of decreasing trends in the early period in Era-20C, which is not seen in the reconstructions; again this most likely reflects the artificial trends in the reanalysis discussed previously.
Figure 4.15. 30-year running trends in hPa per decade at Amundsen-Scott by season. (20CR is excluded because of errors at Amundsen-Scott stations). X-axis is starting year of 30-year period.
Figure 4.16 shows the running trends per decade at Bellingshausen. These trends are much more similar than those at Amundsen-Scott across various products. DJF and MAM are the seasons that the three are nearest one another, while SON is the least similar. The overall pattern of the running trends show a peak in the 1950s to 1960s in both DJF and MAM and decreases in trends before and after in all datasets. A minimum is seen in the trends around 1940 in MAM, while DJF has significant differences between the three datasets in the early period. JJA shows decreasing trends after 1950 and then an increase after 1970 in all datasets. Additionally, there is a minimum in trends in both reanalyses during the 1930s and 1940s but trends are steadier in the reconstructions; the reanalyses exaggerate the negative trends as they converge to observations beginning in the late 1940s in this region. There is a significant amount of variability between the datasets in the early period in SON. All four however agree well in the increasing trends after 1970.

Finally, running trends per decade are shown for Casey in Fig. 4.17. Like Bellingshausen, DJF is the most similar, especially during the latter part. MAM is quite similar at Casey as well, even in the early period of the 20th century. Like the other stations, SON is the least similar at Casey, perhaps reflecting the lower reconstruction skill in this season. Compared to the other two stations, running trends between the reanalyses and reconstructions are most different at Casey. DJF has the best agreement between the reanalyses, where trends decrease through the early period, increase in the middle, then decrease again in both the reanalyses. In the reconstructions, trends are steady through the later period then decreasing trends begin, which is similar in all
datasets. For MAM trends are similar in all datasets in the later period of the 20th century, however during the early period, times when the trends are most positive, trends are quite different between the three datasets. JJA and SON tell a similar story with trends from Era-20C decreasing through about 1920, then increasing through about 1940 in both seasons. Additionally, Era-20C reaches another minimum around 1965 before increasing again at the end of the period in JJA. SON shows a more variable trend. In these two seasons, the reconstructions reach a peak in positive trends around 1930, then decrease and become steady through about 1960 where they both begin to increase again. Finally for 20CR, in JJA, trends decrease slightly through the early period, reaching a minimum in about 1950 and then begin to increase again after that. Trends in SON for 20CR are relatively steady throughout until about 1970 where they begin to increase like the other datasets. It is likely that the reanalyses are producing an artificial trend here since there are not currently any known mechanisms to produce such varying trends in Antarctic pressure during a time when external forcing is quite weak (Fogt et al. 2016b).
Figure 4.16. 30-year running trends in hPa per decade at Bellingshausen by season. X-axis is starting year of 30-year period.
Figure 4.17. 30-year running trends in hPa per decade at Casey by season. X-axis is starting year of 30-year period.
4.6 Spatial trends of reanalyses

Based on the assessment above, it has been shown how well each of the reanalyses compares with the observations as well as reconstructions. Now, trends from each of the reanalyses can be discussed. Era-Interim will be the first reanalysis to be discussed. Fig. 4.18 shows the spatial pressure trends from Era-Interim across the continent from 1979-2014 per decade, separated seasonally. In this figure, significance is shaded ($p < 0.10; p < 0.05; p < 0.01$) and trends are contoured every 0.1 hPa per decade. The most notable trends over Antarctica are in DJF, which has significant negative trends at $p < 0.05$ for most of the continent. The season with the least significance is JJA with no significant trends across the continent. This is shown in order to visually compare the pressure trends to the other reanalyses which will be shown later in this section (see Appendix for station specific plots of trends per decade for each reanalysis at station locations), especially since this reanalysis performs the highest consistently (Fig. 4.9; Bracegirdle and Marshall 2012).
Figure 4.18. Era-Interim MSLP trends (1979-2014) by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).
Other reanalyses are also assessed in this chapter in order to gain a fuller understanding of how well they represent Antarctic trends. The next reanalysis that will be discussed is the CFSR reanalysis because it has a shorter time frame, beginning in 1979 like Era-Interim, so the dates that will be compared will be 1979-2000. The spatial pressure trends are shown in Fig. 4.19. Few significant trends are seen in MAM in CFSR. JJA, however, shows positive trends with significance of $p < 0.05$ for a large portion of East Antarctica, which is unique to this reanalysis, and therefore not reliable. Both SON and DJF are most similar to Era-Interim with CFSR showing positive significant trends over the eastern part of the continent in SON and negative trends over much of the continent in DJF. The exception is that negative significant trends are confined mostly to the Peninsula region for CFSR in DJF, whereas in Era-Interim, significant negative trends are seen across the entire continent.
Figure. 4.19. CFSR MSLP trends (1979-2000) by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).
Trends for CFSR are quite different from the observations with values being much lower for both DJF and MAM. There are some similarities with significant trends with CFSR showing significant trends across East Antarctica during DJF, which is comparable to the observations. Additionally, significant trends are seen over many stations in East Antarctica in MAM and at Esperanza on the Peninsula during both seasons. For JJA and SON, trends are more positive for CFSR, which is comparable to the observations, with no significant trends during these two seasons.

The overall trends of Era-20C are shown in Fig. 4.20 from 1979-2010 in order to compare to other reanalyses. Similar to before, significance is shaded seasonally and trends per decade are contoured. As before, DJF is the most significant season for Era-20C, though not as high over the continent compared to Era-Interim. Both Era-Interim and Era-20C have few significant trends during JJA for this time period over the continent, however one notable difference is the opposite trends near Syowa station. During MAM, few significant trends exist, with the exception of some negative trends near the Peninsula. No significant trends exist in SON, which is different than Era-Interim, which shows positive significant trends in this season. DJF shows negative trends across the continent, with significant negative trends concentrated around East Antarctic and in the Weddell Sea region.

Since Era-20C extends back farther than Era-Interim, trends are also assessed over a longer time period. Figure 4.21 shows the trends for Era-20C from 1957-2010. More significant negative trends are seen around the continent, particularly around the coast while there are only significant negative trends on the interior of the continent in
DJF. There are many significant trends seen in East Antarctica in all four seasons. There are also significant trends across the Peninsula in DJF, JJA, and SON. Compared to other reanalyses, Era-20C has fewer positive trends in all seasons over this time period.

The final reanalysis that will be examined is 20CR. The 20CR reanalysis contains data from 1905-2011, therefore it will be assessed over both 1979-2011 and 1957-2011 like Era-20C. Figure 4.22 shows 20CR trends per decade and seasonally over the time period of 1979-2011. Trends in MAM and JJA match well between 20CR and Era-Interim, with no significant trends seen across the continent in JJA, and positive but insignificant trends across the continent in SON. SON is slightly different than Era-Interim and Era-20C, with more negative significant trends in the Amundsen and Bellingshausen Seas for 20CR. While trends remained negative, fewer significant trends are seen over the continent in DJF in 20CR compared with Era-Interim. However, significant trends of $p < 0.01$ are seen in 20CR in the Amundsen and Bellingshausen Seas, where Era-Interim and Era-20C show significant trends ($p < 0.01$) farther east near the Weddell Sea. Additionally, positive trends are seen over a portion of the continent in East Antarctica in SON.
Figure 4.20. Era-20C MSLP trends (1979-2010) by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10$; $p < 0.05$; $p < 0.01$).
Figure. 4.21. Era-20C MSLP trends (1957-2010) by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).
Figure. 4.22. 20CR MSLP trends (1979-2011) by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).
Figure 4.23 looks at 20CR on a longer time scale from 1957-2011 (see Appendix for stations specific trends). In 20CR, significant trends are seen in all four seasons across East Antarctica. DJF and MAM are the seasons with the most significant trends over the continent. These seasons also have the most significant positive trends seen at higher latitudes, and the general pattern of the trends projects onto the positive polarity of the SAM. In both seasons, many of the significant negative trends are concentrated in the Amundsen and Bellingshausen Seas and in West Antarctica. Significant trends are also seen around the coast of East Antarctica in these seasons as well. For JJA and SON, most of the negative significant trends are concentrated in the Southern Ocean, specifically in the Amundsen and Bellingshausen Seas in SON.

4.7 Antarctic station pressure trend summary

Bringing all these trends together and as a summary of what is currently known about the Antarctic pressure trends from a variety of sources, Tables 4.3-4.6 show the trends and 95% confidence at each station and for each reanalysis, reconstruction, or observations. Each of these tables is separated by season. First, Table 4.3 shows the trends and 95% confidence intervals for the data during MAM. Additionally, significant trends at $p < 0.05$ are indicated by the (*). Overall for MAM, there are more significant trends for the longer period of observations compared to after 1979. The reconstructions are very similar to the observations in this season and have more positive trends on the Peninsula and more significant negative trends in East Antarctica. Additionally, trends in CFSR are much larger than all other data. Looking regionally, trend differences are
notable in different datasets. CFSR shows the most regional differences with trends on 
the Peninsula being less negative than trends across East Antarctica in MAM. 20CR also 
shows more negative trends in East Antarctica but positive trends on the Peninsula. Era- 
20C shows consistent negative trends throughout MAM at all stations with the exception 
of the stations on the interior (Amundsen-Scott and Vostok).

Table 4.4 compares the datasets during JJA. Fewer significant trends exist for 
JJA compared to MAM. For the observations, Novolazarevskaya, Rothera, and Mirny 
are the only stations with significant trends during either of the time periods. Trends are 
negative across the observations from 1957-2014, but become more positive from 1979- 
2014. Era-20C also has a large number of significant trends, which is different than the 
observations here, and is also seen throughout other seasons. Regionally, for JJA, 
negative trends are consistent across the Peninsula for Era-Interim, but positive trends are 
seen across East Antarctica. The same is true for CFSR which shows much more positive 
trends in East Antarctica. The longer-term trends in Era-20C show consistent large 
significant negative trends throughout the continent in this season. The exceptions are 
Amundsen-Scott and Vostok, which show positive trends. The long-term trends in 20CR 
also are negative throughout the continent in this season and show less regional 
variability. The same is true for the reconstructions, which show negative trends during 
this time period across most of the continent with the exception of Bellingshausen on the 
Peninsula. Additionally, negative trends in the reconstructions are significant at several 
stations in East Antarctica.
Figure 4.23. 20CR MSLP trends (1957-2011) by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10; p < 0.05; p < 0.01$).
Table 4.3. Trends in hPa per decade with 95% confidence interval for all reanalyses, observations, and reconstructions over different time periods for MAM. Significant trends at \((p < 0.05)\) indicated by (*).

<table>
<thead>
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<td>-0.03 ± 0.95</td>
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<td>-0.39 ± 0.87</td>
<td>-0.24 ± 0.52</td>
<td>0.32 ± 0.52</td>
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<tr>
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<td>-0.72 ± 0.71*</td>
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<td>-0.28 ± 0.52</td>
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Table 4.4. Trends in hPa per decade with 95% confidence interval for all reanalyses, observations, and reconstructions over different time periods for JJA. Significant trends at ($p < 0.05$) indicated by (*).

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<td>-0.7 ± 0.66*</td>
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<td>-0.56 ± 0.54*</td>
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<td>-0.20 ± 0.68</td>
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<td>-0.43 ± 0.56</td>
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<td>Vostok</td>
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<td>0.18 ± 1.38</td>
<td>0.31 ± 0.61</td>
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<td>-0.13 ± 0.30</td>
<td>-0.07 ± 0.63</td>
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Table 4.5 compares the trends of the datasets during SON. It is clear that SON is the season that has the fewest significant trends across the datasets. Only Vostok is significant across the observations as well as in Era-Interim. Trends in SON are generally more positive than the other seasons in the observations, particularly across East Antarctica. Regional differences are seen in Era-Interim and CFSR in SON, where stations on the Peninsula have larger negative trends, while East Antarctica has smaller negative or even positive trends. Era-20C trends range very little throughout and are consistently negative with the exception of the two stations on the interior. 20CR shows negative trends across East Antarctica while stations on the Peninsula and Halley station, which is nearest the Peninsula, show positive trends. For the reconstructions in this season, significant positive trends are seen at the stations on the Peninsula, while negative trends are seen across East Antarctica, with the exception of the interior, which shows positive trends.
Table 4. Trends in hPa per decade with 95% confidence interval for all reanalyses, observations, and reconstructions over different time periods for SON. Significant trends at ($p < 0.05$) indicated by (*).

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<td>Bellingshausen</td>
<td>-0.64 ± 0.83</td>
<td>-0.94 ± 2.06</td>
<td>-0.12 ± 0.96</td>
<td>-0.77 ± 0.55*</td>
<td>-0.03 ± 0.53</td>
<td>0.43 ± 0.41*</td>
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<td>Davis</td>
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<td>0.70 ± 0.87</td>
<td>-0.58 ± 0.44*</td>
<td>-0.41 ± 0.41*</td>
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<td>0.28 ± 1.20</td>
<td>-0.62 ± 0.61*</td>
<td>0.03 ± 0.59</td>
<td>0.17 ± 0.30</td>
<td>0.28 ± 1.20</td>
</tr>
<tr>
<td>Mawson</td>
<td>-0.36 ± 0.79</td>
<td>0.51 ± 1.91</td>
<td>0.83 ± 0.85</td>
<td>-0.54 ± 0.44*</td>
<td>-0.31 ± 0.42</td>
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</tr>
<tr>
<td>Scott Base</td>
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<td>0.04 ± 1.09</td>
<td>-0.42 ± 0.55</td>
<td>-0.28 ± 0.55</td>
<td>-0.07 ± 0.25</td>
<td>0.04 ± 1.09</td>
</tr>
<tr>
<td>Mirny</td>
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<td>0.08 ± 2.22</td>
<td>0.69 ± 0.88</td>
<td>-0.61 ± 0.44*</td>
<td>-0.29 ± 0.41</td>
<td>-0.49 ± 0.36*</td>
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</tr>
<tr>
<td>Novolazarevskaya</td>
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<td>1.23 ± 2.41</td>
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<td>-0.16 ± 0.47</td>
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<td>0.49 ± 0.96</td>
</tr>
<tr>
<td>Rothera</td>
<td>-0.97 ± 1.16</td>
<td>-0.77 ± 2.57</td>
<td>-0.20 ± 1.29</td>
<td>-0.69 ± 0.65*</td>
<td>-0.02 ± 0.66</td>
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</tr>
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<td>Syowa</td>
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<td>-0.26 ± 0.45</td>
<td>-0.04 ± 0.34</td>
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</tr>
<tr>
<td>O'Higgins</td>
<td>-0.54 ± 0.86</td>
<td>-1.03 ± 2.31</td>
<td>-0.24 ± 1.24</td>
<td>-0.70 ± 0.58*</td>
<td>0.01 ± 0.56</td>
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<td>-0.24 ± 1.24</td>
</tr>
<tr>
<td>Amundsen</td>
<td>-0.51 ± 0.85</td>
<td>0.90 ± 0.83*</td>
<td>0.19 ± 0.46</td>
<td>0.13 ± 1.03</td>
<td>0.08 ± 0.27</td>
<td>0.90 ± 0.83</td>
<td>0.13 ± 0.03</td>
</tr>
<tr>
<td>Vostok</td>
<td>-0.45 ± 0.98</td>
<td>1.03 ± 0.98*</td>
<td>0.32 ± 0.46</td>
<td>-0.25 ± 0.58</td>
<td>0.38 ± 0.26*</td>
<td>1.03 ± 0.98*</td>
<td>0.38 ± 0.26*</td>
</tr>
</tbody>
</table>
Finally, Table 4.6 compares trends for all datasets for DJF. It is clear that DJF has the most significant trends in all reanalyses, as well as the reconstructions and observations, particularly in East Antarctica. Once again, trends from the CFSR reanalyses are much greater than any of the other data. For Era-Interim and CFSR, trends are more negative and more significant across East Antarctica compared to the Peninsula. As in other seasons, Era-20C has little variability regionally, but consistently has large negative trends across the continent with the exception of the interior stations. 20CR is also consistently negative across the continent with significant trends at stations around the coast of East Antarctica. The reconstructions in this season also show significant negative trends across a majority of the continent with the exception of a few stations on the Peninsulas.

4.8 Chapter summary

The reanalyses were compared with observations, and correlations, biases, and root mean square errors were assessed. Era-Interim performed the best by far, having the highest correlations, and lowest positive biases and root mean square errors. CFSR also performs fairly well, however, biases and RMSE values are slightly higher, and correlations are slightly lower at a few stations. Also, CFSR is over a much shorter time period than the other reanalyses, and only MSLP data are available, therefore Amundsen-Scott and Vostok were not included. Of the two century-long reanalyses, Era-20C performs better than 20CR. For 20CR, there are a few stations that performed poorly compared to the rest, including Mawson, Vostok, and Amundsen-Scott. Similarly these
Table 4.6. Trends in hPa per decade with 95% confidence interval for all reanalyses, observations, and reconstructions over different time periods for DJF. Significant trends at ($p < 0.05$) indicated by (*).

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
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</thead>
<tbody>
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<td>Bellingshausen</td>
<td>-0.59 ± 0.93</td>
<td>-1.16 ± 2.17</td>
<td>-0.77 ± 0.90</td>
<td>-0.94 ± 0.47*</td>
<td>-0.32 ± 0.50</td>
<td>-0.20 ± 0.38</td>
<td>-0.43 ± 0.44</td>
</tr>
<tr>
<td>Casey</td>
<td>-0.98 ± 0.92*</td>
<td>-3.93 ± 1.68*</td>
<td>-1.03 ± 0.87*</td>
<td>-1.06 ± 0.51*</td>
<td>-0.70 ± 0.53*</td>
<td>-0.58 ± 0.40*</td>
<td>-0.68 ± 0.49*</td>
</tr>
<tr>
<td>Davis</td>
<td>-0.90 ± 0.09*</td>
<td>-3.26 ± 1.59*</td>
<td>-1.13 ± 0.89*</td>
<td>-1.12 ± 0.55*</td>
<td>-0.81 ± 0.50*</td>
<td>-0.57 ± 0.36*</td>
<td>-0.55 ± 0.49*</td>
</tr>
<tr>
<td>Dumont</td>
<td>-0.81 ± 0.80*</td>
<td>-2.32 ± 1.75*</td>
<td>-1.07 ± 0.80*</td>
<td>-0.97 ± 0.54*</td>
<td>-0.72 ± 0.53*</td>
<td>-0.56 ± 0.42*</td>
<td>-0.43 ± 0.45</td>
</tr>
<tr>
<td>Esperanza</td>
<td>-0.71 ± 1.00</td>
<td>-1.69 ± 2.28</td>
<td>-0.34 ± 1.11</td>
<td>-1.04 ± 0.52*</td>
<td>-0.42 ± 0.54*</td>
<td>-0.40 ± 0.49</td>
<td>-0.42 ± 0.52</td>
</tr>
<tr>
<td>Faraday</td>
<td>-0.54 ± 1.06</td>
<td>-1.87 ± 2.27</td>
<td>-0.69 ± 1.01</td>
<td>-1.40 ± 0.56*</td>
<td>-0.65 ± 0.58*</td>
<td>-0.47 ± 0.48</td>
<td>-0.61 ± 0.46*</td>
</tr>
<tr>
<td>Halley</td>
<td>-1.21 ± 1.07*</td>
<td>-2.92 ± 2.12*</td>
<td>-1.50 ± 1.03*</td>
<td>-1.33 ± 0.61*</td>
<td>-0.81 ± 0.54*</td>
<td>-0.86 ± 0.45*</td>
<td>-0.86 ± 0.50*</td>
</tr>
<tr>
<td>Marambio</td>
<td>-0.73 ± 1.06</td>
<td>-2.00 ± 2.34</td>
<td>-0.83 ± 1.03</td>
<td>-1.14 ± 0.55*</td>
<td>-0.51 ± 0.57*</td>
<td>-0.50 ± 0.32*</td>
<td>-0.89 ± 0.69*</td>
</tr>
<tr>
<td>Mawson</td>
<td>-0.90 ± 0.91</td>
<td>-2.71 ± 1.69*</td>
<td>-0.94 ± 0.90*</td>
<td>-1.13 ± 0.55*</td>
<td>-0.7 ± 0.51*</td>
<td>-0.67 ± 0.39*</td>
<td>-0.61 ± 0.45*</td>
</tr>
<tr>
<td>Scott Base</td>
<td>-1.28 ± 1.19*</td>
<td>-2.66 ± 2.3*</td>
<td>-1.67 ± 1.22*</td>
<td>-0.95 ± 0.68*</td>
<td>-0.81 ± 0.68*</td>
<td>-0.75 ± 0.49*</td>
<td>-0.63 ± 0.67</td>
</tr>
<tr>
<td>Mirny</td>
<td>-0.92 ± 0.86*</td>
<td>-2.93 ± 1.49*</td>
<td>-1.05 ± 0.87*</td>
<td>-1.15 ± 0.51*</td>
<td>-0.76 ± 0.48*</td>
<td>-0.82 ± 0.35*</td>
<td>-0.84 ± 0.44*</td>
</tr>
<tr>
<td>Novolazarevskaya</td>
<td>-1.08 ± 0.95*</td>
<td>-2.14 ± 2.02*</td>
<td>-1.58 ± 0.92*</td>
<td>-1.23 ± 0.61*</td>
<td>-0.78 ± 0.57*</td>
<td>-0.93 ± 0.40*</td>
<td>-1.19 ± 0.54*</td>
</tr>
<tr>
<td>Rothera</td>
<td>-0.60 ± 1.15</td>
<td>-1.97 ± 2.35</td>
<td>-0.73 ± 1.09</td>
<td>-1.53 ± 0.61*</td>
<td>-0.79 ± 0.61*</td>
<td>-0.72 ± 0.46*</td>
<td>-0.78 ± 0.57*</td>
</tr>
<tr>
<td>Syowa</td>
<td>-1.02 ± 0.93*</td>
<td>-2.27 ± 1.68*</td>
<td>-1.20 ± 0.91*</td>
<td>-1.18 ± 0.57*</td>
<td>-0.68 ± 0.53*</td>
<td>-0.62 ± 0.32*</td>
<td>-0.74 ± 0.46*</td>
</tr>
<tr>
<td>O'Higgins</td>
<td>-0.69 ± 1.00</td>
<td>-1.65 ± 2.25</td>
<td>-0.85 ± 0.96*</td>
<td>-1.06 ± 0.52*</td>
<td>-0.42 ± 0.54*</td>
<td>-0.47 ± 0.35*</td>
<td>-0.88 ± 0.54*</td>
</tr>
<tr>
<td>Amundsen</td>
<td>-0.99 ± 0.88*</td>
<td>-0.81 ± 0.86</td>
<td>-0.45 ± 0.51</td>
<td>-0.16 ± 0.84</td>
<td>-0.58 ± 0.37*</td>
<td>-0.45 ± 0.41*</td>
<td>-0.45 ± 0.41*</td>
</tr>
<tr>
<td>Vostok</td>
<td>-0.81 ± 0.98</td>
<td>-0.88 ± 0.93</td>
<td>-0.36 ± 0.57</td>
<td>-0.66 ± 0.68</td>
<td>-0.54 ± 0.41*</td>
<td>-0.34 ± 0.49</td>
<td>-0.34 ± 0.49</td>
</tr>
</tbody>
</table>
stations also did not perform well for Era-20C, however they were much better than in 20CR.

Each of the reanalyses and the reconstructions were assessed and trends were discussed. For Era-Interim (which is the closest reanalysis to observations), spatial trends are most significant during DJF. This is seen across all the reanalyses. The season with the least significance is JJA and SON for Era-Interim. Also, across all the reanalyses, reconstructions, and the observations, trends per decade are more negative during DJF and MAM than during JJA and SON. Additionally, the Peninsula is unique across all datasets with trends being more positive on the Peninsula. Of all the reanalyses, Era-Interim is most similar to the observations from 1979-2013. DFJ and MAM both show negative trends across the entire continent, with the significant trends in MAM being confined to the Amundsen and Bellingshausen Seas. In JJA and SON, positive trends are seen across the continent in Era-Interim.

To look at the overall long term trends of pressure changes across Antarctica, a few stations were looked at specifically. From the time series at Amundsen-Scott, Bellingshausen, and Casey, it was clear that the reconstructions and reanalyses were most close to observations in DJF. Additionally, the time series showed regional difference in pressure variability across the continent. From the time series, it is clear that there is much more year-to-year variability at Bellingshausen compared to the other stations. Also, there is a greater difference in pressure between seasons at Amundsen-Scott and Casey than at Bellingshausen. Running trends for these stations also show the changes during the century long period. While there are differences between datasets at each
station in the early periods seasonally, in general, the later period shows decreasing
trends in DJF and MAM at all three stations and increasing/more steady trends during
JJA and SON at all three stations.
CHAPTER 5: MODELING RESULTS

5.1 Introduction

As discussed in previous chapters and summarized in Table 3.3, three experiments have been conducted to isolate the role of ozone and radiative forcing over the 20th century. Each experiment was run and each has several ensemble members, as well as prescribed sea surface temperatures (SSTs) in the tropics only in two of the three experiments. The first experiment (called Ozone) has nine ensemble members and only time varying ozone changes and climatological SSTs globally. The second experiment (called No Rad) has 10 ensemble members and is the experiment with radiative forcings set at 1990 values; variability and change in this simulation is therefore only related to internal variability or from the tropical SSTs. The final experiment (called All Rad) has 10 ensemble members and radiative forcings that vary in time (i.e. ozone and greenhouse gas changes together) as well as tropical SSTs, but with climatological SSTs and sea ice conditions in the extratropics as in the No Rad experiment. Ensemble means were computed for each of the experiments and are used for the trend analysis. The following sections go into further detail with the pressure trends over different time periods and over different regions of the Antarctic continent. Table 5.1 provides an overview of how significant trends in each simulation are related back to the various forcing mechanisms.
Table 5.1 Interpretation of significant trends from each experiment.

<table>
<thead>
<tr>
<th>Explanation of significant trends</th>
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<tbody>
<tr>
<td>Experiment with significant trends:</td>
<td>Interpretation:</td>
</tr>
<tr>
<td>Ozone only</td>
<td>Ozone forcing alone is producing negative trends</td>
</tr>
<tr>
<td>No Rad only</td>
<td>Tropical SSTs alone are producing a negative trend</td>
</tr>
<tr>
<td>No Rad and All Rad</td>
<td>Tropical SSTs are the primary mechanism with perhaps a smaller contribution from radiative forcing</td>
</tr>
<tr>
<td>All Rad only</td>
<td>Radiative forcing and/or tropical SSTs are causing changes, the relative magnitude of which is determined by the magnitude of the trends in the Ozone or No Rad experiment</td>
</tr>
</tbody>
</table>

5.2 Spatial trends

The following plots discuss the sea level pressure trends from each experiment’s ensemble mean over four different time periods seasonally. The ensemble mean is used to best remove internal variability and to highlight the forced response unique in each simulation, as outlined in Table 5.1. The longest time period that is assessed is 1905-2014, as shown in Fig. 5.1. The shading represents the two-tailed probability that the trends are zero; since the time period is over 100 years, even small trends of $\pm 0.1$ hPa per decade can be statistically significant at $p < 0.01$. In the No Rad experiment in the first column of Fig. 5.1, trends are near zero but yet significant across much of the continent in most seasons. When compared to the All Rad experiment (right column of Fig. 5.1), where the only commonality is tropical SST forcing, trends are similar, suggesting a dominant role from tropical SST variability alone (Table 5.1). DJF, MAM,
and SON show trends below -0.1 hPa per decade near the Peninsula (-0.2 hPa per decade for SON), significant at $p < 0.01$ and negative trends approaching zero across the rest of the continent and fewer significant trends. JJA is the most similar to the All Rad trends with trends of -0.2 hPa per decade across the continent and trends of -0.4 hPa per decade in the Bellingshausen Sea region, all of which are significant at $p < 0.01$. The middle column shows the trends of the Ozone experiment over the full time period seasonally. In DJF ozone-related pressure trends are negative across the continent (around -0.2 hPa per decade), with and positive trends in the midlatitudes; both trends are statistically significant at $p < 0.01$. Based on Table 5.1, a strong role of forcing from ozone is seen in DJF in the 20th century. In MAM Ozone trends are small but negative over the period and show significance at $p < 0.05$ over a majority of the continent, showing a weaker but meaningful influences from ozone. The last column shows the All Rad trends for the full time period. As mentioned before this experiment includes both natural and anthropogenic forcings, and forcing from SSTs. Trends in MAM and JJA are similar with significant negative trends ($p < 0.01$) around -0.2 hPa per decade over the continent and lower negative trends near the Peninsula, mostly due to tropical SSTs but also a small role of ozone in MAM. SON has negative trends as low as -0.5 hPa per decade near the Peninsula that are significant at $p < 0.01$, however trends are much smaller (around -0.01 to 0 hPa per decade) and are not significant across much of East Antarctica, due to opposing effects of ozone and tropical SSTs. Finally, DJF exhibits a similar trend with more negative trends (around -0.5 hPa per decade) over the Peninsula and less negative trends (around -0.2 hPa per decade) over East Antarctica, with ozone depletion being the
dominant influence in this season. In all seasons in the All Radiative experiment, positive significant trends are seen in the midlatitudes. Based on this column, over the 20th century, greenhouse gases, ozone depletion, and/or tropical SST variability deepened the pressures across much of the Antarctic continent, and increased pressures in the southern midlatitudes, with the relative magnitudes varying seasonally. This trend pattern in the All Rad experiment, reflects a shift toward the positive phase of the Southern Annular Mode (SAM), and would ultimately result in a strengthening of the midlatitude pressure gradient and polar jet stream in all seasons.
Figure 5.1. Trends (1905-2014) by season. Trends contoured every 0.1 hPa per decade and significance shaded ($p < 0.10$; $p < 0.05$; $p < 0.01$). The first, second, and third columns show trends per decade from No Rad, Ozone, and All Rad experiments respectively.
Since radiative forcings (and internal variability related to tropical SSTs) are different with time, additional time periods are investigated. The next time period that was examined is the first half of the century (1905-1956), as shown in Fig. 5.2. Similar to Fig. 5.1, each experiment is shown in a different column and seasonally. In the No Rad experiment, trends are quite different than the full period. In MAM and SON, small positive trends of 0.1 hPa per decade are seen across the continent with strong negative trends seen in the South Pacific, similar to the All Rad trends (-0.4 hPa per decade, \(p < 0.05\)), indicating that SSTs are forcing these changes in these seasons. For the Ozone trends in this time period, trends are still quite small in MAM and JJA, which is similar to trends during the full 20\(^{th}\) century, and no significant trends exist over the continent. In SON, Ozone shows positive trends around 0.2 hPa per decade across portions of Eastern Antarctica, significant at \(p < 0.10\). Finally for DJF, trends are also similar to the full century with negative trends around -0.2 to -0.3 hPa per decade significant at \(p < 0.05\) or lower over the entire continent, which suggests a role of ozone depletion even in the early 20\(^{th}\) century. For the All Radiative experiment, trends are somewhat different over this period compared to the entire century. In all four seasons there is a strongly negative trend as high as -0.6 hPa per decade in SON located in the South Pacific, significant at \(p < 0.05\) or lower. One slight exception is during JJA when the negative trends seem to be shifted more toward South America. The similarity between the All Rad trends and the No Rad trends in this season indicates that the deepening in the Amundsen Sea Low, which is seen here, is driven by SSTs. Ozone forcing only plays a role in DJF in this time period for deepening for the Amundsen Sea
Low, which is consistent with previous work (Raphael et al. 2016; Fogt and Zbacnik 2014, Fogt and Wovrosh 2015). Over the continent in the All Rad experiment, trends are small (near zero) and generally insignificant. In most seasons, the All Rad trends over the continent are very similar to the No Rad trends, indicating that most of the forcing is from tropical SSTs. DJF does show more negative trends across the continent than the No Rad trends, indicating that there has been an influence from ozone depletion in this season.

The next time period where trends are examined is the second half of the century (1957-2014), as shown in Fig. 5.3, which approximately corresponds to the period of Antarctic surface meteorological observations and enhanced forcing both from ozone depletion and greenhouse gas during the 20th century. First, the No Rad experiment in the first column is assessed. Trends are more negative across the continent from 1957-2014, and largely reflect the All Rad trends, indicating the tropical SST influence over this time. JJA is the season with the most negative trends across the continent (around -0.4 hPa per decade at $p < 0.01$). Also, similar to other time periods, trends are more negative in the Amundsen Sea near the Peninsula, which is most evident in SON and DJF. SON has trends as low as -0.6 hPa per decade ($p < 0.01$) and near zero trends over the rest of the continent. DJF has a similar pattern, although trends are only around -0.2 hPa per decade over the Peninsula. For this time period, there are some differences in trends across the continent in the Ozone experiment, specifically during JJA and DJF. Compared to 1905-1956, JJA has much lower and more significant trends during 1957-2014 (-0.2 hPa per decade; $p < 0.10$), and for DJF, the later time period is also much
more negative (around -0.4 hPa per decade in West Antarctica; $p < 0.01$). During this time period, the other seasons show very small trends across the continent, indicating a much smaller role from ozone depletion in MAM and SON. Finally, for the All Rad experiment, trends are much more negative in all seasons from 1957-2014 compared to 1905-1956, primarily as a result of stronger tropical forcing, but also stronger ozone forcing in DJF. Trends in MAM and JJA are around -0.02 hPa per decade across most of the continent and around -0.4 hPa per decade over the Peninsula. These trends are significant at $p < 0.01$ across the entire continent in MAM and over West Antarctica in JJA. SON and DJF have a similar pattern during this time period with very negative trends over the Peninsula (as low as -0.8 hPa per decade in DJF, significant at $p < 0.01$) and trends closer to zero across the rest of the continent in both seasons. As in the previous time periods, the All Rad trends are quite similar to the No Rad trends in MAM, JJA, and SON indicating that the main influence in the All Rad trends are from SSTs. DJF is somewhat more negative across the continent than the No Rad trend showing that radiative forcing has influenced the trend in addition to the SSTs in this season.
1905–1956 MSLP Trends

Figure 5.2. As in Fig. 5.1, but for 1905-1956.
Figure 5.3. As in Fig. 5.1, but for 1957-2014.
Finally, a shorter time period (1979-2014) is examined in Fig. 5.4, as this corresponds to the strongest known ozone forcing (Thompson and Solomon 2000) and the period of the most reliable reanalysis data from Era-Interim examined in Chapter 4. First, for the No Rad experiment in this period, trends are quite different than from 1957-2014, indicating a more quiet role from tropical SSTs on a shorter and more recent time scale. JJA shows near zero and insignificant trends across the continent in 1979-2014. While SON, is slightly similar across Eastern Antarctica, trends near the Peninsula are not more negative from 1979-2014, and the lower negative trends seem to be shifted more toward the midlatitudes. For this time period, DJF is more negative and significant across the continent compared to 1957-2014. In 1979-2014 trends are around -0.4 hPa per decade across most of the continent and are significant at, at least $p < 0.05$, indicating that at least a portion of the reanalysis trends in DJF discussed in Chapter 4 are due to tropical SSTs. For this time period in the Ozone experiment, there are fewer significant trends overall in all seasons, although the strongest forcing in seen from ozone there are notable difference between seasons. For the Ozone experiment in MAM trends are slightly more negative (-0.2 hPa per decade) across the continent, though insignificant. Trends in JJA are closer to zero in the shorter time period compared to 1957-2014 and trends are not significant from 1979-2014. Trends in SON and DJF are somewhat similar with trends from 1957-2014 with DJF showing trends around -0.4 hPa per decade over West Antarctica and around -0.2 hPa per decade across East Antarctica, though trends are less significant in the later time period. The weakening of Ozone trends in DJF, in both significance and in magnitude is initially surprising, given that previous time periods
show strong forcing from ozone in this season, however this will be discussed in more
detail later. Finally, for the All Rad experiment, the trend pattern is similar from 1979-
2014 to 1957-2014, though like in the Ozone experiment trends are less significant in all
seasons. For the most part, the trend pattern is the same in this period compared with the
pattern discussed in the 1957-2014 period, with perhaps the exception of JJA and DJF,
which show trends closer to zero in East Antarctica in the later time period. Unlike the
full century, forcing mechanisms over this short time period are much more difficult to
identify, emphasizing the need for longer datasets spatially across the continent, apart
from the reanalyses outlined in Chapter 4.

5.3 Trends with error bars

To further visualize the differences in the simulation trends, the magnitude and
95% confidence intervals of the trends are presented in this section. Here, sea level
pressure from each simulation is averaged over the continent, and trends are calculated
from these area-averaged time series, giving a continental average trend by season for
each experiment. Additionally, the reconstructions are also be averaged over the
continent and trends are displayed with each of the experiments for comparison. The
comparisons with the reconstructions are meant to provide a rough estimate of the actual
Antarctic trends since they are not complete spatially and are themselves not a perfect
match to observations (Fogt et al. 2016a,b).
Figure 5.4. As in Fig. 5.1, but for 1979-2014.
Figure 5.5 shows the Antarctic averaged trends for MAM and JJA. Over the full century, error bars are small, which agrees with the larger area of significance seen in the spatial trends in the previous section. In the fall season, reconstruction trends are slightly positive, while the trends from the model experiments are negative. Further, in this season, trends from the All Rad experiment, which includes all radiative forcing and tropical SST variability, are the lowest. Comparing the first and second half of the century gives a clearer comparison to how these forcing mechanisms impact trends through time. During MAM in 1905-1956, reconstruction trends and No Rad trends are more positive, while Ozone and All Rad trends are (insignificantly) negative. During 1957-2010 reconstruction trends become negative along with a decrease in the All Rad trends; however, because the No Rad trends are also statistically significant negative, this suggests that tropical variability is the largest contributor to the negative trends. Finally in 1979-2010, error bars increase as seen in the fewer significant trends in this time period, with a suggestion again of tropical forcing being the dominant mechanism leading to the negative trend, as the All Rad and No Rad experiments are the most negative. As such, the recent negative trends in the continent-averaged reconstruction since 1957 appear to be largely a result of changes in the tropical SSTs rather than radiative forcing in MAM. This is further justified by the reconstructions changing signs through the 20th century, because forcing from ozone or greenhouse gases would be consistently negative through the 20th century, while forcing from tropical SSTs vary with time.

JJA exhibits similar trends to those discussed in MAM with a few exceptions. One difference is seen during the early period (1905-1956) where the No Rad trends are
(insignificantly) negative during this season. This indicates that tropical SSTs likely had more of an influence on the All Rad trends than in MAM. During the 1957-2010 time period both All Rad trends and No Rad trends are significantly negative indicating that much of the forcing in this time period is from tropical SSTs. Additionally there are much greater differences in the later time period (1979-2010) where the reconstructions trends are positive. Notably, the trends are uniform and are statistically significant and negative in the 1957-2010 period, however trends are insignificant during the latter period. The most negative trends are seen in the No Rad experiment, and the most change is seen over time, indicating that again, tropical SSTs play an important role in this season.

Figure 5.6 shows the continentally averaged trends with error bars for SON and DJF. During SON, trends over the full century are relatively small with the exception of All Rad trends, which are slightly more negative. These negative All Rad trends are somewhat surprising and difficult to understand, but perhaps point to the role of greenhouse gasses or tropical SSTs leading to the negative trend, since the Ozone trends are near zero and insignificant at all time periods in SON. It should also be noted that during all of the different time periods, both the experiments and the reconstructions show insignificant trends with the exception of the 1957-2010 period. It is clear that during the 1957-2010 period, the negative modeled trends were most influenced by tropical SST forcing, as both the All Rad and No Rad trends are significantly negative. As with the other seasons, continent-averaged pressure trends appear to be most influenced by tropical SSTs if anything.
Figure 5.5. Trends per decade from each experiment and the reconstructions are displayed for MAM and JJA and for 1905-2010, 1905-1956, 1957-2010, and 1979-2010. The 95% confidence intervals are also displayed with the trends.
Austral summer tells a much different story however. During DJF, reconstruction trends are slightly negative over the full century, especially in the latter half of the century after 1957. In every time period except the latter, Ozone trends and All Rad trends are most negative, while the No Rad trends are slightly less negative. This is in contrast to all the other seasons, suggesting a dominant role of ozone depletion on the negative pressure trends, with tropical SSTs only playing a minor secondary role, especially after 1957 when ozone forcing is known to be the strongest. In the final period (1979-2010), there is a significant change in the No Rad trends becoming much more negative, while All Rad trends remain similar and Ozone trends increase slightly. In the later time period, it appears as though the strong negative trends are most influenced by tropical SST variability, however the influence of ozone (and particularly the reason why this trend weakens even through ozone forcing is still ongoing) in this time period is best shown in the following sections. Overall, during this season, as mentioned previously, it is very clear that ozone has a stronger influence during the second half of the century, while tropical SST variability seems to have more of an influence during the first half of the century. The exception is during the 1979-2010 time period when the No Rad trends are much more negative which will be discussed in section 5.5.
Figure 5.6. As in Fig. 5.5, but for SON and DJF.
5.4 Time series

5.4.1 Antarctic averaged time series

In this section, pressure anomalies for each experiment along with the reconstructions are discussed seasonally. Like in the previous sections, these anomalies are averaged over the entire continent. It is noted that while examining the trends regionally would provide more information, climate models are not yet designed to provide much information on small scales. Because of this, using a continent-wide average will be the most conservative use of the model simulations. However, a regional average will also be investigated, but only for DJF, when radiative and ozone forcing in the models is the strongest, as seen in previous sections. For the reconstructions, continental pressure averages are computed using the pressure values from each station and averaging these together.

Figure 5.7 shows the time series of the averaged anomalies (from the full period mean) seasonally. In each of the seasons, pressure anomalies are, for the most part within the range of the reconstructions. During DJF, reconstructions anomalies vary much more than in other seasons, with a much larger range in anomalies, which may partly reflect the higher reconstruction skill in the summer. In this season, anomalies in the model simulations follow the general pattern of the reconstructions (note, there is no explicit reason why any year should match between reconstructions and experiments unless that year was due to a forced response since anomalies are constructed using the model ensemble means, which considerably dampens internal variability that is still present in the reconstructions) with all three experiment anomalies decreasing after 1980.
Additionally, during about 1980-1990 trends from Ozone and All Rad experiments are lower than the reconstructions and the No Rad trends, indicating that they likely have had an influence on the decreasing anomalies in the reconstructions. Additionally, this season shows that the Ozone trends actually seem to be matching better with the All Rad trends through the later part of the 20th century, and that the No Rad trends along with the Ozone trends match well after about 1998. This indicates that ozone may have had a stronger influence toward the end of the 20th century. However, as ozone began to recover (or at least not deplete as rapidly after the late 1990s), perhaps SSTs also began to play a role. This is investigated further in the running trends in section 5.5.

During MAM, reconstruction anomalies begin the century more negative, while anomalies from the three experiments are somewhat positive. There is more variability among the experiments in this season, and they are slightly less within the range of the reconstructions. At the end of the century, a similar trend is seen in this season with a decrease in the reconstruction anomalies after 1980 and negative anomalies in both Ozone and All Rad experiments. However, the model over-exaggerates the negative trends and the anomalies, and the Ozone experiment has much lower values prior to the ozone hole. Therefore the role of ozone depletion appears to be much weaker.

Anomalies in JJA are somewhat similar to the anomalies in MAM, with reconstruction trends beginning the century more negative, and then becoming somewhat positive mid-century, and decreasing again at the end of the century. For the experiments, both Ozone and the All Rad anomalies are more positive at the beginning of the century and then decrease at the end of the century, which is again inconsistent with
the reconstructions. For the No Rad experiment, it remains somewhat negative through the earlier part of the century and then anomalies vary around zero for much of the mid century, and sharply increase at the end of the century; this experiment is also the most variable which may be due to the fact that it has much weaker forcing in comparison to the other simulations.

Finally, during SON, reconstruction anomalies do not exhibit much of a change overall across the century, with anomalies varying around the zero line. For the experiments, they exhibit a similar pattern through much of the century, with the exception of anomalies from the No Rad experiment, increasing slightly after 1950 and All Rad anomalies decreasing after 1980. Overall, the anomalies in the summer season tell the clearest story with the decreasing radiative and ozone trends following the reconstruction trends in the 1980s. The time series plots in all seasons, with the exception of DJF, show much weaker and time varying forcing, which is consistent with the dominant role of tropical SSTs influencing the trends in the model and the reconstructions.
Figure 5.7. Time series of trends in hPa per decade of pressure anomalies for the reconstructions and for the Ozone, All Rad, and No Rad experiments seasonally through the 20th century.
5.4.2 Regional time series

Because changes in the Antarctic climate have been seen to be occurring asymmetrically, it is also important to look at how the pressure anomalies behave in the reconstructions and in each experiment regionally. Antarctica will be divided into six different regions, the location of which are shown in Fig. 5.8. This figure, from Fogt et al. (2016b), shows the stations located within the regions and how the stations from the reconstructions are divided.

Figure 5.8. Six regions of Antarctica with each station labeled in appropriate regions. Figure extracted from Fogt et al. (2016b).
Figure 5.9 shows these anomalies for the DJF season in each region. Only the DJF season will be focused on here because as seen in the previous section, this is the season in which the link between changes are the most clear, and therefore the simulations would likely have better skill at capturing the regional changes due to the stronger forcing. Starting with the Peninsula regions in Fig. 5.9, it can be seen that the anomalies from the experiments fall within the range of the reconstruction anomalies. Another interesting thing to note about both Peninsula regions is that the decreasing anomalies are less discernible than in other regions, which is perhaps due to the farther north location (Fig. 5.8) and the fact that the signature for ozone depletion is most discernable over the continent (Figs. 5.1-5.4). For the Dronning Maud Land region in coastal East Antarctica, which is the area located east of the Weddell Sea, decreasing pressure anomalies are much more evident at the end of the century in the reconstructions. Additionally, Ozone and All Rad pressure anomalies seem to be much lower through this time period in this region, like in the continental average, which provides clear evidence of the dominant role of ozone in the negative regional trends and the secondary role of tropical SST variability. In the Ross Sea area, decreasing pressure anomalies are quite evident in the reconstructions, particularly through the 1990s. Like in the continentally averaged anomalies, it also appears that the Ozone and All Rad pressure anomalies are somewhat lower than the reconstructions at the start of 1980 until the reconstruction anomalies decrease to meet these more negative anomalies later in the century. The difference seen here may be due to an uneven average between the reconstructions and the model, but the exact cause is unknown. Nonetheless, a
decreasing reconstruction pressure anomaly is also seen in the Interior during this season, though it is less clear than the previously discussed regions. In this region, which is equal to the size of the United States, the differences between the experiments and the reconstructions are the greatest because there are only two stations, which are averaged to create the reconstructions’ regional average. For the models in the Interior, all of the experiments also have anomalies that decrease during the later part of the century as well, not just the simulations containing ozone depletion. East Antarctica follows this pattern of decreasing reconstruction pressure anomalies at the end of the century, with all three experiments. Additionally, all regions show more consistent anomalies, which vary around zero in the first half of the century. Overall, it appears that decreases in the pressure anomalies have been most notable across areas other than the Peninsula, while the Peninsula has shown anomalies closer to zero at the end of the century during this season. For the regional comparison, the model simulations have reasonable skill, especially, in representing the weaker trends near the Peninsula. Additionally, there is reasonable skill in the overall timing of when negative and decreasing anomalies begin in each region.
Figure 5.9. Trends in hPa per decade of pressure anomalies for DJF for reconstructions, Ozone, All Rad, and No Rad experiments for each region.
5.5 Running trends

Because there were some notable differences in how the trends in each of the experiments behaved through time, it is important to look at the running trends to assess these changes more qualitatively, rather than using semi-arbitrary time periods. Thirty year running trends per decade are shown in Fig. 5.10 for the reconstructions and each of the experiments through the entire century. Thirty-year running trends per decade are calculated using the anomaly data, and trends are plotted in Fig. 5.10.

Starting with DJF, the reconstructions show a clear downward trend starting around 1955 and remaining negative through present times. This agrees with the negative trends and anomalies that have been seen in this season throughout the previous sections. For both the Ozone and the All Rad experiments, 30-year running trends begin as negative in the early part of the century, increase around 1940 and then sharply decrease around 1950, with the reconstruction beginning to decrease around 1960. The one thing that stands out in this season is the running trends from the No Rad experiment. They are very high around 1950 and then decrease through about 1980 and begin to increase again, highlighting the more variable role of tropical SSTs. This explains the extremely low negative anomalies seen in the 1979-2010 trends. Looking at the specific values of the anomalies, very high values above one are seen around 1955, which accounts for this sharp difference in the running trends in this season. Additionally, running trends in all three experiments begin to increase after about 1975, while the reconstructions remain on the downward steady trend. In the early part of the century, negative trends appear to be more influenced by tropical SST variability while after about
1955, the All Rad trends follow the Ozone trends very closely. The very low No Rad trends that were seen in the 1979-2010 period in section 5.3 are also seen in the running trends around the 1975 period, however it can also be seen that both the Ozone trends and the All Rad trends follow each other closely through this time period showing the influence of radiative trends in this season. The weakening of the Ozone trends around 1979, seen in Fig. 5.4 and Fig. 5.6, is an arbitrary time issue. The later period was the period where the No Rad trends become most negative, and the Ozone trends move toward much higher values (trending toward zero at the end of the running trends and to non-zero in DJF, seen in Fig 5.10). This suggests that ozone forcing is still marked through the end of the 20th century and the beginning to the early 21st century, which is in contrast to what was seen in Figs. 5.4 and 5.6, when only the 1979-2010 period was examined separately.

For MAM, the pattern in the running trends is less clear. In the early part of the century, running trend anomalies for the reconstructions peak around the 1930s as they do in JJA and SON, however the running trends for the three experiments remain fairly constant, which implies weak forcing overall. Trends for the All Rad experiment show the biggest decrease in this season during the 1950-1965 period, while the other experiments show less of a decrease and the reconstructions increase. Finally, the reconstructions begin to decrease at the end of the century around 1965 while the other running trends remain consistent. The discrepancies here is between the running trends in the models and reconstructions indicate that the forcing is weak, or due to normal
internal variability, which may be partly tied to tropical SST forcing. It is also evident that the role of radiative forcing is weak in this season from Fig. 5.10.

JJA has more consistent running trends with changes in the reconstructions and in the three experiments occurring together. Around 1930 all four begin to increase through about 1935 and then all begin to decrease steadily through the 1960s. Running trends from the All Rad forcing experiment remain the lowest throughout this period. After 1960 all four begin to increase slowly and the running trends approach zero by the 1980s. In the running trends, the reconstructions most closely follow the Ozone experiment, showing that ozone forcing has had an influence on this season. The influence is perhaps more so than has been shown in previous sections. However, the No Rad forcing also aligns well with the reconstructions showing that SST variability plays an important role during this season.

Finally, patterns in running trends in SON are somewhat similar to the running trends in MAM, however, the second half of the century is not as clear. In this season, trends peak around 1925 for the reconstructions, Ozone experiment, and No Rad experiment, and there is a peak in trends in the All Rad experiment in 1935. For the rest of the century, reconstruction trends seem to hover around zero before increasing after about 1970. The No Rad forcing and Ozone trends have a secondary peak around 1950. After this, the Ozone decreases slightly while the No Rad decreases slightly more. The All Rad trends have the largest decrease over this time period, and finally begin to gradually increase to near zero with all the other experiments around 1980. Overall, the weaker magnitude and considerable fluctuations in the trends in time suggest a dominant
role from tropical forcing as well as natural or internal variability, driving the changes in pressure in SON over the continent.

5.6 Chapter summary

Trends for each experiment were examined spatially through this research and many differences were found in the early half of the century compared to the second half of the century. This indicates that there has been a change through time in the forcing mechanisms and their influence on the pressure across the continent.

Spatial trends from the Ozone experiment were much more negative and significant during the later period in both JJA and DJF. Trends for the Ozone experiment were also negative consistently over the entire continent. For the All Radiative experiment, trends tended to be more negative in all seasons in the later half of the century compared to the first half of the century. In the All Radiative experiment, there are more negative trends seen over the Peninsula and the Amundsen and Bellingshausen Seas, typically manifested in the deepening of the Amundsen Sea Low. These spatial characteristics show the strong influence of tropical SSTs in most seasons, and particularly off the coast of West Antarctica, with the exception of DJF. For the No Radiative spatial trends, more negative trends are once again seen in the later half of the century. Additionally, like in the All Rad experiments trends are most negative near the Peninsula, specifically in DJF and SON, and again reflect a dominant role of tropical SST forcing in all seasons except DJF.
Figure 5.10. 30-year running pressure anomaly trends per decade by season for reconstructions, Ozone, All Rad, and No Rad experiments averaged over the continent. X-axis is starting year of 30-year period.
Over the full time period, it appears as though tropical variability has had a larger impact on significant negative trends. There is a clear similarity in MAM, JJA, and SON between the No Rad and All Rad trends indicating the influence of the tropical SSTs. Additionally, trends are clearly more negative in the Amundsen and Bellingshausen Seas region in the radiative trends showing the deepening of the Amundsen Sea Low in the 20th century tied to tropical variability. The exception in the full century is during DJF when All Rad trends more closely resemble the Ozone trends, especially in the positive trends surrounding the continent in the midlatitudes and the negative trends over the entire continent, resembling positive SAM phase.

In the first half of the century a similar pattern is seen to the full century. The exception in this period is that in the spatial trends, DJF also appears to be more influenced by tropical forcing, however it is shown that ozone still has an impact in this season in the early time period. This suggests that perhaps both Ozone trends and tropical SSTs have had an influence the earlier half of the century, after which ozone depletion became dominant in DJF in the later part of the century.

A similar pattern is seen in the 1957-2014 and 1979-2014 periods, which reflect the trend mentioned above in the full century. In most seasons (MAM, JJA, and SON) there is a notable strong link between the All Rad trends and the No Rad trends showing the influence of tropical SST forcing during these seasons. The exception in both of these time periods is again DJF where All Rad trends are most similar to the Ozone trends, and a SAM-like pattern is evident. This explains why the full time period also exhibits this trend in the summer season.
Trends throughout time have shown decreases in the reconstructions at the end of the 20th century, particularly in DJF. These decreases are also seen in all three experiments in this season particularly. These changes throughout the century are best seen in the running trends. Ozone and All Rad trends begin to decrease around 1950 and the reconstructions follow shortly after. This is also seen in the 1957-2010 error bars during DJF, which show significant negative trends in both the All Rad and Ozone experiments, both of which are consistent with the known Antarctic ozone hole around 1980 (Thompson and Solomon 2002). While the 1979-2010 period appears to be more influenced by tropical SST forcing during DJF (based on the more significant trend in this simulation), both the running trends and the spatial trends show the influence of radiative forcing in DJF. From the spatial trends, the similarity in trend patterns between Ozone and All Rad is evident, especially with the positive significant trends in the midlatitudes in the All Rad trends and the slightly significant negative trends over the continent as well. Additionally, in the running trends, both the Ozone and All Rad closely match through the later part of the century. Notably, toward the very end of the century, there begins to be an upward, though still negative, trend in all three experiments in the running trends, while the trends in the reconstructions remain fairly consistent. This indicates that the lesser influence from ozone seen in the error bar plot is merely an issue with the time periods chosen and does not indicate a true lesser influence from ozone.

As a whole, it seem that both Ozone trends and All Radiative have had a significant influence on the changing trends in pressure over the second half of the 20th
century. This is best seen in the trends in DJF. The sharp decline in Ozone trends in the 1950s and then the lag of the reconstructions indicates that it is likely that ozone had large role in these changes across the continent in the DJF season. Additionally, these decreasing trends are also seen in the All Rad and No Rad trends, which demonstrated the influence of tropical variability on the continent in MAM, JJA, and SON through the century, and how tropical variability also may have played a part during DJF prior to 1957. Finally, it is clear that these trends in tropical variability have not influenced the continent uniformly with a consistent divide in the behavior or magnitude of trends on the Peninsula or West Antarctica compared to the Interior and East Antarctica, while the ozone trends on the other hand have caused negative trends seen over the entire continent.
CHAPTER 6: CONCLUSIONS

Past research has shown that the Antarctic climate has been changing dramatically over the last several decades. Temperature changes have been most notable during this time period, with more warming being noted over the Antarctic Peninsula compared to East Antarctica, where cooling has been noted (e.g., Steig et al. 2009; Bromwich et al. 2013; Nicolas and Bromwich 2014). Specifically, a study by Turner et al. (2005) showed warming of 1.09°C per decade from 1951-2000 during the winter as well as warming of 0.3°C per decade during the summer months on the Peninsula. Temperate reconstructions by Steig et al. (2009) come to similar conclusions with the greatest warming occurring in West Antarctica in the last 50 years, occurring during both spring and winter. Additionally, Steig et al. (2009) finds cooling over East Antarctica during this time, however this is found to be less significant. It is also noted by Turner et al. (2005) that these insignificant cooling trends could possibly be attributed to the scarcity of data over the continent, which helps motivate some of this work.

Observed pressure changes have also been noted by Turner et al. (2005) in the last several decades. Using data from the READER surface archived, Turner et al. (2005) note that there has been a decrease in MSLP across the continent during 1971-2000. The largest of these changes is noted at Molodezhnaya station (located on East Antarctica near Syowa station) with decreases of 1.63 hPa per decade, significant at $p < 0.01$ during DJF. These changes in the last several decades have been linked to changes in atmospheric patterns, such as changes in the Southern Annular Mode (SAM), as well as to ozone forcing, however the time period over which these observations have been made
has been very short. Therefore it is imperative that these relationships be understood on a
century long time frame to understand their uniqueness in a longer historical context,
which is foundation of this research.

In short, the goal of this research was to answer the following main questions:

• How well can a state-of-the-art non-coupled climate model accurately depict the
  Antarctic atmospheric variability and changes when directly compared to
  reconstructions?

• What are the relative roles of natural / internal climate variability (sea surface
  temperature changes and circulation patterns) and external forcing mechanisms
  (such as ozone depletion and greenhouse gas changes) on Antarctic pressure
  changes during the 20th century from a coupled model framework and pressure
  reconstructions?

• How do these processes influence the asymmetry of changes in East and West
  Antarctica?

These questions were answered using data from the READER Antarctic archive,
reanalysis data, as well as pressure reconstructions through the 20th century. First the
reanalysis data were assessed in comparison with the observations at each of the stations
seasonally. The four reanalyses that were assessed were Era-Interim (1979-2014), CFSR
(1979-2000), Era-20C (1905-2010), and 20CR (1905-2011). In this assessment,
correlations for Era-Interim were relatively high at most stations, especially during DJF.
SON showed the worst correlations with the observations, for the two full century
reanalyses specifically. Like Era-Interim, CFSR performed somewhat well in the
correlations, however biases and root mean square error values were slightly higher at a few stations. Of the two full century reanalyses, Era-20C performed the best, however there were several stations that performed poorly. Overall, Era-Interim performed the best of the reanalyses overall, while there were some issues in the longer reanalysis, especially prior to the modern satellite era. The spatial trends in Era-Interim were the most significant during DJF, which is seen across all of the reanalyses. Additionally, the Peninsula has fewer negative trends than across East Antarctica.

Pressure reconstructions are used in this research to address the issue that the reanalyses do not extend far enough back in time, especially given that the century long reanalyses have been proven, here and elsewhere, to be less reliable prior to 1957. Pressure reconstructions extend back through the entire century, and allowed for an examination of the historical significance of the Antarctic pressure trends at several stations to be assessed. These reconstructions were created in a companion project to this work and use several midlatitudes predictor stations with pressure available through the 20th century, which were given weights in order to reconstruct pressure at Antarctic stations. Reconstructions were evaluated by Fogt et al. (2016a,b) and it was found that the skill of the reconstructions is the highest in the summer months. Additionally, the Peninsula showed the highest skill in all seasons due to its nearness to the predictor stations.

Trends from the seasonal Antarctic pressure reconstructions of Fogt et al. (2016a,b) were also assessed in this research in comparison to the trends at the observation stations, and it was found that DJF performs well overall. Other seasons
however also perform well, such as MAM at Bellingshausen station, located on the Peninsula. Trends in the reconstructions at Bellingshausen (Peninsula), Casey (East Antarctica), and Amundsen-Scott (Interior), become strongly negative in the last few decades during DJF. Also trends become positive during JJA and SON. With the reconstructions showing skill through the 20th century, they were used and discussed with the model results of this research, particularly in the evaluation of early 20th century pressure variability, and the historical significance of recent changes in the observed pressure across Antarctica.

To answer the research questions, the newest version of the Community Atmosphere Model, version 5 (CAM5) was employed. Sea surface temperatures were prescribed in this climate model configuration, therefore this is a non-coupled atmosphere only model. Three experiments were run using the CAM5 model in order to answer the research questions and identify forcing mechanisms over the 20th century. The first experiment (All Rad) used time-varying tropical sea surface temperature (between 30°N and 35°S) and radiative forcing (both ozone and greenhouse gases), with remaining extratropical sea surface temperature prescribed to a climatological cycle. This experiment includes both natural and anthropogenic forcing and is most similar to the real world, especially in the tropical oceans. In the next experiment (No Rad) radiative forcing is fixed at 1990 values, but with the same sea surface temperature configuration as in the All Rad experiment. The goal of this experiment is to isolate the role of tropical SSTs, or when compared with the All Rad experiment, understand the role of radiative forcing. In the final experiment (Ozone), most radiative forcing and the sea surface
temperatures are set at 1990 values, while ozone forcing varies in time, obtained from observations and a previous model experiment (Marsh et al. 2013).

Each of these experiments was completed at the National Center for Atmospheric Research (NCAR), and data were made accessible through an account on the NCAR computers. Several ensemble simulations were completed for each experiment. Both the No Rad and All Rad experiments had 10 ensemble members, while the Ozone experiment had nine. Ensemble means were computed for each of the experiments and used for the analysis of the results in order to best highlight the forcing and dampen internal variability unique in each ensemble member.

First, seasonal trends per decade were calculated for each of the experiments over four different time periods along with the significance. The four time periods that were assessed were 1905-2014 (or 2010 when compared to reconstructions; full century), 1905-1956, 1957-2014 (or 2010 when compared to reconstructions), and 1979-2014 (or 2010 when compared to reconstructions).

It is found that spatial trends for the Ozone experiment were much more negative and significant ($p < 0.05$) during the 1957-2014 period over the entire continent. This is in contrast with the early period (1905-1956) that shows slightly less negative trends over the continent during DJF and positive trends over the continent in SON. Trends for Ozone in the 1979-2014 period during DJF are the most negative though they are less significant than other periods, perhaps due to ozone recovery or other model biases. All Rad trends are negative in all seasons and more negative in the latter half of the century. Additionally, trends in All Rad are most negative in the Amundsen and Bellingshausen
Seas region, indicating the deepening of the Amundsen Sea Low through the 20th century, particularly from tropical SSTs. This is determined by the fact that the No Rad spatial trends are again most negative in the second half of the century and near the Peninsula and in the Amundsen and Bellingshausen Seas.

There is a clear difference in trends in the first half of the century compared to the later half. This is evident first in the differences in the spatial trends in the 1905-1956 period compared with the 1957-2014 period. Additionally, the full century spatial trends (1905-2014) reflect the decreasing trends in the later part of the century after 1957, rather than the weaker and often opposing trends during 1905-1956 indicating this change.

Over the full century MAM, JJA, and SON show strong similarities between the All Rad trends and the No Rad trends, meaning that during these seasons, it is clear that tropical SST forcing played the strongest role in the negative trends, particularly over the Peninsula, West Antarctica, and in the Amundsen and Bellingshausen Seas region. The role of tropical forcing in these seasons is also seen in the Antarctic-averaged trends, with these trends being the most negative and significant during the full period, as well as in other periods in these seasons. As mentioned before, the exception is DJF, where ozone forcing is dominant, indicated by the strong negative trends in this simulation throughout this research. There are also similarities in the spatial signatures between the Ozone trends and the All Rad trends, which indicate the dominant role of ozone again. Only prior to 1957 has there been tropical SST variability that may have dominated over ozone forcing for Antarctic pressure trends in DJF.
In the 1957-2014 period, JJA is the season with the most negative trends of -0.4 hPa per decade at $p < 0.01$ in the All Rad trends. Additionally, as seen before, trends are most negative around the Amundsen and Bellingshausen Seas area in the All Rad trends, indicating a deepening of the Amundsen Sea Low and the overall tropical influence in this season. Similarly, for MAM and SON, pressure trends in the No Rad and All Rad experiments are quite similar over this time period, indicating that in MAM, JJA, and SON, there has been a large influence on the negative trends from tropical forcing. Ozone trends in DJF are negative and significant at $p < 0.05$ or lower across the entire continent, while there are significant positive trends in the midlatitudes, resembling a shift toward the positive phase of the SAM. The similarities between the Ozone trends and the All Rad trends suggests that ozone has had a large impact on the negative trends across Antarctica in DJF, while the tropical forcing has been less dominant during this time period for this season. Regardless, it is clear that after 1957, tropical SST variability plays an important role on Antarctic pressure trends outside of DJF as well as near the Peninsula, West Antarctica, and in the Amundsen and Bellingshausen Seas.

The final period (1979-2014) has trends that are, for the most part, similar to the 1957-2014 period. There are, however, fewer significant trends due to the shortness of the time period. MAM, JJA, and SON all exhibit similarities in trends in the All Rad experiment and in the No Rad experiment, with more negative significant values seen in the Amundsen and Bellingshausen Seas region. Like in the 1957-2014 period, trends in DJF in the All Rad experiment more resemble the trend in the Ozone, best shown in the 30-year running trends, indicating that over this shorter time period there has been an
influence from Ozone on the negative trends. Running trends of the three experiments and the reconstructions make the influence from Ozone during this later time period most clear. Around 1955, 30-year running trends in both the Ozone and All Rad experiments sharply decrease with the reconstructions following. No Rad trends also decrease over this period but are much less negative compared to Ozone and All Rad over most of the time period. Additionally, the upward trend in the All Rad and Ozone trends is clearly seen in the 30-year running trends at the very end of the century showing the ozone recovery during this time.

Overall, the results of this research have shown that MSLP trends have changed dramatically from the early part of the 20th century compared to the latter half. The pressure changes have been shown to be largely influenced by tropical forcing during a majority of the year through much of the entire 20th century. Tropical forcing has also played a dominant role in the asymmetric nature of pressure changes, with more negative trends seen in the Amundsen Sea region. The exception is during DJF when a clear influence from ozone has largely impacted the negative trends over the entire Antarctic continent, and positive trends in the southern midlatitudes, resembling a positive SAM trend in the 1957-2014 period, which is consistent with past research (Gillett and Thompson 2003). While this chapter as a whole is meant to give an overview and understanding to the main findings of this work, the research questions, and main findings are best and most simply summed up as follows:

- The CAM5 model, which was used for this work, contained several experiments with different forcing mechanisms including ozone, tropical variability, and
radiative forcing, and while the simulations still resulted with interannual variability as expected, the results were still well within the range of the reconstructions, and when smoothed, many more similarities were found. The climate model was therefore deemed both reliable and useful for the present study.

- Based on the results of the simulations, it is found that a) tropical SSTs have a significant influence on the negative pressure trends in MAM, JJA, and SON in all time periods during the 20th century; b) Tropical SSTs and ozone forcing influence the negative pressure trends in DJF in the early part of the 20th century; and c) In the latter half of the 20th century, forcing from ozone is much more dominant in comparison to tropical SSTs in DJF on Antarctic pressure.

- Some of the simulations of the model produced results that were asymmetric in nature. In the seasons in which tropical SST forcing is strong (MAM, JJA, and SON), an asymmetric pressure pattern is noted with more negative trends over the Peninsula, West Antarctica, and in the Amundsen and Bellingshausen Seas compared to the rest of the continent. In seasons when ozone forcing is strongest (DJF), the influence of negative trends is seen more uniformly across the entire continent, with more positive trends in the midlatitudes.

In summary, it is hoped that the conclusions and findings of this work have brought light to a few of the many unknowns in the Antarctic climate. While further work should be continued in the attempt to answer what has caused these pressure changes over the continent, it is hoped that this work had accomplished this goal with the newest
and most reliable data available, especially for the early 20th century. As improvements are made to datasets across Antarctica, it is hoped that more studies will provide similar results in order to answer even more questions about the climate unknowns of Antarctica.
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Figure A.1. Era-Interim MSLP trends in hPa per decade 1979-2014 by season and by station. Significant trends at $p < 0.05$ indicated by (*) after station name.
Figure A.2. 20CR MSLP trends in hPa per decade 1957-2011 by season and by station. Significant trends at $p < 0.05$ indicated by (*) after station name.
Figure A.3. CFSR MSLP trends in hPa per decade 1979-2000 by season and by station. Significant trends at $p < 0.05$ indicated by (*) after station name.
Figure A.4. Era-20C MSLP trends in hPa per decade 1957-2010 by season and by station. Significant trends at $p < 0.05$ indicated by (*) after station name.