20th Century Antarctic Pressure Variability and Trends Using a Seasonal Spatial Pressure Reconstruction

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This thesis titled

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ABSTRACT

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Across Antarctica, most meteorological observations did not begin until the International Geophysical Year of 1957-58, making it difficult to understand Antarctic climate variability during the early 20th century. To overcome this hurdle, this thesis creates, evaluates, and analyzes several seasonal spatial pressure reconstructions that extend back to 1905 across the Antarctic continent. A kriging interpolation method is used to generate the seasonal spatial pressure reconstruction using 19 Antarctic stations as predictors. Multiple evaluation techniques were used to assess the reliability of the spatial pressure reconstructions when compared to ERA-Interim, which is deemed the most reliable gridded pressure dataset after 1979. From all these evaluation metrics, it is concluded that the most reliable spatial pressure reconstructions are for the summer and winter seasons, but all seasons have enough skill to be useful in interpreting pressure variability throughout the 20th century.

Using the newly generated spatial reconstructions, it is clearly seen that the negative pressure trend in the late 20th century across the entire continent in DJF is unique when compared to the 100+ year record. Given this uniqueness and contemporary modeling studies, it is likely that stratospheric ozone depletion plays a leading role in the recent negative Antarctic pressure trends in summer. In contrast, the early 20th century in
DJF and the entire 20\textsuperscript{th} century for the other seasons are characterized by interannual variability, with strong decadal-scale variability especially prevalent in winter. This highlights the importance of natural variability in causing the majority of ongoing Antarctic circulation pattern changes.
DEDICATION

To my wife, Morgan:

whom I met at this university six years ago as Freshman,

for all your continual love and support.
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CHAPTER 1: INTRODUCTION

Antarctica is a unique continent, with three major geographically different sectors (Fig. 1.1). The Antarctic Peninsula, located south of South America, essentially acts as a dividing point in the Southern Ocean between the South Pacific and South Atlantic Oceans. The peninsula extends northward to almost 60ºS, allowing for it to have slightly different climate characteristics than the rest of the continent. One of the most susceptible locations to climate change and its potential impact on sea level rise is West Antarctica (Harig and Simons 2015). West Antarctica has a much closer ice elevation to mean sea level than the rest of the continent (while much of the West Antarctic bedrock elevation lies below mean sea level), and is a region of great concern not only due to atmospheric warming, but especially ocean warming trends that melt the West Antarctic grounded ice from below (Turner et al. 2005; Steig et al. 2009; Nicolas and Bromwich 2014; Bromwich et al. 2014; Gomez 2015). However it is challenging to understand this region fully, as Byrd station is the only observation station in West Antarctica that has long-term observations through the last half-century (except for missing observations through the 1970s, however). Finally, the largest portion of the continent is East Antarctica. This vast amount of ice grounded on land has very high elevations above sea level, and is also referred to the Antarctic Plateau / Interior. Only two observation stations with reliable long-term records lie in the interior of East Antarctica, and those are Amundsen-Scott (South Pole) and Vostok stations. The remaining majority of stations lie along the East Antarctic coast, as it allows for easy access. East Antarctica and West Antarctica are divided by the Transantarctic Mountains, which have peaks above 4000+ meters. Also,
the continent is asymmetric about the South Pole; East Antarctica is essentially symmetrical as its northward extent is roughly between 65ºS – 70ºS, while West Antarctica is far from symmetrical (Fig. 1.1). This geographical asymmetry has important effects on the pressure patterns (air flow) around the continent.

Figure 1.1: Digital ice elevation map of Antarctica. The elevation data was retrieved from the British Antarctic Survey. Black dots represent 18 staffed research stations across the continent. Labeled are important geographic locations across the continent and important seas in regards to this study. Figure was created using ArcGIS.
The climate of Antarctica has endured significant changes in past decades. Specifically, temperature has not been uniformly changing across the continent, with some areas rapidly warming (Steig et al. 2009; Bromwich et al. 2013; Nicolas and Bromwich 2014), whereas pressure has been decreasing more uniformly across the continent on annual and seasonal timescales (Turner et al. 2005; Fogt et al. 2016b). These changes are associated with changes in sea ice and grounded ice loss, all of which can impact terrestrial and marine ecosystems. Although the Antarctic temperature and pressure trends have been linked to regional and large-scale pressure patterns, little is known about their uniqueness on centennial timescales.

The Antarctic Peninsula and West Antarctica have experienced the strongest warming trends, as presented in several studies (Turner et al. 2005; Steig et al. 2009; Bromwich et al. 2013; Nicolas and Bromwich 2014). Conversely, cooling trends, albeit weak and insignificant, have been experienced in East Antarctica and the interior of the continent in recent decades (Turner et al. 2005). Broadly, the cooling trends can be linked to the Southern Annular Mode (SAM), a pressure / wind pattern across the entire middle and high latitudes of the Southern Hemisphere, while the warming trends have further been linked to the non-annular (i.e., more regional, smaller scale) component of the SAM.

One of the most important atmospheric variables to understand the Antarctic climate is atmospheric pressure, which has been changing during recent decades (Turner et al. 2005; Fogt et al. 2016b). Changes in the atmospheric circulation patterns have been associated with temperature and sea ice changes through the near-surface wind field
Forcing mechanisms that impact sea level pressure in the Antarctic region vary from tropical teleconnections to the SAM.

Another key atmospheric pressure feature that has been known to influence temperature and sea ice concentrations in West Antarctica and the Antarctic Peninsula is a regional climatological low pressure known as the Amundsen Sea Low (ASL; Turner et al. 2009; Holland and Kwok 2012; Fogt et al. 2012a,b). As its name suggests, the ASL resides in the Amundsen Sea, but can oscillate between the Ross and Bellingshausen Seas as well (see Fig. 1.1). All three of these seas are located in the vicinity of the Antarctica Peninsula and West Antarctica, and this juxtaposition has important implications for the positive temperature trends and sea ice trends in these locations. Whereas the SAM plays an important role in the climate of East Antarctica (Marshall 2007), the ASL plays a very important role in the West Antarctic and Antarctic Peninsula climate (Turner et al. 2013). Due to the clockwise rotation of low pressure in the Southern Hemisphere, northerly flow on the eastern flank of the ASL allows for significant warm air advection onto the peninsula and West Antarctica. It is this asymmetry in the atmospheric circulation around the continent that a plays a large role in the regional climate trends seen today. The atmospheric circulation associated with the SAM around East Antarctica has nearly symmetrical climatic impacts, while around the Antarctic Peninsula and West Antarctica the ASL is a regional (asymmetrical component of the SAM) circulation. These forcing mechanisms and atmospheric pressure features will be discussed in further detail in the literature review.
Very little is known or understood about atmospheric pressure patterns in the high southern latitudes prior to the late 1950s, due largely to the fact that most Antarctic observation stations didn’t exist prior to then. Much research and understanding has been applied to global atmospheric temperature, including the high southern latitudes, but the mechanisms behind Antarctic temperature and sea ice trends in recent decades are not as well understood. This research focuses on atmospheric pressure across Antarctica throughout the entire 20th century using novel reconstruction techniques, helping to fill the large observational gaps and better understand recent climate trends in Antarctica. This is done to not only put recent atmospheric pressure trends in a long-term context, but to also find and understand the uniqueness of any changes over the 20th century. Importantly, very short observational records challenge all recent studies on Antarctic climate, which was a motivation for this work: to develop a century long, seasonal, spatially complete (temporally and horizontally complete), reconstructed pressure dataset across all of Antarctica.

Until very recently, pressure variability in the high southern latitudes in the early half of the 20th century has been poorly understood. Global atmospheric gridded datasets have become available in recent years to try to help with the understanding of a wide variety of atmospheric parameters, although they do have deficiencies throughout the early to mid 20th century in the high southern latitudes, including uncertainties in mean sea level pressure (more detail in Chapter 3). The most commonly used products are the National Oceanic and Atmospheric Administration – Cooperative Institute for Research in Environmental Studies (NOAA-CIRES) 20th century reanalysis, version 2c (20CR,
Compo et al. 2011), European Centre for Medium-Range Weather Forecasts Interim (ERA-Int; Dee et al. 2011), the European Center for Medium range Weather Forecasting (ECMWF) 20th century reanalysis (ERA-20C), and the Hadley Centre gridded mean sea level pressure version 2 (HadSLP2; Allan and Ansell 2006). Considering the known deficiencies in these gridded pressure datasets, a seasonal spatial pressure reconstruction that is constrained by observations (or more reliable reconstructions / data) will provide for a more reliable dataset to help better understand atmospheric pressure throughout the 20th century in a fuller context.

In this vein, the Fogt et al. (2016a) seasonal pressure reconstructions at 18 staffed research stations across the continent have begun to shed light on century long pressure variability across the continent (Fogt et al. 2016b). These reconstructions were performed at a single grid points (stations) across the continent, so challenges in trying to understand pressure variability between stations, and in the Antarctic Interior and across West Antarctica, still exist. With the Fogt et al. (2016a) pressure reconstructions being the foundation of this research, a spatially complete gridded pressure reconstruction can be performed through a spatial interpolation of these station reconstructions across the entire continent and along ocean basins near the coasts of Antarctica, extending northward to 60oS, the farthest northward extent of the Antarctic continent. Although extending the domain to 60oS presents challenges due to the high interannual variability in the Southern Ocean surrounding Antarctica, attempting to reconstruct pressure northward to 60oS is important as it will hopefully capture atmospheric circulation patterns, such as the ASL, near the Antarctic coast. Being able to successfully reconstruct the pressure pattern of the
ASL would be crucial due to its relationship with the climate of West Antarctica and the Antarctic Peninsula.

Although research has increased on atmospheric pressure in the high southern latitudes in recent years, there is considerable room for advancement, especially when interpreting variability in the early 20th century. Therefore, this research here within was motivated by several research questions pertaining to changes in Antarctica in the last century and how reliable a spatial pressure reconstruction can be across the continent.

The following questions that will be investigated in this work are:

1) What is the skill (reliability) of an Antarctic continent-wide pressure reconstruction based on long-term station reconstructions?

2) Using a 20th century spatially complete gridded reconstruction of pressure, what changes in the Antarctic circulation appear to be unique over the last century, especially at locations away from the reconstructed stations?

3) What is the range and scope of natural variability in pressure across Antarctica over the last century?

The structure of this thesis is as follows: Chapter 2 discusses the relevant literature and introduces important concepts in depth; Chapter 3 discusses the data and statistical methods used to produce and evaluate / analyze the spatial pressure reconstructions; Chapter 4 is an evaluation of the spatial pressure reconstructions against select observations and the ERA-Interim reanalysis (addressing question 1 above); Chapter 5 is an analysis of the spatial pressure reconstructions (addressing questions 2
and 3 above); and lastly Chapter 6 provides an overall summary and conclusions resulting from this thesis.
CHAPTER 2: LITERATURE REVIEW

2.1 Global Temperature Trends

Globally averaged annual mean surface temperatures have been increasing rapidly and at an average rate of 0.07°C per decade since 1880, and at an average rate of 0.17°C per decade since 1970 (NOAA, 2017). Recent decades have shown the most rapid warming seen in the last several centuries, as indicated by the difference in annual mean trends noted above. Furthermore, the beginning of the 21st century has been the warmest decade on record since 1850, and the 12 warmest years on record occurred since the year 2003, with the exception of 1998, which was the 8th warmest year on record due in part by a record breaking strong El Niño. Also to note, 2016 became the warmest year in NOAA’s 137-year record, again due to a similarly strong El Niño as in 1998 (NOAA, 2017). Overall in a global context, the planet has been rapidly warming; however, this warming is not uniformly occurring across the planet.

2.2 Temperature Trends in Antarctica

Antarctic temperatures have also been warming, but changes are observed in an asymmetrical pattern across the continent throughout the last several decades (Marshall 2007; Turner et al. 2005). The Antarctic Peninsula has been one of the most rapidly warming places on Earth, while East Antarctica has seen slight cooling, as depicted in Fig. 2.1. These asymmetric changes in temperatures are not only seen in a geographical sense, but also seasonal differences in temperature trends have been observed (Turner et
Turner et al. (2005) was a groundbreaking first study aimed to examine observational temperature trends across the continent, and their results clearly depicted a non-uniform change in temperature across the continent (results displayed in Fig. 2.1). Figure 2.1 shows near-surface temperature trends from 1971-2000 across the continent at 16 key observation stations. These stations were selected because they have the most complete observational records, in which many extend back to ~1957 and were obtained from the Reference Antarctica Data for Environmental Research (READER) archive (Turner et al. 2004).

Figure 2.1: Near-surface temperature trends from 1971-2000 at 16 select stations across the Antarctic continent; annual and seasonal trends are shown. Shading represents statistical significance while vertical bars represent the annual/seasonal temperature trend in °C/century. Figure extracted from Turner et al. (2005).
It is seen that the most significant warming trends are limited to the Antarctic Peninsula and are most pronounced in the summer season (December, January, February [DJF], with vertical bars representing the annual/seasonal temperature trend and the shading representing the statistical significance); however, cooling trends are experienced across the Antarctic Plateau and East Antarctica. Furthermore, even with only one observation station in West Antarctica (Byrd Station; not plotted here), which has large observational gaps during the 1970s, new reconstructions of temperature across West Antarctica have shown strong, seasonal warming trends here also (Steig et al. 2009; Bromwich et al. 2013, 2014; Nicolas and Bromwich 2014). Prior to the International Geophysical Year (IGY) of 1957-58, observations across the Antarctic continent were sparse, and mostly limited to early explorer and whaling expeditions. Yet, even after observation stations became operational around ~1957, they are sparsely located across the continent with large portions of area remaining where no observations are taken; most stations fall along the coast of East Antarctica and on the Antarctic Peninsula as these locations are most easily accessible (note that Fig. 2.1 is not an all-inclusive station plot). Therefore, it is pertinent that global atmospheric reanalyses / gridded pressure products and reconstructions help our understanding of Antarctic climate in a spatially complete context back through time.

2.2.1 West Antarctic Warming

With having only one weather station (Byrd station) recording data in West Antarctica that has reliable, long-term observations, it may seem to pose issues of dependable data collection for all of West Antarctica (especially since it is an immense
amount of area to cover). However, Bromwich et al. (2013, 2014) have shown that the spatial footprint (correlation) of Byrd near-surface temperatures to all of West Antarctica is very high (Fig. 2.2): almost all of West Antarctic temperatures are strongly correlated (above 0.6) with the Byrd temperatures, making the Byrd temperature record very important in further understanding climate variability in this region.

Since the Byrd record is unfortunately not continuous and has a large observational gap throughout the 1970s, corrections and infilling methods had to be used to make the data as complete as possible. The correction and infilling methods used by Bromwich et al. (2013, 2014) include using atmospheric reanalysis data and adjusting the reanalysis data to fit the observation mean bias for the period from 1957-1975, and by using other observations from nearby Antarctic research stations with data going back to the 1950s and performing kriging interpolation to help fill in the gaps in the Byrd record. In doing so, a linear increase in temperature in 52 years (between 1958-2010) was found to be $2.44 \pm 1.19^\circ C$, which is statistically significant at the 99% confidence level (Bromwich et al. 2013, 2014) and makes West Antarctica one of the fastest warming places on Earth in recent decades. Furthermore, significant warming at Byrd was found throughout all seasons except in autumn (March, April, May [MAM]). Broadly, these results mirror the results of Steig et al. (2009), where significant warming in West Antarctica was found in all seasons except austral summer (DJF). Both Steig et al. (2009) and Bromwich et al. (2013, 2014) agree that the two seasons of strongest warming occur in spring (September, October, November [SON]) and winter (June, July, August [JJA]).
However, the observational records and reconstructions are short, and do not allow for conclusions to be made within timescales longer than roughly half a century.

Figure 2.2: Byrd station (denoted by star) annual mean surface temperature spatial footprint across the continent. Shading represents the correlation of the Byrd annual mean temperature with the annual mean temperature at every other grid point using ERA-Interim 2m temperatures from 1970-2011. Figure extracted from Bromwich et al. (2013).

\[ \text{Annual temperature correlation with Byrd} \]

\[ \begin{array}{cccccccc}
-0.3 & 0.3 & 0.4 & 0.5 & 0.6 & 0.7 & 0.8 & 0.9 \\
\end{array} \]

2.2.2 West Antarctic Ice Loss

As proven by the Byrd temperature record, West Antarctica is known to be one of the most rapidly warming regions on Earth (Bromwich et al. 2013, 2014) and most
susceptible to climate change and its potential impact on global sea level rise due to its immense amount of ice grounded below sea level. Grounded ice and sea ice are very different, yet many times used incorrectly. Sea ice is ice that has already displaced water, as it forms on water and its changes are therefore not of concern when speaking of global sea level rise. However, grounded ice is much different, as it is ice that forms on land and has not (yet) displaced water in the ocean.

Grounded ice is of major concern when speaking of sea level rise, because as it melts, it will eventually make its way to the ocean, and therefore will contribute to sea level rise. A study by Harig and Simons (2015) found that West Antarctic grounded ice loss continues to outpace East Antarctic grounded ice gains, resulting in a negative continental trend in grounded Antarctic ice. The region with the greatest grounded ice deficit is located in West Antarctica, near the Amundsen Sea region. Two important glaciers, namely the Pine Island Glacier and the Thwaites Glacier, are primarily responsible for the grounded ice loss in West Antarctica due to warming surface and ocean temperatures (Harig and Simons 2015). Grounded ice forms/gains mass from snowfall accumulation from above on the surface, but with warming temperatures, especially of the ocean, these glaciers are melting from below, making them unstable and calving into the ocean at much quicker rates and initiating faster ice flow down the glacier toward the ocean (Gomez 2015). As the grounding line continues to move inland and the glaciers are melting faster than ice gains are occurring from snowfall above, it is clearly evident that West Antarctic warming should be of great concern to sea level rise in the future.
2.2.3 Spatial Antarctic Temperature Reconstructions

As previously mentioned by Turner et al. (2005), the Antarctic Peninsula has been rapidly warming. Spatial temperature reconstructions by Steig et al. (2009) and Nicolas and Bromwich (2014) confirm this (Fig. 2.3). Steig et al. (2009) used Regularized Expectation Maximum (RegEM) to produce their spatial reconstructions, while Nicolas and Bromwich (2014) used a kriging interpolation method. Figure 2.3 represents the spatial temperature reconstruction produced by Nicolas and Bromwich (2014). This figure shows spatially complete (horizontal and temporal) temperature trends (°C/decade) across the continent from 1958-2012. Figure 2.3a shows the annual trend and Figs. 2.3b-e show seasonal trends. The solid black line represents areas where trends are significant at the 95% confidence level and the abbreviation NS indicates areas where trends are not significant. As seen, the strongest warming of the Antarctica Peninsula, along with West Antarctica, occurs in SON, while JJA is the second season of strongest warming; this result is also in agreement with Schneider et al. (2012). Also to note, the majority of regions where any significant warming is occurring is on the Antarctic Peninsula and in West Antarctica. Conversely, East Antarctica has seen insignificant cooling and warming trends that vary between seasons; this is also dependent on what reconstruction technique was employed. These non-uniform spatial temperature trends across the continent can be attributed to regional and large scale atmospheric circulation patterns, further explained in section 2.4.
Figure 2.3: Reconstruction of annual and seasonal mean temperature trends from 1958-2012. Solid black line indicates significance at p<0.05 and NS shows regions of non-significance. Figure extracted from Nicolas and Bromwich (2014).

Figure 2.4 is another version of Fig. 2.3, except here only spatially averaged annual mean temperature reconstructions are shown in timeseries format. Three distinct regions are spatially averaged: (a) East Antarctica, (b) West Antarctica, and the (c) Antarctic Peninsula. The solid black line in Fig 2.4 represents the temperature reconstruction from Nicolas and Bromwich (2014). The blue, green, and red dashed lines represent other temperature reconstructions performed by Monaghan et al (2008), Steig et al. (2009), and O’Donnell et al. (2011), respectively. As seen by the timeseries, East Antarctica has essentially no temperature trend, but is instead characterized by high year-to-year variability. However, an entirely different story is seen when examining West Antarctica and the Antarctic Peninsula. These locations again have high interannual
variability in their temperature reconstructions, but a significant positive trend is still observed. Nicolas and Bromwich (2014) attribute the seasonal variations behind the insignificant cooling and warming trends in East Antarctica to the Transantarctic Mountains, as they effectively act as a dividing point between the West and East Antarctic climate, therefore separating the effects that regional- and large-scale atmospheric circulations around the continent have on East Antarctica and Antarctic Peninsula climate. Steig et al. (2009) and Nicolas and Bromwich (2014) both find MAM to be the season of strongest cooling in Antarctica, though at an insignificant rate as indicated by Fig. 2.3c. However, observational cooling trends in East Antarctica and the Antarctic interior should be taken with caution, as spatially complete long-term trends are impossible to determine due to the scarcity of observations and shortness of records in these locations (Turner et al. 2005, Fig. 2.1), which therefore exemplifies the importance of these spatially complete temperature reconstructions.
Figure 2.4: Nicolas and Bromwich (2014) reconstruction (black line) of annual mean temperature spatially averaged over (a) East Antarctica, (b) West Antarctica, and the (c) Antarctic Peninsula; colored lines represent other temperature reconstructions. See text for more details. Figure extracted from Nicolas and Bromwich (2014).
As seen in the studies discussed above, asymmetric temperature changes have been occurring across the continent, with West Antarctica and the Antarctic Peninsula among the most rapidly warming places on Earth. Sea ice concentration trends around the continent have also been studied in regards to temperature and regional- and large-scale atmospheric circulation trends, and have been closely tied to one another. More about Antarctic sea ice and how it is related to temperatures and atmospheric circulation patterns will be further discussed in section 2.5. Yet to further gain an understanding of these changes seen today around the continent, previous atmospheric pressure patterns need to be discussed, as atmospheric pressure depicts atmospheric circulation patterns which in turn affect temperatures through thermal advection changes. However, no such long-term, spatially complete and reliable dataset currently exists for atmospheric pressure in the high southern latitudes prior to ~1957.

2.3 Observation Based Pressure Trends in Antarctica

Turner et al. (2005) examined annual and seasonal mean sea level pressure/surface pressure trends using observational data from 16 stations across the continent with the most complete records, and their results are depicted in Fig. 2.5. Surface pressure is used for Vostok and Amundsen-Scott stations due to their high altitudes and unreliable surface pressure to mean sea level pressure reductions. This figure is similar to Fig 2.1, except now looking at pressure trends from 1971-2000. Interestingly, all of the stations examined show negative pressure trends in the annual mean, except for the island station of Orcadas, located northeast of the peninsula. Also of
interest is that the most significant negative pressure trends are located in the interior of Antarctica and in East Antarctica. Pressure trends are generally smaller in the Antarctic Peninsula, but during DJF, the trend is the largest across the entire continent for most stations.

Figure 2.5: Same as Fig. 2.1, but for Antarctic mean sea level pressure/surface pressure (Vostok and Amundsen-Scott stations use surface pressure). Figure extracted from Turner et al. (2005).
These pressure trends seen in recent decades across the continent are strongly tied to a large scale Southern Hemisphere climate pattern, further discussed in section 2.4.1. Due to this, it does not come as a surprise that the largest, most pronounced negative pressure trends are seen in East Antarctica while more minimal trends are seen on the Antarctic Peninsula. Until very recently, atmospheric pressure data across the continent had been mostly limited to only the last several decades; however, Fogt et al. (2016a,b) reconstructed pressure back to 1905 at 18 key stations across the continent and also found negative pressure trends during DJF at these locations for the last several decades. The Fogt et al. (2016a,b) pressure reconstructions will be examined extensively in section 2.6 as they have begun to shed light on Antarctic atmospheric pressure variability throughout the entire 20th century and are the foundation of this work investigated here.

2.4 Atmospheric Circulation Variability

Large-scale climate patterns are known to significantly impact the Antarctic climate, such as the Southern Annular Mode (SAM) and the El Niño-Southern Oscillation (ENSO; Turner et al. 2005; Marshall 2007). The asymmetry noted in the temperature and pressure patterns in Antarctica (as mentioned above) can likely be linked back to these hemispheric atmospheric circulations, but more specifically the warming in West Antarctica and the Antarctic Peninsula may be linked to more regional atmospheric circulations (Tuner et al. 2005). However, many patterns of climate variability in Antarctica can be hard to discern on long time-scales due to the sparse observation
network, and in recent decades, changes have occurred that have yet to be tested for uniqueness on a century-long timescale.

2.4.1 The Southern Annular Mode (SAM)

The reasons behind the asymmetry in Antarctic warming in the latter half of the 20th century and beginning of the 21st century has been studied thoroughly. One of the most influential climate modes on the Southern Hemisphere extratropical region is the SAM. The SAM plays a significant role in altering the Antarctic climate and makes up approximately 35% of the extratropical climate variability in the Southern Hemisphere (Marshall 2007). The SAM is characterized by pressure differences, or rather the strength of the meridional pressure gradient, between the Southern Hemisphere midlatitudes and Antarctica. When the SAM is in its positive polarity/phase, higher (lower) than average pressure is experienced in the midlatitudes, around ~45º (Antarctica). Likewise, when the SAM is in its negative phase, higher (lower) than average pressure is experienced over Antarctica (midlatitudes).

Figure 2.6a-b depicts characteristics of the positive phase of the SAM. Over Antarctica, lower geopotential height anomalies are seen (Fig. 2.6a) while higher geopotential height anomalies are seen in the midlatitudes. Figure 2.6b shows temperature anomalies during the positive SAM, and this shows cold temperature anomalies over much of the continent, except for the northern most portion of the Antarctic Peninsula. Throughout the latter half of the 20th century and into the early portion of the 21st century, the SAM has been trending to its positive phase, resulting in more frequent negative pressure anomalies over the Antarctic continent. This is seen in
Fig. 2.6c where the thin solid black line represents the SAM trend and the vertical columns represent the seasonal SAM index. This is in agreement with Turner et al. (2005) (as discussed in section 2.3), who find from 1971-2000, all stations on the Antarctic continent have negative pressure trends on an annual scale. Notably, the main atmospheric mechanism attributed to the slight cooling in East Antarctica is the positive trend in the SAM index in summer and autumn, essentially locking in cold, polar air over the continent due to the enhanced/stronger zonal jet (westerlies) and not allowing for any meridional heat transfer (Turner et al. 2005). Interestingly, during the summer, Amundsen-Scott station (geographic South Pole) saw the strongest SAM-related below average temperature anomalies, which is consistent with the positive SAM (Marshall 2007). Marshall (2007) also notes that autumn is the season with the largest seasonal temperature trend, but the SAM contributes a higher proportion of observed warming on the Antarctic Peninsula in summer than other seasons. This is true because the SAM is strongest during DJF and other atmospheric circulation patterns are more influential in the other seasons. Again however, this is a relatively short timescale with data only extending back to ~1957, making it hard to discern the uniqueness of these pressure trends on longer timescales.
Figure 2.6: (a) Geopotential height anomalies during the positive phase of the SAM. (b) Near-surface temperature anomalies during the positive phase of the SAM. (c) Timeseries of the SAM index from 1957-2015. Figures (a-b) extracted from the IPCC (2013) report, Figure 3.6.5.
Nicolas and Bromwich (2014) extend their temperature reconstruction study and show that SAM-temperature correlations are negative on the northern tip of the Antarctic Peninsula, and insignificant SAM-temperature correlations are found across West Antarctica in all seasons except MAM. Marshall (2007) claimed that during austral summer, the positive SAM trend was responsible for the warming of the northern Peninsula and a cooling elsewhere on the continent (see Fig 2.6b). Qualitatively this is correct, as a positive SAM phase does not allow for meridional transfer of heat due to increased westerlies; essentially, the cold air is locked in over the polar cap during positive SAM events. However, the exception lies in the Amundsen and Bellingshausen Seas, where a climatological low pressure resides during the positive polarity of the SAM (Fogt et al. 2012a). This climatological low pressure, the Amundsen Sea Low (ASL), allows for warm northerly air to pass over the Peninsula, and descend dry adiabatically on the lee side (northeast side), resulting in warming during a positive SAM phase (cooling in the negative phase; Fogt et al. 2012b; Clem et al. 2016).

The vectors in Fig. 2.7 represent the ERA-Interim 10m wind and the shading represents trends in sea level pressure from 1992-2010 for MAM. It is clearly seen that off the coast of West Antarctica resides an enhanced, or deeper, ASL during this time period. Also, note that in Fig. 2.6c during this time period (1992-2010) the SAM has been trending positively, which will further deepen/strengthen the ASL. This deepened ASL spins clockwise in the Southern Hemisphere, therefore effectively advecting warm, northerly air onto the Antarctic Peninsula, as seen in Fig. 2.7. Similarly, the deepened ASL results in cold, southerly air being advected off the Ross Ice Shelf into the Ross Sea.
The ASL has also been studied to be in connection with tropical Pacific sea surface temperatures and sea ice trends in this region, and will be further explained in later sections.

![Figure 2.7](image)

Figure 2.7: Shading represents trends in sea level pressure from 1992-2010 for April-June. ERA-Interim 10m wind vectors are also plotted. White, grey, and black contours show significant trends at p<0.10, p<0.05, and p<0.01, respectively. Figure extracted from Holland and Kwok (2012).

2.4.2 Ozone Influence on the SAM

Many studies have revealed how stratospheric ozone depletion impacts the phase and magnitude of the SAM (Thompson et al. 2000; Thompson and Soloman 2002; Arblaster and Meehl 2006). During the seasons of decreased ozone over the continent,
the SAM favors its positive polarity as there is a coupling between the stratosphere and troposphere. It was concluded by Thompson and Soloman (2002) that the greatest decrease in ozone over Antarctica occurs during winter and can linger into early spring. During the winter, the continent sits in complete darkness, and when sunlight begins to return in spring, decreased ozone results in less ultraviolet radiation to be absorbed by the ozone in the stratosphere. Due to this weakened absorption of solar insolation, the stratosphere remains relatively cold, and subsequently increases the polar to midlatitude temperature gradient, which therefore in turn enhances the pressure gradient and increases the circumpolar westerlies (polar jet / polar vortex). These increased westerlies and pressure gradient therefore produce a positive SAM phase. To further understand why the SAM is strongest in DJF, a modeling study has been completed by Gillett and Thompson (2003), who found that there is approximately a two-month lag for the increased stratospheric polar jet to propagate downward into the troposphere. Therefore, this result confirms the fact that the positive SAM trend is most pronounced/strongest during the summer season. Simply, this means that ozone depletion in SON results in a positive SAM trend in DJF, due to about a two-month lag for the polar jet to extend from the stratosphere down into the troposphere.

Arblaster and Meehl (2006) used a state-of-the-art global coupled climate model to see if SAM trends were attributed to natural or anthropogenic components of the climate system. The authors found that the largest contributors to the phase of the SAM is due to ozone depletion and increasing greenhouse gases, with the latter playing a much more minimal role, at least during the summer. Their study would suggest that even if
ozone recovers to pre-industrial levels, increasing greenhouse gases may still suggest a positive SAM, or at least a neutral SAM due to the cancellation of opposing effects from greenhouse gas increases and ozone recovery. Simpkins and Karpechko (2011) also agree, suggesting as ozone recovers, the SAM may trend negatively, but once ozone is completely recovered and greenhouse gases continue to increase, the increased greenhouse gases eventually outweigh ozone recovery and trend the SAM positively again. Perlwitz et al. (2008) also suggest that once ozone begins to recover, a warming of the stratosphere is likely during SON. This warming of the stratosphere would have an impact on the general atmospheric circulation patterns around the continent, as it would effectively act to weaken the tropospheric westerlies in summer due to a weaker upper-atmospheric thermal gradient between the pole and the midlatitudes. This could result in significant changes in the SAM, possibility reversing the recently seen positive trend, which would further result in significant changes in the Antarctic climate. Unlike Simpkins and Karpechko (2011), Perlwitz et al. (2008) suggest that even though greenhouse gases are likely to increase and ozone recovery will act to oppose each other, ozone recovery will outweigh the increasing greenhouse gases response on the general circulation pattern, resulting in significant impacts on the polarity of the SAM during the summer.

In a recent study by Soloman et al. (2016), it was found that ozone is starting to recover, but very slowly due to the fact that ozone depleting chemicals remain in the atmosphere for many years even after they are released. Since restrictions under the Montreal Protocol phased out ozone depleting chemicals from being released into the
atmosphere, it does not come as a surprise that ozone is beginning to recover. Due to this recovery of atmospheric ozone, the ozone hole has become smaller and started to develop later in the season (Soloman et al. 2016). A trend shift in the SAM may now eventually be seen in upcoming years, which could significantly impact the Antarctic climate. Since atmospheric ozone plays an important role on atmospheric circulation patterns around Antarctica, ozone depletion/recovery is an important component to fully understand back throughout time to help predict future general circulation patterns around the continent.

2.4.3 Other Sources of Antarctic Circulation Variability – Introduction to Tropical Teleconnections

Since the SAM has a weaker surface temperature response in seasons outside of summer and autumn, the recent positive temperature anomalies in West Antarctica have been further studied in winter and spring. West Antarctic warming is strongest in winter and spring (Steig et al. 2009) when the SAM plays a weaker role; a strong positive SAM response in West Antarctica would act to cool this region due to increased westerlies and reduced meridional heat transfer, but there would be warm, northerly flow on the eastern edge of the ASL, consistent with the asymmetric component of the SAM (as described above). Therefore, other studies have looked into tropical teleconnections which have been linked to the non-uniform temperature changes across the continent as well, and especially the warming seen in West Antarctica has been the focus of most recent work (Nicolas and Bromwich 2014; Bromwich et al. 2013).
2.4.4 El Niño-Southern Oscillation (ENSO)

Another large-scale atmospheric circulation and its associated tropical teleconnections that affect Antarctic climate is ENSO. Essentially, ENSO is made up of sea surface temperatures and pressure variations in the tropical Pacific collectively. El Niño is defined by above sea surface temperatures across the equatorial Pacific, while the Southern Oscillation is defined by pressure differences between the western and central equatorial Pacific. ENSO is an important circulation pattern because of its strong teleconnections with (in particular for this research) the Southern Pacific Ocean and regional climatological circulations that develop there (Ding et al. 2011; Schneider et al. 2012; Clem and Fogt 2015).

Over the last 30 years, anomalous sea surface temperatures in the tropical Pacific have been connected to West Antarctic warming in austral winter (JJA; Ding et al. 2011). Tropical sea surface temperatures and deep convection can have a significant influence on the regional circulation in the Amundsen Sea region due to a Rossby wave train associated with the Pacific-South American (PSA) pattern, leading to warm air advection onto the continent. In Fig. 2.8, Ding et al. (2011) claim that sea surface temperatures in the central tropical Pacific, rather than both the central and tropical eastern Pacific, strongly influence the climate of West Antarctica due to regional atmospheric circulation changes. A strong anticyclonic circulation anomaly develops near West Antarctica over the Amundsen Sea in response to atmospheric response to above-average tropical sea surface temperatures. The increased sea surface temperatures outlined by the dashed box in Fig. 2.8a are strongly correlated to the wave-train pattern, resulting in higher than
normal geopotential heights off the coast of West Antarctica, as seen in Fig. 2.8b. Due to this high pressure anomaly in the Amundsen Sea region, warm northerly air is advected poleward over western West Antarctica and the Amundsen Sea, while cold, southerly air is advected equatorward over the Antarctic Peninsula and Bellingshausen Sea.

The atmospheric wind fields associated with these atmospheric circulation patterns are also linked to decreasing sea ice in the Amundsen Sea and increases in the Bellingshausen Sea in winter (Ding et al. 2011). This is contrary to the results from Turner et al. (2005) who found that the Antarctic Peninsula is warming, and also many other studies that show a decrease in sea ice extent in the Bellingshausen Sea. However, according to Ding et al. (2011), the warming in West Antarctica can be attributed to the anomalous circulation changes in West Antarctica/Amundsen Sea region during winter (JJA; as depicted in Fig. 2.8), which are primarily due to central tropical Pacific sea surface temperatures. Conversely, Schneider et al. (2012) find opposite results for the spring (SON) season. Here, they find that cooler than normal sea surface temperatures in the central Pacific (black box in Fig. 2.8a) result in lower geopotential heights, or a low pressure anomaly to reside off the coast of West Antarctica. Schneider et al. (2012) find that the cyclonic circulation in spring in the Amundsen Sea is connected to the warming of West Antarctica and also the regional sea ice changes in the Amundsen and Bellingshausen Seas. Furthermore, spring warming of West Antarctica is strongly correlated ($r = -0.73$) to the area of sea ice in the Amundsen and Bellingshausen Seas.
Figure 2.8: (a) Tropical sea surface temperatures (shading) and 200hPa geopotential heights and the (b) correlation between the 200hPa geopotential heights and sea surface temperatures averaged over the central tropical Pacific (outlined by black box in (a)). Figure extracted from Ding et al. (2011).

Clem and Fogt (2015) found the strongest warming in West Antarctica occurs in spring while the strongest warming on the western Antarctic Peninsula is in winter. The warming on the western Antarctic Peninsula is statistically significant over both winter and spring, while the strongest warming in West Antarctica is only significant in the early portion of the record. Moreover, only the warming of western West Antarctica is found to be statistically significant ($p<0.10$) during spring from 1979-2012. Due to the differences in regional warming, Clem and Fogt (2015) attribute different regional circulations to the regional warming trends. Since 1979, the tropical Pacific has experienced several significant changes, with the Southern Oscillation Index (SOI) trending significantly positive ($p<0.05$) and the Pacific Decadal Oscillation (PDO) trending significantly negative ($p<0.01$). The positive SOI was found to have a weak influence on the warming of West Antarctica (congruent with approximately 10-15% of the warming seen at Byrd station and all of West Antarctica), but the positive SOI was linearly congruent with approximately 40-50% of the warming on the western Antarctic Peninsula. In Fig. 2.9,
the deepened ASL is strongly congruent with the SOI. It is clearly seen that off the coast of West Antarctica, a negative trend is observed (strong cyclonic ASL). This cyclonic flow around the ASL advects warm air onto the peninsula and cold air off the Ross Ice Shelf. It should also be noted that the SOI is congruent with a high pressure anomaly that resides off the northeast coast of the Antarctic Peninsula in the South Atlantic (Weddell Sea). A high pressure in the Southern Hemisphere will spin counter-clockwise, resulting in warm, northerly air to again be advected onto the Antarctic Peninsula, resulting in warming there. Figure 2.9 again reinforces the fact that the climate of West Antarctica and the Antarctic Peninsula is strongly tied to the tropics. Furthermore, Clem and Fogt (2015) found that the negative PDO is linearly congruent with approximately 20-30% of the warming of West Antarctica.

Figure 2.9: Mean sea level pressure trends congruent with the Southern Oscillation Index (SOI). Shading represents the percentage of statistically significant trends that are linearly congruent with the SOI. Figure extracted from Clem and Fogt (2015).
These results shown above are significant in terms of our understanding of regional circulation trends and their impacts in the Southern Hemisphere, especially on the continent of Antarctica. In the eastern Amundsen Sea/western Ross Sea, a negative pressure trend is seen (see Fig. 2.7), in agreement with several other studies (Fogt et al. 2012b; Tuner et al. 2013; Hosking et al. 2013). Furthermore, a positive pressure anomaly is seen in the South Atlantic, which allows for warm northerly flow across the Antarctic Peninsula, resulting in warming on the western side of the Peninsula from 1979-2012. Southerly flow across the Ross Sea from the negative pressure anomaly in the Amundsen Sea allows for cooling here, while northerly flow on its eastern flank allows for the warming of the western portion of West Antarctica. Overall, it was concluded by Clem and Fogt (2015) that the PDO plays a more significant role in the deepening of the ASL than does ENSO, which is also consistent with the PDO influence of warming of West Antarctica. However, the increased pressure anomaly in the South Atlantic is primarily responsible for warming of the Antarctic Peninsula, showing that different regional pressure circulations can be tied to Antarctic warming in recent decades. Nonetheless, all of these aforementioned studies are challenged by short time periods of 30-50 years at most. Moreover, the warming in West Antarctica is concerning given that the West Antarctic Ice Sheet is unstable and has been losing grounded ice mass in recent decades, which is attributed to global sea level rise as discussed in section 2.2.2.

As seen in the previous studies showing that the SAM and ENSO do influence the ASL, there have also been several studies showing the atmospheric circulation changes when the SAM and ENSO events happen in conjunction with one another. When positive
SAM events occur alongside with La Niña events, the ASL becomes even deeper (Fogt and Bromwich 2006; Stammerjohn et al. 2008). Stammerjohn et al (2008) attribute the deepened ASL throughout the 1990s to the positive SAM, and especially deeper when a La Niña event occurred with positive SAM events. Liu et al. (2004) also agree that a positive SAM with an El Niño produce conflicting atmospheric circulation changes, while a positive SAM and La Niña produce regional atmospheric circulations that would produce sea ice changes and wind field patterns similar to trends experienced today (see section 2.5).

Overall, the regional asymmetry of the ASL plays an important role in the temperature changes in West Antarctica and the Antarctic Peninsula outside of the summer season; in summer the SAM is the most influential climate mode responsible for the temperature and pressure trends during that season. The ASL is also deeper during positive SAM events and the meridional location is strongly influenced by the SAM, as noted by Turner et al. (2013). The longitudinal position of the ASL also plays a significant role on West Antarctic climate by influences from the atmospheric wind field. The 10m-wind field, near-surface air temperature, precipitation, and sea ice concentrations in West Antarctica can be linked to the magnitude and location of the ASL (Hosking et al. 2013). Fogt et al. (2012b) also conclude that the Antarctic Peninsula and Pacific sector temperatures are strongly tied to the asymmetric structure of the SAM (the ASL), while East Antarctica temperatures are more tied to the zonally symmetric structure of the SAM.
2.5 Sea Ice Trends

The atmospheric circulation changes in the Amundsen Sea can also be linked to changes in sea ice properties in the Amundsen, Bellingshausen, and Ross Seas. It has been known that total Antarctic sea ice extent has been increasing in extent in recent decades, while Arctic sea ice has been drastically decreasing (Turner et al. 2009). But, Antarctic sea ice has been experiencing strong contrasting, regional trends as seen in Fig. 2.10. The largest contrasting sea ice trends exist in autumn (total Southern Hemisphere increase of 2.08% dec$^{-1}$), where a dipole of increasing sea ice extent in the Ross Sea is rivaled by decreases in sea ice extent in the Amundsen and Bellingshausen Seas (decreases in these seas are roughly -6.63% dec$^{-1}$; Turner et al. 2009). Figures 2.10a-2.10e are regional sea ice extent time series while Fig. 2.10f is the overall sea ice extent of the entire Southern Hemisphere. Each figure is from November 1978-December 2010 and sea ice data were collected from three different satellites. As explained above, all seas around Antarctica have experienced sea ice gains except for the Amundsen and Bellingshausen Seas during this time period, with the Ross Sea being the most significant increase. This is thought to be linked to the deepening (stronger cyclonic flow) of the ASL in autumn due to stratospheric ozone loss (Turner et al. 2009), but other studies show a much weaker response to ASL depth and ozone loss in autumn (e.g. Fogt and Zbacnik 2014, Fogt and Wovrosh 2015). As a result, northerly flow toward the Amundsen and Bellingshausen Seas (Fig. 2.11b; same figure as Fig. 2.7) has allowed for earlier retreat/later advance of sea ice, whereas southerly flow in the Ross Sea has allowed for earlier advance/later retreat of sea ice (see Fig. 2.11a-b). Fig. 2.11a depicts
sea ice motion vectors and sea ice concentration trends (shading) for April-June from 1992-2010 from Holland and Kwok (2012), which demonstrates how the atmospheric wind field can be related to sea ice concentrations. The cold, southerly air being advected off the Antarctic Plateau over the Ross Ice Shelf is likely helping the sea ice to expand the sea ice in the Ross Sea while warm, northerly air acts to decrease sea ice concentration near the Antarctic Peninsula in the Bellingshausen Sea. Therefore, this study by Holland and Kwok (2012) concluded that wind-driven changes were the dominant driver in ice motion around much of West Antarctica from 1992-2012.

Figure 2.10: Monthly sea ice extent deviation plots, from November 1979-2010, calculated from several different data measurements. See text for full details. Figure extracted from Parkinson and Cavalieri (2012).
Figure 2.11: (a) Ice-motion trend vectors and ice-concentration trends (shading) for April-June from 1992-2010. (b) Same figure as Fig. 2.7. Figure extracted from Holland and Kwok (2012).
Since it has been shown how the SAM and ENSO influence the ASL, a study by Stammerjohn et al. (2008) examined ENSO and SAM activity and how it affects sea ice concentration trends around Antarctica. During the 1980s, the SAM was trending negative (see Fig. 2.6c) and more pronounced El Niño events occurred (warm phase). In this study, these years were compared to the relatively positive SAM years of the 1990s, which was also more consistent with La Niña events. Like noted in Fogt and Bromwich (2006), Stammerjohn et al. (2008) also find similar results: when a positive SAM occurred alongside with a La Niña, the ASL was deeper and this is consistent with the sea ice concentration trends. When a positive SAM occurred with La Niña conditions, a strong ASL existed in the Amundsen Sea region. This produced clockwise flow and therefore earlier advance of sea ice in the Ross/Amundsen Seas (colder conditions there) and later advance of sea ice in the Bellingshausen Sea (warmer conditions there). Their results are shown in Fig 2.12 with shading representing earlier sea ice advance (cool colors) and later sea ice advance (warm colors) with regards to SAM composites; contouring shows autumn SLP anomalies. Sea ice anomalies are not as strong when the SAM is not occurring with an ENSO event, but nonetheless, the SAM did contribute more to the sea ice anomalies than ENSO activity did. Interestingly, a negative SAM occurring with an El Niño is quantitatively opposite (i.e., like multiplying the atmospheric circulation and sea ice anomalies by negative one) that of a positive SAM occurring with a La Niña. This can be seen by simply comparing Fig. 2.12a and Fig. 2.12c. There is a clear dipole between the Bellingshausen and Ross Seas, which essentially flips sign between Fig. 2.12a and Fig. 2.12c. The authors conclude by saying
that the strengthening of the SLP anomalies in the South Pacific (namely the ASL), consistent with positive SAM and La Niña events in the 1990s, help to explain the contrasting sea ice trends in these seas due to the atmospheric wind patterns. Therefore, simply stated, the SAM and ENSO strongly influence the ASL which in turn impacts sea ice in the Amundsen, Bellingshausen, and Ross Seas by the ASL wind pattern. Given these connections, it is pertinent to understand regional atmospheric circulations around Antarctica, as they can strongly influence the climate in numerous ways.

Figure 2.12: SAM composites of sea ice advance (color shading) and MAM sea level pressure (color contours) anomalies. See text for more details. Figure extracted from Stammerjohn et al. (2008).
2.6 Antarctic Station-Based Pressure Reconstructions

Until very recently, only a few long-term continuous pressure records existed for Antarctica prior to the IGY (1957-58). Prior to the IGY, observation stations across the continent were very sparse and only early explorer and whaling expedition data are available. However, these data are again patchy, often inconsistent, and have numerous errors. Likewise, prior to the modern satellite era of 1979, global reanalysis data are also unreliable in the high southern latitudes (Bromwich et al. 2007; Bracegirdle and Marshall 2012). Therefore, to be able to further understand Antarctic pressure variability and circulation patterns around the continent in a long-term context prior to the IGY was essentially impossible. Even with many observation stations beginning in the late 1950s and early 1960s, these records are still relatively short in nature and long-term trends are difficult to fully understand. This was the motivation of Fogt et al. (2016a) in developing pressure reconstructions for 18 individual stations across the continent. Now, with seasonal pressure reconstructions dating back to 1905 at 18 locations across the continent, long-term pressure trends could now begin to be fully understood (Fogt et al. 2016b).

The seasonal pressure reconstructions presented in Fogt et al. (2016a,b) effectively doubled the length of the observations back to 1905 and helped to begin to understand the atmospheric pressure variability throughout nearly the entire 20th century, even prior to the IGY when observations were sparse. Figure 2.13a provides a map showing the locations of all the stations reconstructed in Fogt et al. (2016a). As expected,
most of the stations lie along the Antarctic Peninsula and along the coast of East Antarctica, due to easy access.

The 18 station-based reconstructions from Fogt et al. (2016a) in Fig. 2.13a were based off the READER archive where the data are quality controlled and freely published online (Turner et al. 2004). Only stations with the most complete and longest observational records were used; however, Byrd station had large gaps in its surface pressure data. Bromwich et al. (2013, 2014) could infill gaps in the temperature record (as previously mentioned above in section 2.2.1), but the data they used to infill those gaps did not include surface pressure data, so therefore Fogt et al. (2016a) could not infill similarly large gaps of missing surface pressure data at Byrd. Due to this, the Byrd reconstruction posed more challenges in its reconstruction due to missing observations in the record. Everywhere but three stations used mean sea level pressure data in the reconstructions; Amundsen-Scott, Byrd, and Vostok stations used surface pressure data.

These Antarctic pressure reconstructions were developed using pressure records from the Southern Hemisphere midlatitude regions. The Southern Hemisphere midlatitude stations used are shown in Fig. 2.13b. For a midlatitude station to be considered, its observational record had to extend back to at least 1905 and be more than 75% complete. All Southern Hemisphere midlatitude station data were obtained from the Global Historical Climate Network (GHCN; Peterson and Vose 1997; Peterson et al. 1998), the University Corporation for Atmospheric Research (UCAR) research data archive dataset ds570.0, or quality-controlled observations from the Climatic Research Unit (Jones 1987; Jones et al. 1999).
Figure 2.13: Map of (a) Antarctic pressure stations reconstructed and (b) midlatitude predictor stations used for the reconstructions of stations in (a). Figure extracted from Fogt et al. (2016a).
The Fogt et al. (2016a) pressure reconstructions at individual stations were reconstructed using principal component regression (PCR). For each station and season, two different subsets of midlatitude predictor pressure data were used, namely the 5% and 10% networks, as stated in Fogt et al. (2016a). These networks represented those midlatitude stations that were significantly correlated ($p < 0.05$ and $p < 0.10$) to the Antarctic station being reconstructed. Simply stated, if the surface pressure at Amundsen-Scott station in DJF was strongly correlated to the surface pressure in Auckland, NZ, Perth, Australia, etc., those midlatitude predictor stations would be used in the PCR model to produce the surface pressure reconstruction at Amundsen-Scott in DJF back to 1905.

Three different validation methods were used in the Fogt et al. (2016a) reconstructions. The first method calibrated the PCR model during 1957-2011/2013 and used a leave-one-out cross-validation procedure; these are termed the ‘original full’ period reconstructions. In this validation technique, PCR is performed as many times as there are observational years, either 55 or 57 (this is because multiple different reconstructions were produced, with ending years of 2011 and then again extending them by two years to make the ending year 2013). Each time, the center year is left out (i.e. the year being predicted), along with two years on each side of the center year to remove any autocorrelation. After the PCR model is ran, either 55 or 57 times, all the predicted years are concatenated to produce the full timeseries. Two other methods that were used were named the ‘early’ and ‘late’ reconstructions. Here, during these validation procedures, data were withheld during the model calibration. For the ‘late’ reconstructions, the first
30 years were withheld (1957-1986; calibration timeframe) and for the ‘early’ reconstructions, the last 30 years were withheld (1982-2011 or 1984-2013; calibration timeframe) to produce an independent validation timeseries and to address more uncertainties and the reliability and consistency / robustness of the model. For purposes off this thesis however, only the ‘original full’ reconstructions will be used, as they were generally deemed more skillful than those produced in the ‘early’ and ‘late’ reconstructions. Reconstructions were also performed using raw / original data and detrended data; both will be used in this thesis. Steig et al. (2009) used a similar approach in their Antarctic spatial surface temperature reconstruction which proved to be successful, further giving confidence in the work presented here within.

The pressure reconstructions were deemed skillful in all seasons (see Fig. 2.14), but austral summer and winter were the most skillful; this can likely be attributed to stronger correlations between pressure in the Southern Hemisphere midlatitudes and Antarctica in these seasons. To assess reconstruction skill and the uncertainty in the PCR model, Fogt et al. (2016a) evaluated each reconstruction individually using several statistical methods (calibration correlation, validation correlation, reduction of error (RE), and coefficient of efficiency (CE)). The calibration correlation is the correlation between the observations and reconstructions during the time of overlap; the validation correlation is the correlation between the observations and the validation timeseries. The RE and CE values can range from \(-\infty\) to +1.0; if an RE or CE value is greater than zero, the reconstruction performed better than just using the climatological mean, and if the RE or CE value is +1.0, it is a perfect reconstruction. The reconstructions had very high skill
metrics across all approaches and seasons, therefore being deemed skillful. The skill can also be thought of as the reliability of the reconstructions in evaluating the likely range of historical pressure variations. During DJF and JJA, the skill was greatest, and this can again be attributed to the fact that during DJF at least, the air flow around the continent is more zonally-symmetric in nature, and correlations between the Antarctic and the Southern Hemisphere midlatitudes are greatest. In recent years, this is especially true during the austral summer as the SAM has been trending positively, which is associated with stronger correlations between Antarctica and the Southern Hemisphere midlatitudes. However, the skill of the reconstructions is reduced slightly in the transition seasons of MAM and SON. During these seasons, the SAM plays a much weaker role in Antarctic climate (as discussed previously) and more pronounced regional circulations allow for more meridional flow around the continent, therefore resulting in weaker correlations between the Antarctic and Southern Hemisphere midlatitudes.

To help improve reconstruction skill during the transition seasons, and most noticeably in winter, Fogt et al. (2016a,b) presented results also using ‘pseudo-proxy’ reconstructions. The pseudo reconstructions used ‘pseudo observations’ from the Southern Hemisphere oceans, which included data from several global atmospheric gridded pressure datasets as well as direct observations. The pressure datasets that were used in the pseudo reconstructions of Fogt et al. (2016a) were the Hadley Centre gridded mean sea level pressure version 2 (HadSLP2; Allan and Ansell 2006), and the National Oceanic and Atmospheric Administration 20th – Cooperative Institute for Research in Environmental Studies (NOAA-CIRES) century reanalysis, version 2c (20CR, Compo et
al. 2011). HadSLP2 is an observational land- and marine-based gridded pressure dataset, while 20CR is a gridded atmospheric reanalysis. These gridded pressure products will be further explained in detail in Chapter 3.

By using these gridded products, data from places of strong correlation between the Antarctic stations particularly and areas over ocean basins and land masses where no observations were recorded could now be used. For example, the peninsula station of Bellingshausen was strongly correlated to pressure values in the South Atlantic Ocean, off the southwest coast of Africa in DJF. Therefore, these pseudo observations from the gridded pressure data were then added to the midlatitude predictor data already used to produce the original reconstructions presented above and the PCR model was recompiled for each station and each season. By adding in pseudo data to the PCR model, it helped to constrain the reconstructions, and these pseudo reconstructions generally performed with greater skill than the original reconstructions, in part due to more pronounced pressure correlations between Antarctica and Southern Hemisphere midlatitudes that fall over large ocean basins and land masses where no continuous in situ observations were available (only occasional ship data).

The pseudo reconstruction skill using HadSLP2 and NOAA’s 20CR are compared to the skill of the original reconstructions (i.e., original reconstructions = reconstructions only using midlatitude observation station data) in Fig. 2.14 for the ‘full’ period reconstruction only (i.e. ‘full’ period reconstruction = calibrate over the full length of the observations, and use the leave-one-out cross-validation method). Each of the four metrics are compared for all three reconstructions by season, and the numbers on each
panel represent the difference between the best original full period reconstruction and the best full period pseudo reconstruction. Therefore, a positive value indicates that the Fogt et al. (2016a) pseudo reconstruction performed better than the original reconstruction. Overall, the pseudo reconstructions outperformed the original reconstructions except in DJF, where they had essentially very similar skill metrics. It does not come surprising that DJF was the most skillful season, since this is the time of zonally-symmetric flow around the continent which results in higher and more areas of correlation between the Southern Hemisphere midlatitudes and Antarctica. However, even during the transition seasons, all reconstructions perform better than climatology, as indicated by positive RE and CE values. The pseudo reconstructions outperform the original reconstructions in the transition seasons and quite remarkably in JJA. However, the skill is still slightly weaker than during DJF. Overall, Fig 2.14 further demonstrates the fact that the Fogt et al. (2016a) individual station seasonal pressure reconstructions are skillful and reliable.
Original & Pseudo Reconstruction Performance Comparison

Figure 2.14: Box plots of the reconstruction statistics from the 17 main stations (Byrd station not included here) across Antarctica for the best full period reconstructions. Positive numbers indicate that the pseudo reconstructions outperformed the original reconstructions. Figure extracted from Fogt et al. (2016a).
Another way to assess reconstruction skill across the continent is to examine spatial plots of the calibration correlation by station and season (Fig. 2.15). In this plot where the station-based pseudo reconstructions are compared to the station observations (calibration correlation), there is a clear picture that reconstruction skill is the greatest in DJF and JJA, and on the Antarctic Peninsula across all seasons. Behind the station names are the increase/decrease in the calibration correlations from the original reconstructions. For instance, if the number is positive, the calibration correlation increased for the pseudo reconstruction by that much from the original reconstruction. This is another indicator that shows how the pseudo reconstructions performed compared to the original reconstructions, but allowing for seeing important geographic differences in this improvement. Notice that in DJF, the pseudo reconstructions generally performed slightly weaker than the original reconstructions, but this is insignificant as calibration correlations are still very high. In JJA, the pseudo reconstructions outperformed the original reconstructions quite remarkably, and this can be seen spatially across the continent in Fig. 2.15 (also evident in Fig. 2.14). During the transition seasons of MAM and SON, the spatial uniformity of high calibration correlations across the entire Antarctic no longer exists. High correlations still exist in the Antarctic Peninsula region, likely due to the predictor station Orcadas located off the tip of the peninsula that helps constrain the reconstructions in this region, while in the Antarctic interior and in coastal East Antarctica, reconstruction skill is dampened, due these locations being much farther from the midlatitude predictors. However, these are still deemed skillful, and will be used as a foundation of this thesis work.
Even though the work of Fogt et al. (2016a,b) is highly valuable to the literature and the Antarctic community, their pressure reconstructions leave out major portions of the continent. The continent of Antarctica is immense, and with only producing long-term pressure reconstructions at 18 individual stations, it leaves large amounts of area unaccounted for, especially in West Antarctica and across the Antarctic Plateau. This thesis is an extension of the Fogt et al. (2016a,b) pressure reconstructions, where now a seasonal spatial pressure reconstruction (temporally and horizontally complete) across the entire continent will be attempted to help to fill in the gaps between the 18 stations already reconstructed, in attempts to understand how long-term atmospheric circulation changes are related to ongoing Antarctic climate change and variability.
Figure 2.15: Spatial plot of the pseudo reconstruction calibration correlations. Numbers after the station name indicates the increase/decrease in the pseudo calibration correlation from the original reconstructions calibration correlations. See text for full details. Figure extracted from Fogt et al. (2016a).
2.7 Spatial Interpolation Methods

A common method in atmospheric sciences to predict values where no *in situ* observations are measured is interpolation. Interpolation predicts values by using a limited number of sample observation points to predict nearby grid points. Interpolation is a popular way to predict values in atmospheric sciences because it heavily relies on correlations among the variables being predicted in space; things that are close together normally have similar characteristics and variability. This is also true in Antarctica, where much of the Antarctic Plateau and East Antarctica is homogeneous in nature and there is not much elevation variation, allowing for interpolation methods to even work well when observations are far apart because little variation occurs between observation points. Generally speaking, spatial interpolation is a very important method to help better understand meteorological variables at monthly and seasonal timescales across the globe because of the immense amount of unobserved land and ocean surfaces.

As briefly mentioned in section 2.2, multiple studies have used spatial interpolation methods to reconstruct temperature across the Antarctic continent (Monaghan et al. 2008; Steig et al. 2009; O’Donnell et al. (2011); Nicholas and Bromwich 2014). Steig et al. (2009) used Regularized Expectation Maximum (RegEM) to perform their spatially complete temperature reconstructions. RegEM is a method similar to Principal Component Analysis, which is similar to the PCR method used by Fogt et al. (2016a) in their individual pressure reconstructions, except here Steig et al. (2009) created a spatially complete temperature reconstruction across the continent. The Steig et al. (2009) temperature reconstruction performed well across much of the
continent, with many skill statistics (RE, CE, and r) above 0, meaning their temperature reconstructions are performing better than climatology.

Kriging is another popular spatial interpolation method used in climate and atmospheric sciences, and is the interpolation method used in this study. Originally, a kriging interpolation method was employed by Monaghan et al (2006) to reconstruct Antarctic snowfall, which was further modified by Monaghan et al. (2008) to produce their spatial temperature reconstructions across the continent. Nicolas and Bromwich (2014) also used a kriging interpolation method, similar to Monaghan et al. (2008), to produce their spatial temperature reconstructions, which performed quite successfully across much of the continent.

Figure 2.16 shows skill statistics from the Nicolas and Bromwich (2014) temperature reconstructions. Correlation, $r$, and correlation squared, $R^2$, between the Nicolas and Bromwich (2014) annual spatial temperature reconstruction and one particular atmospheric reanalysis (and station observations, indicated by filled circles) are displayed in Fig. 2.16a-b. As seen, very high correlation values are shown, which indicates that the spatial temperature reconstruction aligns itself very well with this reanalysis during the period of overlap. Verification statistics ($r$ and CE) are also shown in Fig. 2.16c-d. The warm colors in Fig. 2.16d show that the spatial temperature reconstruction is performing better than climatology, but there are multiple regions of cool colors where the reconstruction skill is weaker. Temperature across the continent is much more variable than pressure, further gaining confidence in a more skillful spatial pressure reconstruction conducted in this thesis than from Nicolas and Bromwich (2014).
Furthermore, even with large observational gaps in the Antarctic Interior and West Antarctica, the elevation is quite homogenous in nature allowing for the few stations in these regions to have large similarities with stations farther away. Due to these large spatial relationships and homogeneous land, it again gives further confidence in a more skillful, spatially complete pressure reconstruction across the continent when compared to previous spatially complete temperature reconstructions.

Figure 2.16: Skill statistics for the temperature reconstructions as presented in Nicolas and Bromwich (2014). Statistics are obtained by comparing the reconstructions to reanalysis or observed monthly temperature anomalies at each grid point. Figure extracted from Nicolas and Bromwich (2014).
2.8 Chapter Summary

Global mean temperatures have been rising in recent decades, but ongoing research indicates that temperature trends across the continent of Antarctica act much differently than the global trend. Studies have shown an asymmetric warming across the continent, with the most significant warming in West Antarctica and across the Antarctic Peninsula. These warming trends have also been studied in relation to atmospheric pressure patterns and changes in the atmospheric circulation. Changing pressure trends have been linked to large scale climate modes (i.e. the SAM and ENSO), and these changes in atmospheric circulation have also been linked to recent sea ice changes and changes in ozone.

Due to these known atmospheric pressure/circulation changes in recent decades, this study will now focus on filling in the gaps of missing observations across the continent. This is important for a multitude of reasons. First, it is known that atmospheric pressure/circulations influence temperature, wind patterns, and sea ice, so it is a vital meteorological measurement to fully understand. However, it is hard to fully understand atmospheric pressure/circulation changes in a spatially complete context due to the dearth of observations and due to their short observational time periods. Century length station-based pressure reconstructions were performed at 18 staffed research stations across the continent, but again a fault of this is the large gaps across the continent. Due to this work, these large observational gaps will now be filled in with a best estimate of the atmospheric pressure in a seasonal context back through 1905. This not only helps with the sparse observational network problem, but also with the short observational record
problem, as now seasonal reconstructions will be performed back to 1905 across the entire Antarctic continent.
3.1 Data Utilized

3.1.1 Observational Pressure Records

All observational datasets that will be used for this study can be easily and freely accessed online. Antarctic observations, both from staffed research stations and automatic weather stations (AWS) were retrieved from the Reference Antarctic Data for Environmental Research (READER; www.antarctica.ac.uk/met/READER; Turner et al., 2004) archive. This dataset consists of near-surface climate data, such as temperature, surface pressure, mean sea level pressure, wind direction, and wind speed; it also includes upper air data. This study will primarily use mean sea level pressure and surface pressure observational data from 19 staffed research stations across the continent (while data from select AWSs will also be used for reconstruction evaluation). Seasonal means of this pressure data will be used, as the station-based pressure reconstructions in Fogt et al. (2016a,b) are seasonal means. It is critical for this study to use seasonal means to help eliminate the high day-to-day variability that can occur across the continent. Seasons will consist of December-January-February (summer, DJF), March-April-May (autumn, MAM), June-July-August (winter, JJA), and September-October-November (spring, SON). This method of defining the seasons in this manner is consistent with the seasonal station-based pressure reconstructions in Fogt et al. (2016a,b). DJF is defined from the starting year (i.e. DJF 1979 = December 1979, January-February 1980).
The READER archive includes data that has been quality controlled and has a record of at least 25 years. The development of this dataset has been a valuable tool in helping understand Antarctic climate variability during the observational period (since approximately 1957 when observations began). This work will primarily use staffed research stations and AWSs that have the longest and most complete records. However, only those staffed research stations that were used in the Fogt et al. (2016a) station-based pressure reconstructions will be used here to produce the spatial seasonal reconstructions, with the exception of Orcadas, which has an observational record that extends back to 1903 (red dot in Fig. 3.1). Therefore, 19 stations (N=19) will be used to produce the seasonal spatial pressure reconstructions presented here, while the remaining selected stations will be used for evaluation. Several Antarctic observation station records needed to be patched with other nearby station observation data to make the records as complete as possible. Fogt et al. (2016a) patched many of these records using linear regression of mean sea level pressure / surface pressure by month to produce a more complete record. McMurdo and Scott stations, along with O’Higgins and Marsh stations, were merged together due to the proximity between the stations, now producing more complete records for each. For a complete list of staffed research stations used in this work, refer to Table 3.1 (also see Fig. 2.13a or Fig. 3.1 for geographic reference).
Table 3.1: Details of staffed research stations in Antarctica as used in Fogt et al. (2016a) to produce seasonal station reconstructions (plus Orcadas station located off the northern Antarctic Peninsula).

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Lat °N</th>
<th>Lon °E</th>
<th>Station ID</th>
<th>Start yr</th>
<th>% complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amundsen-Scott</td>
<td>-90.0</td>
<td>0.0</td>
<td>890090</td>
<td>1957</td>
<td>100</td>
</tr>
<tr>
<td>Bellingshausen</td>
<td>-62.2</td>
<td>-58.9</td>
<td>890500</td>
<td>1959</td>
<td>99.85</td>
</tr>
<tr>
<td>Byrd</td>
<td>-80.0</td>
<td>-119.4</td>
<td>893240</td>
<td>1957</td>
<td>84.30</td>
</tr>
<tr>
<td>Casey</td>
<td>-66.3</td>
<td>110.6</td>
<td>896110</td>
<td>1957</td>
<td>99.71</td>
</tr>
<tr>
<td>Davis</td>
<td>-68.6</td>
<td>78.0</td>
<td>895710</td>
<td>1957</td>
<td>92.25</td>
</tr>
<tr>
<td>Dumont d'Urville</td>
<td>-66.7</td>
<td>140.0</td>
<td>896420</td>
<td>1956</td>
<td>99.57</td>
</tr>
<tr>
<td>Esperanza</td>
<td>-63.4</td>
<td>-57.0</td>
<td>889630</td>
<td>1945</td>
<td>94.69</td>
</tr>
<tr>
<td>Faraday / Vernadsky</td>
<td>-65.3</td>
<td>-64.3</td>
<td>890630</td>
<td>1947</td>
<td>95.15</td>
</tr>
<tr>
<td>Halley</td>
<td>-75.5</td>
<td>-26.7</td>
<td>890220</td>
<td>1957</td>
<td>100</td>
</tr>
<tr>
<td>Marambio</td>
<td>-64.2</td>
<td>-56.7</td>
<td>890550</td>
<td>1970</td>
<td>98.48</td>
</tr>
<tr>
<td>Mawson</td>
<td>-67.6</td>
<td>62.9</td>
<td>895640</td>
<td>1954</td>
<td>99.86</td>
</tr>
<tr>
<td>McMurdos / Scott Base</td>
<td>-77.9</td>
<td>166.8</td>
<td>896640/89</td>
<td>1956</td>
<td>99.71</td>
</tr>
<tr>
<td>Mirny</td>
<td>-66.6</td>
<td>93.0</td>
<td>895920</td>
<td>1956</td>
<td>100</td>
</tr>
<tr>
<td>Novolazarevskaya</td>
<td>-70.8</td>
<td>11.8</td>
<td>895120</td>
<td>1961</td>
<td>99.84</td>
</tr>
<tr>
<td>O'Higgins / Marsh</td>
<td>-63.3</td>
<td>-57.9</td>
<td>890590/89</td>
<td>1969</td>
<td>97.55</td>
</tr>
<tr>
<td>Orcadas'</td>
<td>-60.7</td>
<td>-44.7</td>
<td>889680</td>
<td>1903</td>
<td>100</td>
</tr>
<tr>
<td>Rothera</td>
<td>-67.6</td>
<td>-68.1</td>
<td>890620</td>
<td>1946</td>
<td>90.69</td>
</tr>
<tr>
<td>Syowa</td>
<td>-69.0</td>
<td>39.6</td>
<td>895320</td>
<td>1957</td>
<td>91.67</td>
</tr>
<tr>
<td>Vostok</td>
<td>-78.5</td>
<td>106.9</td>
<td>896060</td>
<td>1958</td>
<td>97.02</td>
</tr>
</tbody>
</table>

*Observations, rather than reconstructed pressure data, will be used for this station when producing the spatial reconstructions.

The other set of observational data being obtained from the READER archive are AWS observations across the continent. Again, mean sea level pressure or surface pressure will be used and seasonal means will be calculated using the same methodology as noted above. Nine AWSs across the continent were selected and these can be found in Table 3.2. These stations can also be seen in Fig. 3.1 for geographic reference. Figure 3.1 shows staffed research stations used to produce the seasonal spatial pressure.
reconstructions (green dots and red dot) while the purple dots represent selected AWSs used to help evaluate the spatial reconstructions. These AWSs were selected for two main reasons: first, these nine AWSs represent the three main geographic sectors across the continent in the best manner possible; second, this group of AWSs were the stations with the most complete records. Naturally, AWSs are not staffed which unfortunately leads way to some stations having incomplete records due to equipment failures, likely due to the harsh meteorological conditions and the inability to routinely service the stations, and especially so during the winter and in Antarctica compared to other locations (Lazzara et al. 2012). Even with some discontinuities in the data, these AWS data are of importance as they can be used as evaluation points during the period of overlap between the AWS observations and the seasonal spatial pressure reconstructions. Many of these stations are located far away from staffed research stations, so any observational data collected in between staffed research stations across the continent is very crucial. Large observational gaps in East Antarctica and West Antarctica are still present even with the addition of AWSs; however, this is not surprising as it is very difficult to access many portions of the continent. To help account for these large observational gaps across the continent, gridded pressure datasets (mostly atmospheric reanalyses) will also be used as discussed in the next section.
Table 3.2: Details of automatic weather stations (AWSs) used in this study for spatial reconstruction evaluation.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Lat °N</th>
<th>Lon °E</th>
<th>Station ID</th>
<th>Start yr</th>
<th>End yr</th>
<th>% complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butler Island</td>
<td>-72.7</td>
<td>-60.2</td>
<td>892660</td>
<td>1986</td>
<td>2015</td>
<td>91.67</td>
</tr>
<tr>
<td>Dome C II</td>
<td>-75.1</td>
<td>123.4</td>
<td>898280</td>
<td>1996</td>
<td>2015</td>
<td>98.75</td>
</tr>
<tr>
<td>Gill</td>
<td>-80.0</td>
<td>-178.6</td>
<td>893760</td>
<td>1985</td>
<td>2015</td>
<td>91.94</td>
</tr>
<tr>
<td>Larsen Ice Shelf</td>
<td>-66.9</td>
<td>-60.9</td>
<td>892620</td>
<td>1985</td>
<td>2015</td>
<td>82.5</td>
</tr>
<tr>
<td>Leningradskaja</td>
<td>-69.5</td>
<td>159.4</td>
<td>896750</td>
<td>1971</td>
<td>1990</td>
<td>100</td>
</tr>
<tr>
<td>LGB35</td>
<td>-76.0</td>
<td>65.9</td>
<td>895680</td>
<td>1994</td>
<td>2008</td>
<td>100</td>
</tr>
<tr>
<td>Relay</td>
<td>-74.0</td>
<td>43.1</td>
<td>897440</td>
<td>1995</td>
<td>2015</td>
<td>78.94</td>
</tr>
<tr>
<td>Russkaya</td>
<td>-74.8</td>
<td>-136.9</td>
<td>891320</td>
<td>1980</td>
<td>1990</td>
<td>100</td>
</tr>
<tr>
<td>Theresa</td>
<td>-84.6</td>
<td>-115.8</td>
<td>893140</td>
<td>1995</td>
<td>2015</td>
<td>85.00</td>
</tr>
</tbody>
</table>
Figure 3.1: Spatial plot of staffed research stations and automatic weather stations (AWS) across the continent used in this study. Orcadas is represented by the red dot; this station will use direct observations in the spatial reconstructions.
3.1.2 Gridded Pressure Data

Gridded pressure datasets are useful in many ways, but most importantly to help fill the gaps between direct observations and to examine previous states of the atmosphere before observations began. As already discussed in section 2.6 above, an atmospheric reanalysis is essentially just a model analysis of the past atmosphere in six hour intervals that assimilates surface, satellite, and upper-air data into the reanalysis. Due to such a large amount of data that is assimilated into a reanalysis, they are constrained fairly well and are useful tools; however, this is highly dependent on time and will be demonstrated below. A reanalysis is not considered an observational dataset, but they do provide an immense amount of information that would further be unknown without them. For this study, three gridded pressure reanalyses will be used for spatial reconstruction verification, namely the European Center for Medium range Weather Forecasting (ECMWF) Interim reanalysis (ERA-Interim or ERA-Int; Dee et al. 2011), the European Center for Medium range Weather Forecasting (ECMWF) 20th century reanalysis (ERA-20C), and the National Oceanic and Atmospheric Administration – Cooperative Institute for Research in Environmental Studies (NOAA-CIRES) century reanalysis, version 2c (20CR, Compo et al. 2011). Seasonal means of the atmospheric reanalyses will be used.

Two atmospheric reanalyses that extend throughout the entire twentieth century are examined in Fig. 3.2 to demonstrate how the reliability of mean sea level pressure in these reanalyses across the high southern latitudes is very time dependent. The root mean square difference (RMSD) between ERA-20C and 20CR is shown from 1905-2013
poleward of 60ºS for each season. Root mean square difference depicts the mean difference (regardless of sign) between two variables, with low differences corresponding to good agreement between the two variables. In Fig. 3.2, very high RMSD (i.e., model disagreement) is seen across all four seasons between 60ºS – 90ºS prior to approximately 1960. RMSD doesn’t fall below 2hPa and stay below (or very near) 2hPa until approximately 1980. This indicates that prior to the mid twentieth century, these atmospheric reanalyses do not agree well with each other, and large differences exist in mean sea level pressure back through time; this is due to very few observations being used to constrain the model (occasional ship and exploration data). Ultimately, this is another strong motivation of this work: to improve upon these atmospheric reanalyses that show large discrepancies between one another, but are the only spatial data sources available in the early 20th century (prior to this work).

Gridded reanalyses are calculated at different spatial and temporal resolutions across many different atmospheric parameters, many of which also use different assimilation schemes. The most reliable atmospheric reanalysis used in this study will be ERA-Interim (Bracegirdle and Marshall 2012; Fig. 3.3). This reanalysis has a spatial horizontal resolution of 0.75º x 0.75º grid spacing. This means that there are 480 longitude and 241 latitude grid points with horizontal dimensions of 0.75º x 0.75º. ERA-Interim data can be accessed freely online from http://apps.ecmwf.int/datasets/ and the data used in this study are also hosted locally at Ohio University on the Scalia Laboratory data server. ERA-Interim reanalysis data is available from January 1979-present.

Reanalysis data is most reliable in the high southern latitudes after the modern satellite
era of 1979 during which more data is assimilated into the reanalysis helping to constrain it (Bracegirdle and Marshall 2012; Fig. 3.2 as an example). Due to this, the covariance structure in ERA-Interim will be used for this study to constrain the spatial reconstructions in the generation of the kriging weights. Since the ERA-Interim data is retrieved in latitude-longitude form with a horizontal resolution of 0.75° x 0.75° (or ~80km), it will be converted to an 80km x 80km² Cartesian grid; this makes each cell an even area and simplifies the interpolation procedure.

Figure 3.2: Root Mean Square Difference (RMSD; model disagreement) between ERA-20C and 20CR poleward of 60ºS from 1905-2013.
Figure 3.3 depicts that ERA-Interim is of high reliability when comparing against four other global contemporary reanalyses. Bracegirdle and Marshall (2012) examined five different reanalyses, and Fig. 3.3 shows their mean sea level pressure results. Each circle represents an individual observation station and how well that station’s observations are correlated (size of circle) to each of the five reanalyses over three different decades. Shading represents the bias between station observations and each of the reanalyses at that station grid point. The name of each reanalysis is given in the lower left of each plot and are as follows: 40-yr ECMWF Re-Analysis (ERA-40), Japanese 25-year Reanalysis (JRA-25), ECMWF Interim Re-Analysis (ERA-Interim), Modern Era Retrospective-Analysis for Research and Applications (MERRA), and Climate Forecast System Reanalysis (CFSR). The numbers at the top of each plot show the unweighted multi-station average bias for three regions: (left) all available Antarctic stations in the Western Hemisphere and north of 78ºS, (middle) all interior stations (at or south of 78ºS), and (right) all stations in the Eastern Hemisphere and north of 78ºS. NaN indicates that no interior stations were used in the mean sea level pressure results. Generally, ERA-Interim has the smallest bias and highest correlations with each of the station observations, so it can be concluded that ERA-Interim is the most reliable atmospheric reanalysis in the high southern latitudes when studying mean sea level pressure.
Figure 3.3: Differences between observations and reanalyses across three different time periods. Size of the circle represents correlation between the reanalyses and each observation station. Shading represents bias. See text for more details. Figure extracted from Bracegirdle and Marshall (2012).

The Fogt et al. (2016a) pseudo station-based pressure reconstructions also used data from the 20CR, and furthermore used a gridded pressure dataset (not a reanalysis) known as the Hadley Centre gridded mean sea level pressure version 2 (HadSLP2; Allan and Ansell 2006) to generate pseudo reconstructions as explained in Chapter 2. HadSLP2 is a gridded observational dataset, while the other products mentioned above are global reanalyses. HadSLP2 is a unique dataset that combines monthly globally-complete fields of data across land and marine observations and is represented on a 5° latitude-longitude grid that dates to 1850. Observational data were collected from 2228 land and island stations around the globe, while marine observations came from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). After these observations were collected, the land-based and marine-based observations were blended and reconstructed.
across the globe following an optimal interpolation procedure (Allan and Ansell 2006). Therefore, the HadSLP2 5º gridded latitude-longitude pressure dataset is different from a reanalysis in the fact that it uses direct observational data, unlike a global reanalysis which employs an assimilation scheme based on surface, satellite, and upper-air data to produce a reanalysis back through time.

Similar to ERA-Interim, the ERA-20C and 20CR gridded datasets are global atmospheric reanalyses. However, these are century long reanalyses that date back throughout the entire twentieth century (unlike ERA-Interim that only dates back to 1979). ERA-20C has a spatial resolution of 1.5º x 1.5º while 20CR has a spatial resolution of 2.0º x 2.0º, both resulting in a slightly less detailed resolution than that of ERA-Interim.

Of the previously mentioned gridded pressure datasets, ERA-Interim, ERA-20C, 20CR, and HadSLP2 will be used to help validate the spatially complete seasonal pressure reconstructions produced in this study. However, only ERA-Interim will be used to generate the kriging weights from 1979-2013. Since the most reliable Antarctic observations only extend back to ~1957 and large observational gaps still exist across the continent, these reanalyses will be useful to further validate the seasonal spatial reconstructions; however, as it was shown in Fig. 3.2 above, there are many issues with these century long reanalysis products in the early half of the twentieth century.

3.1.3 Antarctic Station-Based Pressure Reconstructions

The last data source will come in the form of the Fogt et al. (2016a) seasonal station-based pressure reconstructions. As stated in the literature review, these pressure
reconstructions were performed at 18 individual stations across the continent, so large spatial observational gaps still exist. These reconstructions were performed seasonally, primarily to strengthen the pressure relationship between Antarctica and the midlatitudes of the Southern Hemisphere. Fogt et al. (2016a) extended these reconstructions back to 1905, and these station-based pressure reconstructions are crucial to the spatial reconstructions produced here because they are the foundation of the long-term prediction. Instead of using \textit{in situ} observations at each station across the continent to produce a spatial reconstruction that would only date back to \(\sim\)1957, the Fogt et al. (2016a) seasonal station-based pressure reconstructions will be used to extend the spatial reconstruction back to 1905. By doing this, it will more than double the length of the observational records across the continent and more than triple the length of reliable complete spatial and temporal coverage (since ERA-Interim only extends to 1979). The station-based seasonal pressure reconstructions can be used to replace \textit{in situ} observations because of the known high overall skill of the Fogt et al. (2016a) reconstructions, as presented above in chapter 2.6. Also for the purposes of this study, only the ‘full’ reconstructions from Fogt et al. (2016a) will be used here (i.e. full reconstructions used the leave-one-out cross validation method and produced similarly high or often more skillful results than either the ‘early’ or ‘late’ methods).

Twelve different reconstructions methods were used by Fogt et al. (2016a), as discussed in section 2.6. These twelve methods included: 5% and 10% mid-latitude predictor networks, raw vs detrended data, using pseudo-proxy reconstructions, and finally reconstructions that end in either 2011 or 2013. The pseudo-proxy reconstructions
used only raw data (with the trends retained). Out of these twelve methods, eight were produced without using pseudo-proxies, while the remaining four methods used pseudo-proxies. For the purpose of this study, the pseudo-proxy reconstructions will be kept separate from the non-pseudo-proxy reconstructions. Furthermore, for consistency across all reconstruction methods, any reconstruction method that ended in 2011 was updated through 2013.

Of all the station-based reconstructions produced in Fogt et al. (2016a), only the ‘best’ (meaning most skillful) reconstructions were chosen from the original and pseudo reconstructions. These ‘best’ station-based reconstructions at each of the 18 stations provided two new reconstruction datasets (best original and best pseudo) used in generating the two main versions of the spatial reconstructions here. All twelve reconstruction methods will however be examined to test for reconstruction uncertainty against the selected ‘best’ reconstructions that are presented in this research.

3.2 Spatial Reconstruction Method

Here, the steps to create the seasonal spatial pressure reconstructions are outlined. The software programming language used for the generation and analysis of the spatial pressure reconstructions is the National Center for Atmospheric Research (NCAR) Command Language (NCL).

3.2.1 Seasonal Anomaly Calculations

For purposes of this study, seasonal anomalies, or departures from the 1981-2010 seasonal climatology, must be reconstructed due to the extreme terrain differences seen
across the continent from the coast to the interior of the continent. This difference in terrain is also why observational mean sea level pressure is used for staffed research stations near the coast and surface pressure is used for all interior stations. The seasonal anomalies are calculated as follows:

\[
anomaly_{k,n} = \text{observation}_{k,n} - \text{climatological mean}_k
\]

Equation 3.1

where \( k \) represents each individual station (or grid point) used in the study and \( n \) represents each year in the study. The climatological mean is calculated from the reference 30-year observational period of 1981-2010. Simply, in each season an anomaly at location \( k \) for any year \( n \) is calculated by subtracting the climatological mean at the \( k \) station from the \( k \) station observation for year \( n \). This method of calculating seasonal anomalies is consistent across all data used in this study. All gridded pressure datasets, observational datasets, and reconstructions produced and used from Fogt et al. (2016a) are seasonal anomalies.

3.2.2 Kriging Spatial Interpolation

For this study, 19 stations are used in the spatial interpolation (\( N=19 \); Table 3.1). The method used here is directly adapted from Nicolas and Bromwich (2014), formerly used to reconstruct seasonal temperature anomalies across the continent from 1958-2010. Originally however, this kriging method was first developed and successfully used by Monaghan et al. (2006) to reconstruct Antarctic snowfall and then again adapted by Monaghan et al. (2008) to reconstruct Antarctic temperatures. Since then, Nicolas and Bromwich (2014) have refined this method (primarily regarding how the kriging weights
are defined) and have graciously offered the code used in this study, which will be modified to be used with atmospheric pressure. There are two important equations that kriging uses: first, how the interpolation is generated at each individual grid point; and second, how the kriging weights are defined. Both equations are further discussed below.

Ordinary kriging is similar to inverse distance weighting and principal component regression, as it tries to predict/estimate a value at a location where no direct observations are taken. This method of kriging uses known observations and weights them based on how each known observation is related to the unknown locations to be predicted. The kriging interpolation equation can be written as:

$$\Delta y(x, t) = \sum_{k=1}^{N} \lambda_k y_k(t)$$

*Equation 3.2*

where for a certain time $t$, at the grid point location $x$, the predicted value is the sum of the weight(s) at the known observation location(s), $\lambda$, and the measured value, $y$, at the $k$ location for time $t$. For the purposes of this work, and further clarification, equation 3.2 can be expanded and rewritten following the Nicolas and Bromwich (2014) framework as:

$$\Delta \hat{y}(x, t) = \sum_{k=1}^{N} \eta_k(x) \lambda_k(x) \Delta y_k(t)$$

*Equation 3.3*

Similarly, for a certain time $t$, the seasonal pressure anomaly $\Delta \hat{y}$ can be predicted at a certain grid point $x$ based on a combination of several factors. In equation 3.3, $\eta_k(x)$
is either -1 for negative correlations or +1 for positive correlations and this is dependent on the relationship (correlation) between the \( k \) station and the location \( x \) to be predicted; \( \lambda_k(x) \) signifies the weight assigned to the \( k \) station at location \( x \) on the grid and must be \( \geq 0 \); and finally, \( \Delta y_k(t) \) represents the linear combination of seasonal pressure anomalies that are observed (or reconstructed) at \( k_1 \ldots k_N (N=19 \) stations).

Equation 3.3 can further be expanded to help understand the linear combination term and weighting term, as demonstrated in equation 3.4:

\[
\Delta \hat{y}(x, t) = \eta_k(x) \star [\lambda_1 \quad \lambda_2 \quad \ldots \quad \lambda_k] \star \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = \sum_{k=1}^{N} \eta_k(x)\lambda_k(x)\Delta y_k(t)
\]

*Equation 3.4*

The left and right hand sides of equation 3.4 are identical to equation 3.3, and the center represents the linear combination between all of the weights assigned to each individual station \( \lambda_k (N=19) \) and each station’s observed seasonal pressure anomaly \( y_k(t) \).

The kriging weights (\( \lambda \)) are a function of the spatial relationship between a known observation point (\( k \)) and the predicted location (\( x \)). The spatial relationships (or rather footprints) were determined from the seasonal mean surface pressure field in the ERA-Interim reanalysis. The footprints were defined by using the squared Pearson correlation coefficient (\( r^2 \)) between the nearest grid point in ERA-Interim to the observation station (\( k \)) and to every other grid point (\( x \)) in ERA-Interim, from 60ºS – 90ºS. The \( r^2 \) value was calculated from 1979-2013 for every season and staffed research station in Fig. 3.1 (including Orcadas) using detrended data. In other words, these spatial footprints
represent how well each observation station \((k)\) is correlated to every other grid point in ERA-Interim and is represented by \(r^2_{d(x)}\) (see Chapter 4 for further footprinting details).

A key difference between the Monaghan et al. (2008) and Nicolas and Bromwich (2014) kriging reconstructions of temperature deals with how the kriging weights are defined. Nicolas and Bromwich (2014) introduced optimized weighting coefficients, which will also be employed here. Optimized weighting coefficients are used in ordinary kriging to minimize the error of estimation by risk of overfitting. Monaghan et al. (2008) used simple kriging, which allows all contributions of the observations in the interpolation to be included. However, this is a known deficiency because of multicollinearity which increases the risk of overfitting; it is necessary to only look for relationships among stations. To develop the optimal kriging weights \(\lambda\), the following matrix equation can be solved for \(\lambda\), where \(\lambda = (\lambda_1, \ldots, \lambda_N)^T\) are the denoted optimal weights (note that \(k\) and \(N\) are used interchangeably):

\[
\begin{bmatrix}
A & 1 \\
1^T & 0
\end{bmatrix}
\begin{bmatrix}
\lambda \\
\alpha
\end{bmatrix} =
\begin{bmatrix}
b \\
1
\end{bmatrix}
\]

\[\text{Equation 3.5}\]

Each individual matrix in Equation 3.5 is represented by \(A^*, \lambda^*,\) and \(B^*\). Here, \(A^*\) represents a symmetric \(N \times N\) matrix representing the relationships between station observations (more detail forthcoming). \(1\) is a column vector of \(N\) ones, and \(1^T\) denotes the transpose symbol. This matrix accounts for close proximity of stations by reducing their weight and ensuring this strong spatial relationship will not overfit the model, and finally provides information on the relationships between all possible station pairs.
Matrix $\lambda^*$ represents the final weights to be solved for (through matrix inversion), $\lambda$. $\alpha$ represents the Lagrange multiplier. Note that once $\lambda$ is solved for, it can then be used in Equation 3.4 to solve the spatial interpolation at grid point ($x$). Finally, matrix $B^*$ shows the relationships between the station observations and the remaining grid points to be reconstructed; $b$ is a column vector of $N$-elements which contains the spatial footprints calculated at location $x$ where the seasonal pressure anomaly is to be estimated.

To further understand Equation 3.5, it can be rewritten/expanded in matrix notation as:

$$
\begin{bmatrix}
    r_1^2(x_1) & \ldots & r_1^2(x_N) \\
    \vdots & \ddots & \vdots \\
    r_N^2(x_1) & \ldots & r_N^2(x_N) \\
    1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
    \lambda_1 \\
    \vdots \\
    \lambda_N \\
    \alpha
\end{bmatrix} =
\begin{bmatrix}
    r_1^2(x) \\
    \vdots \\
    r_N^2(x) \\
    1
\end{bmatrix}
$$

Equation 3.6

Here, ($x$) is used as a reference to the grid point to be predicted, $N$ indicates the number of observation stations used ($N = 19$ and can be used interchangeably with $k$ as done so above). Matrix $A^*$ can be thought of as the correlation matrix between all observation stations; it shows the relationship between stations and the diagonal is represented by 1s, as all stations are perfectly correlated with itself. Matrix $\lambda^*$ is where the kriging weights ($\lambda$) are solved for each observation station and finally matrix $B^*$ shows the footprinting between the $N$ observation station and the grid point ($x$) being predicted. Equations 3.5 and 3.6 can then be solved for $\lambda$ in matrix $\lambda^*$ by inverting matrix $A^*$. After inverting matrix $A^*$ and solving for ($\lambda_1, \ldots, \lambda_N$), each station will be given an optimized kriging weight and the spatial interpolation (seasonal pressure anomaly) for location ($x$) for at
each time \((t)\) can then be predicted using equation 3.3 or 3.4. This procedure is then repeated again for each season, location, and time step, as well as between spatial reconstructions derived from the pseudo and original station-based reconstructions.

### 3.3 Spatial Reconstruction Evaluation Methods

Here, the steps to evaluate the seasonal spatial pressure reconstructions are outlined.

#### 3.3.1 Model Calibration and Validation

Many spatial pressure reconstructions were performed using different input datasets [i.e. ERA-Interim station grid point data, best original station-based pressure reconstructions, and best pseudo station-based pressure reconstructions; the latter two both from Fogt et al. (2016a)] and by using multiple different validation procedures, as outlined here. The results evaluated below in Chapter 4 are either termed ‘reconstructions’ or ‘validation’ (i.e. validation timeseries). The ‘reconstructions’ statistics evaluate the spatial reconstructions that used the full 1979–2013 timeframe as the calibration period. The calibration period is the period during which the kriging weights were defined. Therefore, the ‘reconstructions’ were calibrated from 1979-2013 and produced a reconstruction timeseries from 1979-2013 for the ERA-Interim spatial reconstruction (i.e. when ERA-Interim data were bi-linearly interpolated to each station location used in the kriging algorithm) or 1905-2013 for the original / pseudo spatial reconstruction (i.e. Fogt et al. (2016a) station-based reconstructions used to generate the spatial reconstruction).
The ‘validation’ timeseries is derived from an additional evaluation procedure following a split calibration / validation period, as previously used in Steig et al. (2009), Nicolas and Bromwich (2014), and Fogt et al. (2016a). The 1979-2013 period is broken into two separate sub-periods; 1979-1996 and 1997-2013. One sub-period is used for model calibration and the remaining period, termed the validation period, is the period that a pressure timeseries was produced and will serve as an independent evaluation measure. For example, the sub-period of 1979-1996 can be used for model calibration to determine the kriging weights used to produce a pressure timeseries from 1997-2013, termed the validation timeseries. This can then be reversed, using model calibration from 1997-2013 and validation being 1979-1996. This will then produce two new independent spatial pressure timeseries (one from 1979-1996 and another from 1997-2013) that can be concatenated to produce one full length validation timeseries from 1979-2013. This validation timeseries can then be compared to the reconstruction timeseries (from 1979-2013) as a way to measure reliability and stability of the kriging reconstruction model, since all the data were withheld in producing this validation series and it is simply a reconstruction of predicted values.

3.3.2 Reduction of Error (RE) and Coefficient of Efficiency (CE)

To help address potential error and uncertainty in the spatial pressure reconstructions, two additional assessment procedures can be assessed: the reduction of error (RE) and coefficient of efficiency (CE). Both RE and CE will be used to evaluate the reconstruction and validation timeseries, respectively.
The RE statistic was used in Fogt et al. (2016a) but first introduced by Lorenz (1956) and is a measure to see if a forecast/reconstruction is more reliable than if just the climatological mean were to be used. For the purpose of this thesis, the RE is explicitly calculated as follows:

\[
RE = 1.0 - \left[ \frac{\sum_{i=1}^{n}(ERA_i - \text{reconstruction}_i)^2}{\sum_{i=1}^{n}(ERA_i - \overline{ERA})^2} \right]
\]

Equation 3.7

where \(ERA\) is the ERA-Interim reanalysis at time \(i\) within 1979-2013 and \(\text{reconstruction}\) is the reconstruction from the full 1979-2013 calibration period. \(\overline{ERA}\) is the mean of the ERA-Interim data from 1979-2013. The RE values can range from \(-\infty\) to +1.0, where anything greater than 0 (zero) indicates the reconstruction is performing better than the climatological mean, and an RE of +1.0 indicates a perfect reconstruction.

The CE statistic was also used in Fogt et al. (2016a) and is calculated explicitly in this thesis as follows:

\[
CE = 1.0 - \left[ \frac{\sum_{i=1}^{n}(ERA_i - \text{validation timeseries}_i)^2}{\sum_{i=1}^{n}(ERA_i - \overline{ERA})^2} \right]
\]

Equation 3.8

Here, the CE equation is almost identical to the RE equation from Eq. 3.7 above. The difference comes in the numerator, where \(\text{validation timeseries}\) is now the concatenated timeseries produced from the split calibration/validation period, and compared against the ERA-Interim reanalysis, our best spatial estimate of pressure variability across Antarctica during 1979-2013. The CE values also range from \(-\infty\) to +1.0, where anything greater than 0 (zero) indicates the validation timeseries is
performing better than the climatological mean, and a CE of +1.0 indicates a perfect validation timeseries. Both the RE and CE will help determine the overall reliability and uncertainty of the kriging model. CE tends to be lower than RE due to the fact that the validation series is based on purely predicted data; as such, the CE is a robust metric to understand the overall reconstruction skill.

3.3.3 Pearson Product-Moment Correlation

The Pearson product-moment correlation is used in this study to help show a linear relationship between multiple different datasets. The Pearson product-moment correlation ($r$) is calculated as follows:

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

Equation 3.9

where $r$ is the correlation coefficient, $x_i$ and $y_i$ are the variables in each separate dataset, and $\bar{x}$ and $\bar{y}$ are the respective means of each dataset. The correlation coefficient $r$ can range from -1 to 1, with $r=1$ representing a perfect positive linear relationship between both datasets and $r=-1$ representing a perfect linear negative relationship. If $r=0$, no linear relationship is seen. In this study correlation strength is represented by $r^2$, or the squared Pearson product-moment correlation (coefficient of determination), which is a measure that indicates the proportion of variance in the dependent variable that is linearly predicted from the independent variable. This value ranges from 0-1, with higher values representing stronger linear relationships.

Correlation analysis and correlation squared ($r^2$; coefficient of determination) will be used across observations, reanalyses, and reconstruction datasets for model evaluation,
generally indicating the strength of linear relationships between two variables (i.e., pressure in this study between two different datasets) with time. Another way of using the Pearson product-moment correlation is in the form of pattern correlations / spatial correlations. The spatial correlation is used in this study to examine the linear relationship of two variables at a given time across a spatial domain, and essentially represents the agreement in the spatial patterns between two variables. All spatial correlations in this work use area weighting (by the square root of the cosine of latitude) as needed, to account for the fact in latitude-longitude gridded data, there is a higher data density near the South Pole (due to the convergence of the meridians), when in fact each data point represents increasingly smaller areas moving poleward.

3.3.4 Mean Absolute Error

Another way to quantify error between Era-Interim from 1979-2013 and the seasonal spatial pressure reconstructions is to examine mean absolute error (MAE). The MAE in this study is used to help visualize the average absolute difference between the spatial pressure reconstruction anomalies and the Era-Interim anomalies. A low mean absolute error is what is strived for, while high mean absolute error values indicate areas of poorer skill (larger absolute difference) in the reconstruction. The MAE measures the average magnitude of error, without considering the direction of the error. The equation used to calculate MAE is as follows:

$$ MAE = \frac{1}{n} \sum_{i=1}^{n} |ERA\ Interim - RECON| $$

*Equation 3.10*
where \( n \) is time, \( ERA \text{ Interim} \) is the pressure anomaly in \( ERA\text{-Interim} \) at a grid point, and \( RECON \) is the pressure anomaly in the spatial reconstruction at that same grid point. Using the term ‘error’ is appropriate given that the goal of the spatial reconstruction is to mimic the best available spatial dataset, namely \( ERA\text{-Interim} \). Comparisons made against this dataset therefore reflect the error that is associated with the reconstruction produced.

### 3.3.5 11-year Hamming Filter

To examine low-frequency (decadal-scale) variability, an 11-year Hamming filter will be used to produce timeseries plots. An 11-year Hamming filter works as follows: years 1 and 11 over the averaging period are weighted by 0.028, years 2 and 10 are weighted by 0.056, years 3 and 9 are weighted by 0.083, years 4 and 8 are weighted by 0.111, years 5 and 7 are weighted by 0.139, and the center, year 6, has the highest weight of 0.167. Unlike a traditional running mean, this method allows the largest weight to be given to the center year, further highlighting decadal-scale variability.

### 3.3.6 Ensemble Standard Deviation

Fogt et al. (2016a) produced twelve different station-based reconstructions using slightly different predictor data methodologies for each separate reconstruction, as outlined previously. Each of these individual reconstruction groups were used to generate the kriging weights and subsequently the spatial pressure reconstructions. As opposed to more sophisticated Monte Carlo approaches, one way to test for reconstruction uncertainty is to examine the ensemble standard deviation. The standard deviation is calculated as follows:
\[ \sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2} \]

*Equation 3.11*

where \( \sigma \) is the standard deviation for a given grid point in the spatial reconstruction, \( x_i \) is the reconstruction value for the \( i^{th} \) reconstruction method, \( \bar{x} \) is the mean of all reconstruction methods at that grid point, and \( n \) is the total number of reconstruction methods. The ensemble standard deviation is the average standard deviation over time. Ensemble standard deviations of the original spatial reconstructions and the pseudo spatial reconstructions were performed.

### 3.4 Spatial Reconstruction Analysis Methods

Here, the methods used to perform an analysis on the spatial pressure reconstructions are listed.

#### 3.4.1 Pearson Product-Moment Correlation

The Pearson Product-Moment correlation (\( r \)) and the coefficient of determination (\( r^2 \)) will also be used as analysis techniques. These methods were previously explained in detail in section 3.3.1.

#### 3.4.2 Trend Analysis

Linear regression is used to investigate linear trends in the spatial reconstructions (also observations, reanalyses, etc.). This method calculates the slope of a line that best fits the data, or in other words produces a line that minimizes distance between the regression line and the actual data. The line of best fit is given by:
where $y$ is the dependent variable (pressure in this instance), $x$ is time (years, the independent variable), $a$ is the y-intercept, and $b$ is the slope of the best fit line. Linear regression calculates the slope of the line ($b$) 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 3.13

where $y_i$ is the dependent variable, pressure, $x_i$ is the independent variable, time (years), and $\bar{x}$ and $\bar{y}$ are the sample averages.

To assess the fit of the line to the data, more calculations are needed. The standard error of the slope ($S_b$) is calculated as follows:

$$s_b = \frac{S_y \sqrt{1 - r^2} \sqrt{\frac{n - 1}{n - 2}}}{S_x \sqrt{n - 1}}$$

Equation 3.14

where $S_y$ is the standard deviation of the dependent variable, $y$ (pressure), $S_x$ is the standard deviation of the independent variable, $x$ (time in years), and $n$ is the number of data points. The correlation coefficient is represented by $r$ and is the correlation between pressure and time. To find the statistical significance of the linear trends, the Student’s t-test is used. This is represented by:

$$t_{n-2} \approx \frac{(b - b_0)}{s_b}$$

Equation 3.15
As in Eqns. (3.12 – 3.13), \( b \) is the actual slope, \( b_0 \) is the hypothesized slope \( (H_0 = 0) \), \( S_b \) is the standard error of the slope from Eqn. 3.14, and \( t_{n-2} \) is the t-value with \((n-2)\) degrees of freedom where again \( n \) is the number of points in the dataset. In all cases, the null hypothesis is \( H_0 = 0 \), and alternative hypothesis is \( H_A \neq 0 \); probabilities given therefore represent the probability of no slope. A two-tailed t-test must be used here in regards to linear trends to allow for both positive and negative slopes, as it is possible to have trends in both directions. The \( t \)-values calculated in Eqn. 3.15 can be used to find the probability that the null hypothesis is true using \( t \)-tables with \( n-2 \) degrees of freedom. Probabilities that linear trends in the data are equal to zero \( (H_0 = 0) \) will be highlighted for probabilities less than 5\% \( (p<0.05) \) and in some cases, also less than 10\% \( (p<0.10) \).

Lastly, 95\% confidence intervals are produced to see the likely range of where the slope is most likely to occur. The 95\% confidence interval is found by:

\[
CI = b \pm t_{n-2, 0.025} \times S_b
\]

*Equation 3.16*

where \( CI \) is the confidence interval, \( b \) is the slope, \( t_{n-2} \) is the two-tailed t-value with \((n-2)\) degrees of freedom with two-tailed \( p<0.05 \), and \( S_b \) is the standard error of the slope. Given this equation, a range can be seen where one is 95\% confident that the actual slope exists within.

### 3.4.3 30-Year Running Trends

To investigate how pressure trends change over time, running trends can be assessed. They are similar to running correlations as they have a moving window of time (30-years in this study) that the trend is calculated over until the end of the dataset is
reached. Specifically, 30-year running trends will be used here as they will allow for the interannual variability to be smoothed out in the spatial pressure reconstructions. These running trends will allow to see how pressure has changed over time (in context of an entire century) over the Antarctic continent.

3.4.4 Spatially Averaged Timeseries

As in Nicolas and Bromwich (2014), the spatial reconstructions will be averaged over the Antarctic Peninsula, and West and East Antarctica to produce a timeseries. These will be compared to ERA-Interim and/or other atmospheric gridded pressure products. Since ERA-Interim is known and widely used due to its high reliability in the high southern latitudes (Bracegirdle and Marshall 2012), it is often treated as ‘observations’ and will be treated as such in this study. To assess the reconstruction uncertainty in these timeseries, another method following Fogt et al. (2016a,b) will be used to calculate confidence intervals used in the timeseries. Here, confidence intervals can be calculated by first calculating the residuals (difference between ERA-Interim and the area-averaged spatial pressure reconstruction) and taking the standard deviation of the residuals over all time steps. Once this is complete, a 95% confidence interval about the area-averaged spatial pressure reconstruction timeseries can be calculated as 1.96 times the standard deviation of the residuals. Confidence intervals designed of this method will be used in all timeseries plots where ERA-Interim is also plotted. If ERA-Interim is not used, the confidence intervals are calculated using the method discussed in section 3.4.2.
3.4.5 Composite Analysis - Comparison of Means

Another analysis method commonly used in climate science is the comparison of means, which is used to investigate the difference of means between two groups of data. In atmospheric sciences, the method of comparing two means is often called composite analysis. For this study, comparison of means will be examined between two different 30-year groups of data from the spatial reconstructions. For example, two 30-year groups of data from the spatial reconstructions would be comparing pressure from 1954-1983 to pressure from 1984-2013. In doing so, it can be seen visually across the spatial domain those locations where the greatest pressure differences between the two time periods are located. Unlike regression analysis, which can be highly sensitive to the starting and ending years of the regression line, this analysis is much less influenced by particular choices made by the analyst. While the difference between groups is important, it is also important to highlight statistically significant differences. A pooled Student’s t-test is used to calculate statistical significance. To begin, the pooled sample variance must be calculated from the following equation:

\[ S_{p}^2 = \frac{(n - 1)S_x^2 + (m - 1)S_y^2}{n + m - 2} \]

*Equation 3.17*

Here, \( n \) and \( m \) are the sample sizes of the two groups (in this study, \( n \) and \( m = 30 \) years) and \( S_x^2 \) and \( S_y^2 \) are the sample variances of each group. After the pooled sample variance, \( S_{p}^2 \), is calculated, the Student’s t-test can be calculated to produce two-tailed t-values from the equation:
\[ t_{m+n-2} = \frac{(\bar{X} - \bar{Y}) - (\mu_x - \mu_y)}{S_p \sqrt{\frac{1}{n} + \frac{1}{m}}} \]

*Equation 3.18*

where \( \bar{X} \) and \( \bar{Y} \) are the means of each group, \( \mu_x \) and \( \mu_y \) are the hypothesized means for each group (here the hypothesized difference of means is zero; \( H_0: \mu_x - \mu_y = 0 \) and that \( H_A: \mu_x - \mu_y \neq 0 \)), and \( S_p \) is the pooled sample standard deviation (i.e. \( S_p = \sqrt{S_p^2} \)).

Again, \( t_{m+n-2} \) represents the two-tailed t-values with \( m+n-2 \) degrees of freedom. In all cases, the null hypothesis is zero difference, and alternative hypothesis is that there is a difference; probabilities given therefore represent the probability that the difference between groups is zero. A two-tailed t-test must be used here to allow for both positive and negative differences between groups. Probabilities less than 5\% (\( p<0.05 \)) will be highlighted to show those areas where the difference between the groups is statistically significant (i.e. 95\% confident that the difference between groups is not zero).
CHAPTER 4: EVALUATION OF 20TH CENTURY ANTARCTIC SEASONAL SPATIAL PRESSURE RECONSTRUCTIONS

4.1 Introduction

To answer the first research question, a thorough evaluation must be performed on the spatial reconstructions. Using multiple different evaluation techniques, it will be determined if a spatial pressure reconstruction across the Antarctic continent and surrounding oceans will be skillful (reliable). However, before an evaluation of the spatial reconstructions can be performed, it must be proven that this is even a feasible task. In other words, it must be shown that this method is possible and yields meaningful results. This will be proven by using several different spatial techniques. First, spatial footprinting (correlations; section 4.2) of observations to ERA-Interim anomalies at every grid point across the spatial domain (60ºS – 90ºS) will be provided. This will help show that even with sparse observations across the continent, a kriging methodology can still be successful to produce the spatial reconstructions. Second, the kriging method will be used to reproduce an already known gridded pressure field across the spatial domain, ERA Interim, from 1979-2013 (section 4.3.1). If using ERA-Interim grid point data at observation locations from 1979-2013 to produce a spatially complete pressure reconstruction is deemed reliable, it should also be useful/reliable to take direct station observations/reconstructions from 1905-2013 to produce a new spatially complete gridded pressure reconstruction.
Once it can be identified that using a kriging methodology to reconstruct pressure across the Antarctic continent is doable and meaningful, an evaluation of the actual spatial reconstructions themselves needs to take place to answer the first research question. A multitude of different techniques will be employed here, which outlines the remainder of the chapter layout: grid point squared correlations, reduction of error (RE), and coefficient of efficiency (CE) all compared with ERA-Interim (section 4.3); mean absolute error (section 4.4); spatial anomaly correlations and spatial mean absolute error (section 4.5), also compared with ERA-Interim and therefore appropriately deemed ‘error’; evaluations of the spatial reconstruction at select grid points and compared with ERA-Interim (section 4.6.1) and automatic weather station (AWS) data (section 4.6.2); an evaluation of the low-frequency and decadal-scale variability (section 4.7); an evaluation of the sensitivity to the input observations used in the kriging model through examining the ensemble standard deviations (section 4.8). In many sections, DJF will first be examined, followed by JJA, and lastly the two transition seasons of MAM and SON, respectively.

4.2 Spatial Footprinting

Observations across the Antarctic continent are very sparse, especially in comparison to how large the continent is. Most stations lie in the Antarctic Peninsula and along the coast of East Antarctica due to easy access (see Fig. 3.1; green/red dot(s) represent stations with longest and most reliable records). The greatest issue of meteorological data collection in Antarctica lies in West Antarctica and over the Plateau
(interior of the continent). In these locations, less than a half dozen reliable stations exist that have long-term observational data. This large spatial gap between stations poses many issues in Antarctic research, but fortunately when examining pressure across the continent, many of the stations have very large spatial footprints (the correlation each station shares with every other grid point in gridded data such as reanalysis data within the domain). This is especially true in DJF when the continent experiences 24 hours of continuous daylight and mostly weak zonal flow around the continent that doesn’t create much deviation in pressure across the continent throughout the season (Turner et al. 2005; Marshall 2007). Furthermore, due to the homogeneous nature of the topography of the continent (except for the Transantarctic Mountains separating East from West Antarctica), the pressure field is relatively similar, hence large spatial footprints with many stations. In this section, spatial footprints based on squared Pearson correlations, will be examined between all 19 stations used in this study and every other grid point on an 80km x 80km² Cartesian grid that overlays the study area spatial domain of 60ºS – 90ºS from 1979-2013. These spatial footprints are calculated by using detrended ERA-Interim grid point data, which means the temporal trends in the reanalysis data have been removed before performing the correlations. Furthermore, understanding the spatial footprints is a very important process in defining the kriging weights for each station. As explained in the previous chapter, one component to defining kriging weights for a given station is how well each station shares a relationship with every other grid point across the continent, and these spatial footprinting plots discussed below help to visualize this process.
Figure 4.1 shows the DJF spatial footprinting ($r^2$) at all 19 stations used in this study to produce the spatial reconstructions. Similarly, Fig. 4.2 represents JJA, Fig. 4.3 represents MAM, and Fig. 4.4 represents SON. These footprints for each station were calculated by extracting the nearest grid point to each station from ERA-Interim and calculating the correlation between that grid point from ERA-Interim with every other grid point in the ERA-Interim spatial pressure field using detrended data. During DJF, the largest spatial footprints are seen, which is not all that surprising given the fact that this is the season where mostly zonal flow is exhibited around the continent, among other reasons mentioned briefly above. During the other seasons, the spatial footprints are not quite as large, but still meaningful in that the grid points over most of the continent never experience an $r^2$ value less than 0.8.

In each figure (Fig. 4.1 – Fig. 4.4), plots a-g depict the spatial footprints for the Antarctic Peninsula stations, plots h-p represent each station around the East Antarctic coast, and finally plots q-r represent the three interior stations used in this study. The Antarctic Peninsula is quite mountainous, and often influenced by the westerly storm track (Simmonds et al. 2003), so these stations have much smaller footprints compared to those outside of the Peninsula region. Basically, the pressure variability in the peninsula region during all seasons is not a good representation of the pressure variability over the greater continent itself. However, these peninsula stations are very important as they help to constrain the spatial reconstructions over the nearby oceans (Amundsen, Bellingshausen, and Weddell Seas) and to produce reliable spatial reconstructions over the peninsula. The peninsula stations have much larger footprints over the Weddell Sea
than the Bellingshausen Sea, so these stations act to produce a better, or more skillful spatial reconstructions in the Weddell Sea region.

The East Antarctic coastal stations exhibit larger spatial footprints during DJF and high $r^2$ values are seen around much of East Antarctica, especially along the coast. Vostok and Amundsen-Scott are two interior stations that have very large spatial footprints in DJF, but are much smaller during the other seasons, especially during the transition seasons of MAM and SON where they exhibit a much weaker relationship with East Antarctic coastal stations. Again, this is likely attributed to the fact that during these seasons, more meridional flow around the continent is experienced, allowing for heat transfer and low pressures to influence the coastal stations. In addition, sea ice is rapidly changing in these seasons, expanding in MAM and retreating in SON, which affects the pressure variability much more along the coasts, making it notably different than the interior of the continent at these times.

Figures 4.1s – Fig 4.4s are also a very important component to this work. As previously mentioned by Nicolas and Bromwich (2014) and their temperature reconstructions, Byrd station has a very important spatial footprint. Currently, West Antarctica is the most susceptible region of the continent to climate change (discussed in literature review), yet it only has one observation station with reliable, long-term data collection (minus the decade of missing data in the 1970s). Fortunately, the lack of other long-term stations in West Antarctica isn’t all too detrimental for this research, as Byrd station has a very large spatial footprint across West Antarctica during all seasons. The extent of Byrd’s pressure relationship with West Antarctic pressure variability is largest
during DJF, but still impressive during the other seasons as well. Due to this large footprint, especially in DJF, it is anticipated that this will not hinder the spatial reconstructions too severely. Since Byrd station shares a relationship with many other grid points across West Antarctica, it is a key station that is needed to be included in the spatial reconstructions, even with knowing of possible reconstruction errors in the Fogt et al. (2016a) station-based Byrd reconstruction due to the missing data in the 1970s. As it can be seen in Figs. 4.1-4.4, no other stations share the relationship to West Antarctica as Byrd does, so it is paramount to include in this work, as similarly concluded by Nicolas and Bromwich (2014).

Lastly, and of most importance in each Figs. 4.1-4.4 is the bottom right panel, labeled MaxAbs. This figure is a representation of the maximum absolute spatial squared correlations from each station from panels a-s. Simply put, all the stations spatial footprints are combined to help easily visualize areas in the spatial domain that have lower footprints, and therefore likely reduced reconstruction skill using a kriging method. Figure 4.1t shows that maximum absolute $r^2$ values across the entire continent and almost all $r^2$ values across the continent are above 0.9 during DJF. This is very impressive, and is promising that even locations far away from observation stations still share a spatial relationship with the limited number of observation points, and can be filled in reliably with a kriging technique. During DJF, the only locations that have slightly lower $r^2$ values are near the Oates Coast (between Dumont and McMurdo stations) and a small area in Dronning Maud Land. During JJA in Fig. 4.32t, again high $r^2$ values are seen across much of the continent, but now spatial footprints have shrunk slightly and lead to
much lower $r^2$ values near the base (southern portions) of the Antarctic Peninsula, near the Oates Coast, and again in Dronning Maud Land. However, most of the continent is still at or above $r^2 = 0.9$. In the transition seasons (Figs. 4.3t and 4.4t), the overall spatial footprints again have reduced markedly. The East Antarctic stations only share strong spatial relationships with grid points in ERA-Interim nearest them along the coast. Progressing inland toward the Pole, these stations (Amundsen-Scott and Vostok) do not have a strong spatial relationship with the coastal stations as they did in JJA or DJF. Expectedly, the same locations that had smaller $r^2$ values in the previous seasons do here in the transition seasons as well. However, after examining all MaxAbs panels (Figs. 4.1t, 4.2t, 4.3t, 4.4t) by season, all grid points across the continent never fall below $r^2 = 0.6$.

As previously mentioned in Chapter 3, the kriging weights are defined based on these spatial footprinting plots described here. This is a possible source of error in the kriging spatial pressure reconstructions as some locations in the spatial domain to do not share strong spatial relationships with the observation stations being weighted, especially in MAM and SON, and closer to the northern extent of the domain in all seasons. Therefore, errors can arise due to error in the spatial relationship each station holds with every other grid point. It also complicates the weighting scheme where grid points are trying to be reconstructed but do not hold strong relationships with observation stations. For example, the Amundsen Sea, located off the coast of West Antarctica, never shows a strong relationship ($r^2 > .9$) with any observation station. Therefore, the spatial reconstructions may be less reliable in this region due in part because of the weak spatial
relationship it holds with the observations located on the continent throughout each season. This issue will be examined in further depth in a following section.
Figure 4.1: Squared Pearson Correlations ($r^2$; footprints) during DJF with each observation station and every other grid point using ERA-Interim detrended data. The label bar indicates $r^2$ values that each individual station shares with every other grid point in the domain.
Figure 4.2: Same as Fig. 4.1 but for JJA.
Figure 4.3: Same as Fig. 4.1 but for MAM.
Figure 4.4: Same as Fig. 4.1 but for SON.
4.3 Skill Statistics of the Spatial Pressure Reconstructions from 1979-2013

All spatial pressure reconstructions and reanalysis data used throughout this research are conducted using an 80km x 80km$^2$ Cartesian grid centered over the South Pole. As previously mentioned, this is done because ERA-Interim data are retrieved in latitude-longitude format with a horizontal resolution of 0.75º x 0.75º, or approximately 80km grid spacing. Therefore, by using an 80km x 80km$^2$ Cartesian grid, all grid points are evenly spaced by 80km in the reconstructions and reanalysis data (after the reanalysis data are interpolated (regridded) onto the Cartesian grid). This makes it very easy to perform grid point calculations such as squared correlations, RE, CE, and mean absolute error (MAE; discussed in section 4.4) between different datasets. Grid point squared correlations ($r^2$) will be examined between the ERA-Interim spatial reconstruction, the original spatial reconstruction, and the pseudo spatial reconstruction against ERA-Interim grid point anomaly data in the following sections. From here forward, original reconstructions refers to the spatial reconstruction created by using the best original station-based reconstruction pressure anomalies from Fogt et al. (2016a) extending back to 1905 (here only 1979-2013 will be evaluated), unless otherwise specified. Similarly, pseudo reconstructions refers to the spatial reconstruction created by using the best pseudo station-based reconstruction pressure anomalies from Fogt et al. (2016a) extending back to 1905 (here only 1979-2013 will be evaluated). Furthermore, recall that 18 staffed research stations were used in the Fogt et al. (2016a) station-based reconstructions which will be used here to help fill in the spatial grid; direct observations from the station Orcadas are also used since its record extends back to 1903, and it is
more accurate to use direct observations than to use a reconstruction when/if possible. The skill statistics (grid point squared correlations and MAE) analyze how well the spatial reconstructions align with ERA-Interim data, while the RE and CE allow to see how reliable a spatial pressure reconstruction is compared to the climatological mean (RE and CE values greater than zero indicate a reconstruction more reliable than if the climatological mean were used). This period of overlap between the spatial reconstructions and ERA-Interim (1979-2013) will be the evaluation period for the original and pseudo spatial reconstructions. The evaluation period can only extend back to 1979 because this is the year when ERA-Interim data begins. Each season will be evaluated for both original and pseudo spatial reconstructions, along with a spatial reconstruction using ERA-Interim grid point station data (termed ERA-Interim reconstruction).

4.3.1 ERA-Interim and Observational Seasonal Spatial Pressure Reconstructions

One of the first measures taken in this research was to examine how well the kriging model could reproduce a known complete spatial pressure field from ERA-Interim during 1979-2013. To do this, seasonal timeseries grid point data from 1979-2013 were extracted from ERA-Interim for all 19 stations (i.e., Fig. 4.1) and used to produce the spatial reconstruction. Once the seasonal timeseries data were extracted from ERA-Interim for each station, anomalies were calculated for each station and then this anomaly data for each station was read into the kriging model to produce the ERA-Interim seasonal spatial reconstruction. In theory, the ERA-Interim driven seasonal spatial pressure reconstruction should align itself very well with the original (raw) seasonal
spatial pressure fields in ERA-Interim (model analysis data constrained by additional observations, including satellite data) since the kriging model is using ERA-Interim grid point data to produce seasonal ERA-Interim spatial pressure reconstructions and essentially interpolating to fill the gaps between observation locations.

Figures 4.5 - 4.8 demonstrate the skill of the ERA-Interim seasonal spatial pressure reconstructions produced from 1979-2013 by using ERA-Interim station data. The background fill in Figs. 4.5 – 4.8 corresponds to the comparison between the spatial pressure reconstruction and the ERA-Interim reanalysis at every grid point. The dots in each of these figures represent each of the nine automatic weather stations (AWS) used in this study (Fig. 3.1), and their fill color corresponds to the comparison between the AWS observations and the closest gridpoint in the spatial pressure reconstruction. Note that AWS observations are not always continuous and none of these stations have complete data (see Table 3.2) from 1979-2013; this time difference therefore results in a comparison that is not fully equivalent to the background fill, which covers the full period of 1979-2013. This is likely the reason of some lower skill statistics at some of these AWSs. Figure 4.5 represents DJF; Fig. 4.6 represents JJA; Fig. 4.7 represents MAM, and Fig. 4.8 represents SON. Each figure (a) depicts the squared grid point correlation between ERA-Interim and the spatial reconstruction produced; figure (b) depicts the validation timeseries squared grid point correlation with ERA-Interim; lastly figure (c) and figure (d) depicts the RE and CE, respectively.

It is seen that across all seasons, the $r^2$ value over the continent for the reconstruction is above 0.9 which is remarkably high. Only in MAM and SON are $r^2$
values 0.8 or above in Dronning Maud Land (East Antarctica between 0º - 30ºE) for the reconstruction. There are $r^2$ values around 0.8 over the Ronne Filchner Ice Shelf near the Antarctic Peninsula and Weddell Sea, but overall, all $r^2$ values are very high across the continent and across each season in the reconstruction. A similar story is seen when examining the squared correlation in the validation timeseries. The validation timeseries $r^2$ values almost mimics the reconstruction $r^2$ values perfectly, but this isn’t that surprising given the known quality of ERA-Interim and how large the spatial footprints are across the continent (the kriging weights don’t change much in the split calibration / validation method when compared to the reconstruction kriging weights). Atmospheric pressure is much more continuous in nature and therefore allows for the validation timeseries to match the reconstruction quite closely. High RE and CE values are also seen across the continent in all seasons, with RE and CE never falling below 0.8, again showing that the spatial pressure reconstructions are producing better results than if just the climatological mean were used.

Due to high $r^2$, RE, and CE values over the continent, it is concluded that the kriging model used in this study does a remarkable job at replicating the spatial pressure field in ERA-Interim over the continent (when using ERA-Interim station data). Due to this conclusion that the kriging model is acceptable and provides skillful results, it can therefore be used to produce spatial pressure fields now using station-based reconstructions from Fogt et al. (2016a) rather than using ERA-Interim input data that only extends back to 1979. With using station-based reconstructions in the kriging model, the spatial pressure fields may now be extended back to 1905. However, before a century
long spatial reconstruction can be performed, an evaluation must be done during the evaluation period of 1979-2013 using the station-based pressure reconstructions, which is done in the following section (sections 4.3.2 and 4.3.3).

For completeness, to further test the reproducibility of the ERA-Interim spatial pressure field, another separate seasonal spatial pressure reconstruction was performed using direct (raw) station observations (not ERA-Interim data at the grid points closest to the station locations or reconstructions). In the previous test, station grid point data were extracted from ERA-Interim and used to generate the kriging weights and produce the reconstruction. However, another way to test for model accuracy is to use direct observations from the 19 stations across Antarctica to generate new kriging weights and a new spatial reconstruction extending from 1957-2013. This spatial reconstruction can now extend back to 1957 since this is the time most station data begin. For stations with missing data (particularly early in their records), multiple linear regression using any available nearby pressure observations was used to predict those missing years. This method of filling in missing data (multiple linear regression) can be used due to the strong relationship some Antarctic stations hold with one another as described above with spatial footprinting.

The observationally driven spatial reconstructions now from 1957-2013 was evaluated during 1979-2013 with ERA-Interim grid point data. Unsurprisingly, very similar results as in Figs. 4.5 - 4.8 were found (these results excluded here for brevity as they are nearly identical to the previously discussed results when using ERA-Interim station data in Figs. 4.5 – 4.8). This was expected, as ERA-Interim data holds to be the
most accurate depiction of pressure fields across the continent and shouldn’t deviate much from in situ observations (Bracegirdle and Marshall 2012; Fig. 3.3). Notably, both spatial pressure reconstructions suggest that using ERA-Interim data to generate kriging weights and preserving that covariance structure found across Antarctica is important. Therefore, all kriging weights will remain constant (based off the ERA-Interim reanalysis) for all spatial reconstructions performed throughout this study. Furthermore, this evaluation provides confidence that the kriging model is appropriate for this work: using ERA-Interim grid point data at station locations and kriging to interpolate between them can produce a very similar depiction of pressure variability across the entire Antarctic continent when compared to the full ERA-Interim reanalysis.
Figure 4.5: Squared Pearson Correlations ($r^2$; Figures [a and b]) during DJF with every grid point using ERA-Interim anomalies and the a) ERA-Interim spatial reconstruction and b) validation. Figures c) and d) represent the RE and CE, respectively, with every grid point between ERA-Interim anomalies and is used on the reconstruction for RE and validation for CE. Dots represent nine AWSs and their fill color represents the magnitude of the skill statistic examined between the AWS observations and the closest grid point in the spatial reconstruction / validation.
Figure 4.6: Same as Fig. 4.5, but now for JJA.
Figure 4.7: Same as Fig. 4.5, but now for MAM.
Figure 4.8: Same as Fig. 4.5, but now for SON.
4.3.2 Original Seasonal Spatial Pressure Reconstruction

In this section, each seasonal spatial pressure reconstruction was created by using the original station-based reconstructions from Fogt et al. (2016a) as well as observations from Orcadas. Figure 4.9 represents the reconstruction performance during the austral summer season (DJF). The figures presented in this section (Figs. 4.9 – 4.12) are identical to Figs. 4.5 – 4.8 above except now examining the original spatial pressure reconstruction. It does not come as a surprise that DJF is the season with highest $r^2$ values across the continent, given the high spatial footprints (Fig. 4.1) and the strong skill of the station-based pressure reconstructions in Fogt et al. (2016a). Impressive $r^2$ values above 0.7 (both reconstruction and validation) are seen across the entire continent (and even extending equatorward over the oceans to a certain extent), which gives strong confidence that this season’s spatial original reconstruction is a good representation of the pressure field over the years 1979-2013. Over the Antarctic Peninsula and across the Weddell Sea, $r^2$ values are above 0.8. Another reason the $r^2$ values are high in this region is due to the clustering of stations here ($N = 7$) as this constrains the reconstructions in this region. Like previously mentioned, these spatial reconstructions are compared to ERA-Interim data, which is known to be very reliable and the best spatial depiction of pressure across the Antarctic continent over the time period of 1979-present. With high $r^2$, RE and CE values over the continent during the evaluation period, it can be said that this season reconstruction back through 1905 should also be a good depiction of the pressure field.
Figure 4.10 examines the austral winter (JJA). The SAM / seasonal mean pressure pattern is much more zonally symmetric in DJF (Fogt et al. 2009b), so it isn’t as surprising that the JJA original spatial pressure reconstruction is not to the caliber of DJF. The reduced skill is also partially reflected in the Fogt et al. (2016a) station-based pressure reconstructions, as the skill of the original reconstructions was weaker during JJA than DJF (Fig. 2.14). These less skillful JJA original station-based pressure reconstructions introduce more uncertainty into the kriging model, allowing for lower $r^2$, RE and CE values across the continent, as demonstrated by the cooler colors in Fig. 4.10 when compared to Fig. 4.9. However, over the Antarctic Peninsula, $r^2$ values in the reconstruction and validation timeseries are mostly above 0.7, again due to the clustering of stations in this region and the better overall Fogt et al. (2016a) station reconstructions here. $r^2$ values are also slightly lower (and resulting in lower RE and CE values also, but all remain positive) over West Antarctica, but again likely due to a poorer Byrd station reconstruction in Fogt et al. (2016a).

The last two figures (Figs. 4.11 – 4.12) examine the reconstruction / validation skill during the two transition seasons of MAM and SON, respectively. The Antarctic Peninsula and extending into the Weddell Sea does decent in terms of $r^2$ (most fall above 0.6), especially on the northern tip of the Peninsula where most stations are clustered and the Fogt et al. (2016a) station reconstruction performance was higher, resulting in higher spatial reconstruction skill or reliability in this region. However, much of the continent in MAM falls below $r^2 = 0.5$ and similarly in East Antarctica in SON. This may be due to error in the station-based pressure reconstructions. Fogt et al. (2016a) acknowledged in
Fig. 2.14 that these seasons had less skill than either DJF or JJA, and is likely attributed to more meridional flow around the continent leading to fewer and/or weaker relationships between the Antarctic and the midlatitudes predictors, especially across the Antarctic Plateau (interior). Due to such a limited number of predictors for some stations in Fogt et al. (2016a), the station-based reconstructions in MAM and SON were not constrained very well, which combined with the lower footprints in these seasons (Figs. 4.2 and 4.4), induced error into the kriging model, which then led to errors being induced into the spatial reconstructions. However, during both transition seasons, RE and CE values never fall below zero, indicating a more skillful pressure reconstruction than by just using the climatological mean. The only instance where a negative RE and CE values are observed is at the AWS of Relay during MAM in East Antarctica. This station has a very short record however, likely influencing the $r^2$, RE, and CE values at this site.

Overall, the original spatial pressure reconstructions have high skill, especially in DJF. To improve upon this skill in the transition seasons and during winter, the next section will discuss a pseudo spatial pressure reconstruction, derived from the Fogt et al. (2016a) pseudo station-based pressure reconstructions.
Figure 4.9: Squared Pearson Correlations ($r^2$; Figures [a and b]) during DJF with every grid point using ERA-Interim anomalies and the a) original spatial reconstruction and b) validation. Figures c) and d) represent the RE and CE, respectively, with every grid point between ERA-Interim anomalies and is used on the reconstruction for RE and validation for CE. Dots represent nine AWSs and their fill color represents the magnitude of the skill statistic examined between the AWS observations and the closest grid point in the original spatial reconstruction / validation.
Figure 4.10: Same as Fig. 4.9, but now for JJA.
Figure 4.11: Same as Fig. 4.9, but now for MAM.
Figure 4.12: Same as Fig. 4.9, but now for SON.
4.3.3 Pseudo Seasonal Spatial Pressure Reconstruction

Each seasonal spatial pressure reconstruction examined here was created by using the best performing pseudo station-based reconstructions from Fogt et al. (2016a), again with the exception of Orcadas, which used direct observations. Figures 4.13-4.16 are identical to the previous figures (Figs. 4.9 – 4.12), except now ERA-Interim grid point data is being compared against the pseudo spatial pressure reconstruction. During DJF, the pseudo spatial pressure reconstruction actually did slightly weaker than the original spatial pressure reconstruction (compare Fig. 4.9 [a and b] with Fig. 4.13 [a and b]). The pseudo spatial pressure reconstruction has slightly lower $r^2$, RE, and CE values across much of the continent; fewer warm colors in Fig. 4.13 compared to Fig. 4.9 across all skill metrics. Unsurprisingly, this is a result of the Fogt et al. (2016a) station-based pseudo reconstructions performing slightly weaker than the station-based original reconstructions (Fig. 2.14). As stated by Fogt et al. (2016a), due to how well the original station-based reconstructions already performed in DJF, it would be difficult to make them any more skillful (reliable) than they already are by including pseudo data.

The most impressive difference between the original and pseudo spatial pressure reconstructions comes during JJA. When comparing Fig. 4.10 with Fig. 4.14, it is clearly visible that when using the JJA pseudo station-based reconstructions to produce the pseudo spatial reconstruction, it outperforms the original spatial pressure reconstruction dramatically (more warmer colors in Fig. 4.14 compared to Fig. 4.10). Now, $r^2$ values are almost all above 0.7 across the continent and RE and CE values are much more positive than in the original spatial pressure reconstruction. The pseudo spatial pressure
reconstruction for JJA outperforms the original spatial pressure reconstruction because of the high quality of the Fogt et al. (2016a) station-based pseudo reconstructions (Fig. 2.14). With the JJA station-based pseudo reconstruction outperforming the JJA original station-based reconstruction across all skill metrics, it is determined that the JJA pseudo spatial pressure reconstruction is of greater reliability than the JJA original spatial pressure reconstruction.

During MAM (Fig. 4.15), the pseudo spatial pressure reconstruction shows many high $r^2$ values across the continent when comparing it to raw ERA-Interim grid points and the original spatial reconstruction. This is again due to similar reasons as above, as the Fogt et al. (2016a) station-based pseudo pressure reconstructions performed with more skill than the original reconstructions did, as seen in Fig. 2.14. It is especially noteworthy to see higher $r^2$ values in West Antarctica in the pseudo spatial pressure reconstruction. This is likely attributed to the Byrd station-based pseudo reconstruction performing better than the original station-based reconstruction. East Antarctica has a location near Vostok that again has lower $r^2$ values, which is likely due to complications in the Vostok station-based reconstructions (both in the pseudo and original station-based reconstructions). RE and CE values are also relatively high across the continent, with only near Vostok station in East Antarctica do RE and CE values fall below 0.40. It is again a similar story where more warm colors are seen in each plot during the MAM pseudo reconstruction compared to the original reconstruction, giving further confidence that the MAM pseudo reconstruction is of higher skill than the original reconstruction.
The spring (SON; Fig. 4.16) spatial reconstructions (both pseudo and original) performed very similarly and again from Fig. 2.14 these station-based reconstructions didn’t differ all that significantly. However, there are regional differences between the two. The original spatial reconstruction is aligned with ERA-Interim much better in West Antarctica and over the Plateau near the Amundsen-Scott station (Geographic South Pole) per the $r^2$ values (Fig. 4.12). This is possibility indicative of complications with the station-based pseudo reconstruction at Amundsen-Scott. Over the East Antarctic coast and over much of the Antarctic Peninsula however, the pseudo spatial reconstruction produced higher $r^2$ values when compared to the original. The RE and CE values also indicate the same thing as noted here above with regional differences between the two sets of spatial reconstructions in SON. However, never are negative RE and / or CE values seen, indicating a good pressure reconstruction during all seasons for the pseudo reconstruction. Overall, both transition seasons and especially in JJA, the pseudo spatial pressure reconstructions outperformed the original spatial pressure reconstructions, which isn’t all that surprising knowing how much of an increase in skill the pseudo station-based reconstructions had. For the pseudo spatial pressure reconstructions, RE and CE values greater than 0.4 are observed much more frequently across the continent, which mirrors the skill seen in Antarctic spatial temperature reconstructions by Steig et al. (2009) and Nicolas and Bromwich (2014).
Figure 4.13: Same as Fig. 4.9, but for the pseudo spatial reconstruction.
Figure 4.14: Same as Fig. 4.13, but now for JJA.
Figure 4.15: Same as Fig. 4.13, but now for MAM.
Figure 4.16: Same as Fig. 4.13, but now for SON.
4.3.4 Original and Pseudo Spatial Pressure Reconstructions Using Observational Driven Kriging Weights

The original and pseudo spatial pressure reconstructions were also reproduced using different kriging weights, based on direct observations from the 19 Antarctic stations (rather than ERA-Interim grid points). After these new observationally driven kriging weights were generated (see Chapter 3 on data and methods for kriging weight details), new original and pseudo spatial pressure reconstructions were generated; however, they are omitted here due to very close similarity to those presented Figs. 4.9-4.16. This method of defining kriging weights is a good check to be sure there are no errors in the ERA-Interim data and that ERA-Interim data doesn’t vary much from in situ observations. These results will be displayed in a limited extent in section 4.5.2, where it will be seen that spatial pressure reconstructions where kriging weights are observationally driven verses kriging weights that are ERA-Interim driven do not vary considerably.

4.3.5 Skill Statistics Summary

Throughout section 4.3, an examination of the squared Pearson product-moment correlation ($r^2$), reduction of error (RE), and coefficient of efficiency (CE) were done in regards to ERA-Interim and multiple different spatial pressure reconstructions using different datasets to produce the spatial reconstruction from 1979-2013. First, it is concluded that the kriging model is sufficient in producing spatially complete (temporally and horizontally) pressure fields across the continent during the evaluation period, due to
the kriging models skillful replication of the ERA-Interim spatial pressure fields when extracting ERA-Interim station data used to produce the spatial reconstruction.

When using station-based reconstructions from Fogt et al. (2016a) to produce spatial pressure reconstructions, it was also concluded that the kriging model did a decent job at replicating the seasonal ERA-Interim pressure fields, especially during DJF and JJA. During DJF, the original spatial reconstruction was deemed most skillful based on the spatial relationship it holds with ERA-Interim. For JJA, the opposite is true, and the pseudo spatial reconstruction is deemed much more skillful than the original because of the higher caliber station-based pseudo pressure reconstructions as seen in Fig. 2.14. Both transition seasons were similar, but had regional differences where the pseudo spatial reconstruction slightly outperformed the original spatial reconstructions; even with the lower skill, the performance was similar and often higher to that obtained with Antarctic spatial temperature reconstructions in Steig et al. (2009) and Nicolas and Bromwich (2014).

Finally, it does not come as a surprise that in the surrounding oceans the overall skill throughout all seasons is weaker. This is due in part because these regions have high interannual variability and are located much farther away from any observation station to help constrain the model over these oceans (very weak spatial footprints moving northward off the continent), therefore resulting in dampened skill. It is much harder to capture that variability given the weaker footprints from the station observations and this weaker skill will be examined more in a later section across the Amundsen Sea, specifically. Also, it must be remembered that these spatial (original and pseudo) pressure
reconstructions are produced using reconstructions, not direct observations. Due to this, error is not only generated from the kriging model, but in the reconstructions themselves used to produce the spatial pressure reconstructions. However, station-based pressure reconstructions must be used to produce the spatial pressure reconstructions back to 1905 simply because observations are essentially nonexistent prior to ~1957. Similarly, ERA-Interim is a reanalysis, not in situ observations. Many different datasets are assimilated into the reanalysis to make it as accurate as possible, but slight errors in ERA-Interim could also allow errors to be seen here when comparing ERA-Interim to the spatial pressure reconstructions. However, any errors in ERA-Interim over the evaluation period (1979-2013) should be minimal as it is the best reanalysis (most reliable; Bracegirdle and Marshall, 2012) to validate the spatial reconstructions.

4.4 Mean Absolute Error (MAE)

Another measure used to analyze how well the spatial pressure reconstructions align with ERA-Interim is to examine MAE between each spatial pressure reconstruction and ERA-Interim anomalies at every grid point. Due to the known high quality nature of ERA-Interim, this can be called error as ERA-Interim is being treated as a benchmark for the spatial reconstruction, as it is impossible to improve upon ERA-Interim using the methods employed here. For this thesis, only regions of high error are of interest, not necessarily the direction of that error (i.e. positive or negative direction). The period of overlap will again be analyzed (1979-2013), the same as in section 4.3.
4.4.1 ERA-Interim Spatial Pressure Reconstruction MAE

Figure 4.17 shows the MAE across all four seasons when using the ERA-Interim spatial pressure reconstruction. Throughout all seasons, MAE is very low over the continent; almost all MAE values fall below 0.75hPa across the continent. This is promising, as it reveals that the spatial pressure reconstructions produced by the kriging model when using ERA-Interim station data only differ over the continent by about a maximum of 0.75hPa during the period of 1979-2013. It isn’t all that surprising that lower $r^2$ values (from section 4.3.1; also RE and CE values) and higher MAE are seen over the Amundsen Sea region, especially outside of the summer season. This is the location of the Amundsen Sea Low, which is marked by high interannual variability (Fogt et al. 2012a) that the kriging model does not fully capture, partially due to this region not having a strong spatial footprint with many stations, as seen in Figs. 4.1 – 4.4. However, since the MAE across the continent is very low, this is again reassuring that the kriging model used in this study is worthy of producing meaningful results since it can reproduce a known gridded pressure field (ERA-Interim) to within 0.75hPa across the continent.
Figure 4.17: Mean absolute error (MAE) by season between each grid point in ERA-Interim and the ERA-Interim spatial reconstruction from 1979-2013.
4.4.2 Original Spatial Pressure Reconstruction MAE

This section examines the MAE between ERA-Interim anomalies and the original spatial reconstruction across all seasons (Fig. 4.18; similar to Fig. 4.17). It is expected that MAE will be higher than seen in Fig. 4.17 due to the results shown in section 4.3 (original spatial reconstruction skill statistics weaker than the skill statistics of the ERA-Interim spatial reconstruction). This is exactly the case seen here; cooler colors (higher MAE) are seen across the continent across all seasons when compared to Fig. 4.17. However, it is notable to mention that over the entire continent (except for the Ross Ice Shelf) the MAE is below 1.5hPa during DJF, meaning that from 1979-2013, the average error between the original spatial pressure reconstruction and the ERA-Interim reanalysis data is less than 1.5hPa. MAE increases slightly over the Amundsen Sea region, but this was expected due to this region’s high interannual variability and weaker footprinting (Fig. 4.1).

During the winter season and the transition seasons, higher MAE is seen, especially in West Antarctica and in the Amundsen Sea. It is unfortunate that very high (+3.5hPa) MAE values are seen across the Amundsen Sea as this region is a very important region to better help understand climate change across the continent, but this was expected for the same reasons mentioned above. The winter season is where the greatest MAE is seen across the entire continent, but this was also expected due to the known dampened skill of the Fogt et al. (2016a) station-based pressure reconstructions in this season (also seen in Fig. 4.10; lower skill statistics overall). Overall, the original
spatial reconstruction MAE is still relatively low during the transition seasons, where much of the continent has a MAE of less than 1.75 hPa from 1979-2013.

**Mean Absolute Error Original Reconstruction 1979-2013**

![Mean Absolute Error Original Reconstruction 1979-2013](image)

Figure 4.18: Same as Fig. 4.17 except now for the original spatial pressure reconstruction.
4.4.3 Pseudo Spatial Pressure Reconstruction MAE

This section examines the MAE between ERA-Interim anomalies and the pseudo spatial reconstruction across all seasons (Fig. 4.19; similar to Fig. 4.17 and Fig. 4.18). During DJF, slightly higher MAE is seen across the continent when compared to the original spatial pressure reconstructions. Unsurprisingly, this is a result of the Fogt et al. (2016a) station-based pseudo reconstructions performing slightly weaker than the station-based original reconstructions (Fig. 2.14), as previously mentioned in section 4.3.2. The largest difference between Fig. 4.19 and Fig. 4.18 is during JJA. Now when examining the pseudo spatial reconstructions, most of the continent has an MAE below 2hPa, with the exception of West Antarctica, which still is an improvement from the original spatial reconstruction. MAM also shows a large improvement in MAE across the entire continent in the pseudo reconstructions, where much of the continent is below a MAE of 1.75hPa. During SON, the original and pseudo spatial reconstructions are similar in terms of MAE, but do have slight regional differences. The original reconstruction has a smaller MAE in the peninsula region and across much of the interior. However, the pseudo reconstruction has a smaller MAE around much of the East Antarctic coast. Overall, the pseudo spatial reconstruction MAE is decent during the transition seasons (similar result as section 4.4.2), and the greatest improvement is seen in JJA where now much of the continent now falls below 2hPa from 1979-2013.
Figure 4.19: Same as Fig. 4.17 except now for the pseudo spatial pressure reconstruction.
4.5 Spatial Anomaly Correlation and Spatial Mean Absolute Error

In this section, the spatial anomaly correlation, along with the spatial mean absolute error (MAE), will be assessed. The spatial anomaly correlation is the Pearson product-moment correlation between two data sets across the same spatial domain (i.e., a correlation calculated over space rather than time). Unlike in the previous section where each grid point between the two datasets were correlated over the evaluation period, here the spatial anomaly correlation is calculated each year poleward of 60°S to see how well the pattern between each dataset agrees throughout each year of the evaluation period. In other words, ‘how well does the ERA-Interim reanalysis pressure field relate to each of the spatial reconstructions produced here each year from 1979-2013 over the entire spatial domain?’ The spatial MAE will also be examined for each year between the ERA-Interim reanalysis and each spatial reconstruction produced. In the previous section, the MAE was examined but it was averaged over the evaluation period (averaged over time, not space), while here each year is examined separately and averaged over the entire spatial domain. By examining the spatial MAE and spatial anomaly correlation by year, it can easily be depicted what individual years need to be examined in further depth if they produce low pattern correlations and/or high MAE.

Three different spatial reconstructions will be assessed against the ERA-Interim reanalysis pressure field, (1) the ERA-Interim spatial reconstruction, (2) the original spatial reconstruction, and (3) the pseudo spatial reconstruction. Each spatial reconstruction will be examined over the entire domain of 60°S – 90°S and then again after shrinking the spatial domain to 70°S – 90°S (except for the ERA-Interim spatial
reconstruction). The ERA-Interim spatial reconstruction will only be examined over the full spatial domain. When shrinking the domain to 70ºS – 90ºS, all the Southern Ocean around East Antarctica is now excluded and a good portion of the Bellingshausen, Amundsen, Ross, and Weddell Seas are also excluded. As seen in the previous sections, high MAE and lower grid point correlations are seen over these oceans, especially over the Amundsen Sea region. To see if these regions are responsible for producing any low spatial anomaly correlations and higher spatial MAE during some years, their influence on these statistics can now be excluded by shrinking the spatial domain to only include the Antarctic continent.

4.5.1 Seasonal Spatial Anomaly Correlations and Spatial Mean Absolute Error Evaluation

Figure 4.20 displays the results of the seasonal spatial anomaly correlations and spatial MAE from 1979-2013. Note that the spatial anomaly correlations are the five lines near the top of each plot, and the spatial MAE (inverted by multiplying by -1 for visualization purposes) are the four lines near the bottom of each plot. Each line in Fig. 4.20 represents a different spatial pressure reconstruction that was generated using kriging weights defined by ERA-Interim data. However, the station data used to produce each spatial reconstruction is different as previously explained. The ERA-Interim 60ºS spatial reconstruction represents the reconstruction using ERA-Interim station data and covering a spatial domain 60ºS to the pole. Likewise, the original and pseudo spatial reconstructions were generated using the original and pseudo station-based
reconstructions from Fogt et al. (2016a), but now with the spatial domain extending 60ºS to the pole and then again 70ºS to the pole.

Generally, across all seasons the ERA-Interim spatial reconstruction produced the highest spatial anomaly correlations. This is not overly surprising as ERA-Interim data have minimized errors over the time frame of 1979-2013. Therefore, it is expected that the ERA-Interim spatial reconstruction will reproduce the ERA-Interim pressure patterns very effectively; this was also seen above in Figs. 4.5 – 4.8 and in Fig. 4.17 with high grid point correlations and low MAE.

However, when using the station-based pressure reconstructions to produce spatial pressure reconstructions, more error is induced into the kriging model from the varying skill of the station-based reconstructions. This is exactly the story seen here; the spatial pressure reconstructions using station-based reconstructions have slightly lower spatial anomaly correlations across all seasons while some years even experience negative spatial anomaly correlations. Notable, even during the years where negative (or very low positive) spatial anomaly correlations are seen, the ERA-Interim spatial reconstruction has a lower spatial anomaly correlation as well, likely representative of high spatial variability (i.e., a complex pressure pattern) over the surrounding oceans not captured by the kriging reconstructions. Generally speaking, across all seasons the spatial anomaly correlations are high, with only a few select years that experience low spatial anomaly correlations. During the years of low spatial correlation, the (inverted) spatial MAE is generally low, and vice versa where the highest spatial MAE is generally seen during years of high spatial correlation. When the spatial MAE is high and the spatial
correlation is high, the spatial reconstruction captures the correct pattern, but not to the magnitude that it should (i.e. reconstructions produce weaker anomalies closer to zero than seen in ERA-Interim). Similarly, when spatial correlations are low, spatial MAE is low, indicating a small difference overall (near zero anomalies), but often of the opposite sign. This will be further examined in the following section.

By shrinking the spatial domain to 70ºS, mixed results were found. By excluding the surrounding oceans, the spatial correlations and MAE improved in some years, while in other years they were dampened. It was expected that when excluding the surrounding oceans from the spatial domain, the spatial anomaly correlation and MAE would improve as the spatial pressure reconstructions do not always capture the high variability of the Amundsen Sea Low. However, when shrinking the spatial domain and yet lower spatial correlations are still seen when comparing it to the full domain, that is likely indicative of not capturing the pressure pattern over the continent fully (but likely capturing the pattern decently over the oceans). When shrinking the domain to 70ºS lowers the spatial anomaly correlation, it is very likely due to less skillful input data from a station-based reconstruction (or multiple) dampening the spatial reconstruction regionally. A further examination of years where low and high spatial anomaly correlations are seen is discussed next.
Figure 4.20: Seasonal spatial correlation/pattern (above 0 line) and seasonal spatial mean absolute error (below 0 line; inverted for clarity purposes) for each kriging spatial reconstruction performed (original and pseudo) and ERA-Interim spatial reconstruction.
4.5.2 Low Seasonal Spatial Anomaly Correlations

There are several reasons as to why low (and even sometimes negative) spatial anomaly correlations are seen across the spatial domain as mentioned above, but these may not still mean a poor reconstruction performance. The years examined here will only include original reconstructions for DJF (no pseudo reconstructions), as this is the season where the most skillful reconstructions are produced, and also for brevity as the other seasons see very similar results. The first year examined is 1987, where spatial correlations are near zero but MAE is near 0.5hPa (Fig. 4.20). Figure 4.21 depicts DJF 1987 spatial (a) ERA-Interim anomalies and (b) the original spatial pressure reconstruction with the domain extending to 60ºS. In Fig. 4.21, both the ERA-Interim anomalies and original spatial pressure reconstruction anomalies are relatively weak, especially the spatial reconstruction anomalies as they hover around zero. Due to these weak anomalies over the continent, many locations see the opposite pattern/sign between datasets. This is especially true over the Antarctic Peninsula and West Antarctica. ERA-Interim anomalies depict relatively weak positive anomalies, but the spatial reconstruction shows weak negative anomalies. Due to these anomalies being so weak, the opposite sign of the anomalies were reconstructed, therefore resulting in a low spatial correlation. Also to note, the MAE is low (~0.5hPa across the spatial domain) indicating that the spatial pressure reconstruction doesn’t differ much from the ERA-Interim anomalies, which is clearly seen here since all anomalies hover around zero.

Another example to reiterate good reconstruction performance despite a year with lower correlation or high MAE can be seen in Figure 4.22, for DJF 1996. ERA-Interim
anomalies for 1996 show much stronger (in magnitude) anomalies than do the spatial pressure reconstruction. The strongest spatial pressure reconstruction anomalies range from +0.5hPa to -0.5hPa, indicating very weak anomalies produced in the spatial reconstruction, many of which are of opposite sign than the ERA-Interim anomalies. From these examples, years when spatial correlations are low should not automatically be considered ‘bad’ or poor reconstructions; many times of low spatial correlation there is low MAE, indicative of capturing the opposite sign of anomalies because they are weak (around zero).

In other cases, low spatial correlations are sometimes seen because of not capturing the high variability in the surrounding oceans of the continent, as occurred in DJF 1995. The spatial correlation is ~0.35 when the spatial domain is 60ºS to the Pole, while the spatial correlation improves to ~0.75 when the spatial domain is shrunk to 70ºS to the Pole (see Fig. 4.20). When shrinking the spatial domain, almost all the surrounding oceans and coastal locations around East Antarctica are now excluded from the calculation, considerably improving the spatial correlations in multiple years. This can easily be seen in Fig. 4.23. ERA-Interim displays very strong positive anomalies around the 60ºS latitude which is not captured at all in the spatial reconstruction. Furthermore, the strength / magnitude of the Amundsen Sea Low is also not captured in the spatial reconstruction. It is promising to see negative anomalies being produced in West Antarctica and off the coast into the Amundsen Sea in the spatial reconstruction, but clearly not to the magnitude as seen in ERA-Interim. As before, this year further demonstrates that just because low spatial correlations are seen doesn’t discount or
discredit the spatial reconstructions. Even in Fig. 4.23 along the coast of East Antarctica, relatively weak anomalies are seen in both ERA-Interim and in the spatial reconstruction, just of opposite sign. The most promising feature in Fig. 4.23 is that the overall pattern across the continent is captured.

4.5.3 High Seasonal Spatial Anomaly Correlations

To help visualize what a high spatial correlation between ERA-Interim anomalies and the spatial reconstruction looks like, DJF 1979 is examined in Fig. 4.24. A very high (near 1) spatial correlation is seen here during this particular year (Fig. 4.20). When examining Fig. 4.24, very strong positive anomalies are seen in both the ERA-Interim and spatial reconstruction anomalies, especially across both the Antarctic Peninsula and West Antarctica (+4 hPa), with slightly weaker positive anomalies are seen across East Antarctica. This is a very promising result as it assures that the spatial reconstruction is capturing not only the correct pattern/sign of the anomalies, but also the magnitude of the anomalies in many locations. The spatial pressure reconstruction even captures the slightly negative anomalies seen in ERA-Interim around 60°S between 150°-120°E, however they are slightly shifted westward in the spatial reconstruction. Another important note is that during this year, spatially averaged MAE is around +1.0 - +1.5hPa, most of which occurs in the surrounding oceans (Fig 4.20), since when the spatial domain is shrunk to 70°S, even lower spatial MAE is seen.
Figure 4.21 (left, 1987) and Figure 4.22 (right, 1996): Panels (a) represent ERA-Interim anomalies and panels (b) represent the original spatial reconstruction anomalies. Both figures are used to help interpret spatial correlation and spatially averaged MAE.
Figure 4.23 (left) and Figure 4.24 (right): As in Figs. 4.21 and 4.22, but for 1995 and 1979.
4.6 ERA-Interim and AWS Timeseries Evaluation with Spatial Reconstructions

Further evaluation of the kriging seasonal spatial pressure reconstructions included investigating seasonal timeseries plots of the original and pseudo spatial reconstructions against ERA-Interim grid point data and the AWSs sparsely located across the continent. Timeseries plots are an important evaluation method for multiple reasons. First, it allows for an examination of select grid points of ERA-Interim anomalies that are located far away (and over the surrounding oceans) from staffed research stations that were used to produce the seasonal spatial reconstructions to examine if the interannual variability is captured well. This is key in helping evaluate the kriging model to see how well it can reproduce ERA-Interim anomalies during the period of overlap (1979-2013). By using ERA-Interim anomalies, it allows for a more complete spatial evaluation across the continent since observation stations are sparse and large observational gaps exist. For instance, no direct observations are taken over the Amundsen Sea or in large portions across the Antarctic Plateau which causes concern when trying to evaluate the spatial reconstructions produced there. However, using ERA-Interim reanalysis data, an evaluation can be fulfilled in these locations. Again, ERA-Interim is an atmospheric reanalysis product so errors can be present in the data, but is the most reliable reanalysis in the high southern latitudes and the next best option after using direct observations. The other advantage of using timeseries plots is to compare the spatial reconstructions to direct observations (AWS observations) not used in the generation of the spatial reconstructions. This will allow for a direct comparison between a reconstruction and *in situ* observations. However, AWS observations cover limited (i.e.,
short) timespans and are usually not continuous in nature, mostly due to harsh conditions in the Antarctic causing equipment failures. Nonetheless, these AWS observations will be beneficial in evaluating the spatial reconstructions in the follow sections.

4.6.1 ERA-Interim Grid Point Evaluation

Five grid point locations across the full spatial domain (60ºS – 90ºS) were chosen to be examined in regards to ERA-Interim anomalies and the spatial reconstructions. These five locations are represented by black ‘X’s’ in Fig. 4.25, which shows that these locations chosen are located far away from the staffed research stations (and also with respect to the selected AWSs shown in Fig. 3.1). The first location chosen was over the Amundsen Sea (65ºS, 113ºW; labeled 1 in Fig. 4.25). This region is of importance due to the Amundsen Sea Low and how this climatological pressure circulation has been believed to influence the climate of the Antarctic Peninsula and West Antarctica, as explained in the literature review. The other four locations include: Oates Coast (70ºS, 160ºE; location 2), the Ronne Ice Shelf (75ºS, 65W; location 3), and two locations on the East Antarctic Plateau (78ºS, 50ºE and 80ºS, 2ºE; locations 4 and 5, respectively). These locations are also important locations because they are all far from any observation station and as a whole include a wide variety of geographic locations across the continent. The Oates Coast grid point is a coastal grid point, the Ronne Ice Shelf is located near the ice shelf itself, and the two grid points in East Antarctica are located very far inland away from any coastal stations and also Vostok and Amundsen-Scott stations in the interior. It should also be noted that lower spatial footprinting correlations were seen in all seasons (least in DJF) along the Oates Coast and across the Ronne Ice Shelf
near the base of the Antarctic Peninsula, giving further significance to the locations chosen here. By using these five select grid points, a good representation of the geography can now be sampled and evaluated where there are no *in situ* observations.

Figure 4.25: Locations of staffed research stations with respect to the five selected gridpoints to be evaluated.

In each figure below, each season will be assessed from 1979-2013. The red line indicates the ERA-Interim seasonal anomalies, the green line indicates the spatial reconstruction produced using ERA-Interim station data, and lastly the black and blue
lines indicate the original and pseudo spatial reconstructions, respectively. Correlation ($r$) was computed for each of the spatial pressure reconstructions with the ERA-Interim anomalies; this is indicated at the top of each timeseries plot (i.e. Original: 0.716 indicates that the original spatial reconstruction was correlated with an $r$ value of 0.716 with the ERA-Interim anomalies across the timeframe of 1979-2013 for that select grid point).

Figures 4.26 – 4.29 are the seasonal (DJF, JJA, MAM, SON, respectively) timeseries plots of the three different spatial reconstructions as mentioned above along with ERA-Interim anomalies at select grid points. DJF is the season where very skillful station-based pressure reconstructions were seen in Fogt et al. (2016a), so it is not surprising to see the highest correlations between ERA-Interim and the spatial reconstructions in this season. This can also be seen in Figs. 4.9 and 4.13 where spatially, DJF is the season where ERA-Interim anomalies align themselves much closer to the spatial reconstructions produced. It is a very promising result to see all correlation coefficients above 0.7, and, if the Amundsen Sea grid point were excluded here, all correlation coefficients would be above 0.78. It can be seen from Fig. 4.26a that there are some years where ERA-Interim anomalies are very high (and these could possibly be exaggerated) and the spatial reconstructions do not capture the magnitude of the anomaly over the Amundsen Sea. The overall variability / change is captured many times during extreme anomalies in the Amundsen Sea, but the magnitude isn’t (i.e. 1982, 1988, 1991, etc.). Even the ERA-Interim spatial reconstruction (where ERA-Interim anomaly data was used to produce the spatial reconstruction) did not capture the magnitude of the
ERA-Interim anomalies; rather the ERA-Interim spatial reconstruction mirrored the
original and pseudo spatial reconstructions much closer (reflecting errors in the kriging
method). However, this does not hold true for Figs. 4.26b-e. The correlation coefficient
was always above 0.97 between the ERA-Interim anomalies and ERA-Interim spatial
reconstruction when over the continent. More impressive, even over the continent for the
original and pseudo spatial reconstructions, $r$ was quite high, and as the timeseries plots
depict, these spatial reconstructions mirror the ERA-Interim anomalies fairly well.
Generally, the original spatial reconstruction outperformed the pseudo spatial
reconstruction for DJF, as noted earlier.

The austral winter (JJA) is also a season of high correlation between the spatial
reconstructions and ERA-Interim anomalies. The high skill of the pseudo spatial
reconstructions in winter is shown in Fig. 4.27, where all the correlation coefficients are
above 0.8 except for the Amundsen Sea region. The same issues discussed for DJF are
seen in the Amundsen Sea region; magnitudes of strong anomalies are not captured in the
spatial reconstructions. However, across much of the continent, the spatial
reconstructions, especially the pseudo reconstructions, capture the variability as seen in
ERA-Interim at these select grid points. Due to the much larger $r$ values for the pseudo
spatial reconstructions (and also as seen in comparing Figs. 4.9 and 4.13), they can be
deemed the most skillful set of spatial reconstructions for the JJA season, as concluded
previously.

Figures 4.28 and 4.29 represent the transition seasons of MAM and SON,
respectively, where the overall skill is the lowest, as discussed earlier. Similar to DJF and
JJA, MAM and SON spatial reconstructions also struggle to capture the Amundsen Sea Low. ERA-Interim has many very strong (negative and positive) anomalies in the region not captured by the spatial reconstruction. The pseudo spatial reconstructions outperform the original spatial reconstructions across the continent. However, during MAM, both the original and pseudo spatial reconstructions do well across East Antarctica, while slightly weaker skill is seen near the Ross Ice Shelf (Oates Coast) and across the southern portion of the Antarctic Peninsula. The opposite is seen in SON, where the original and pseudo spatial reconstruction performance is weaker across East Antarctica when compared to ERA-Interim.

After an evaluation of seasonal timeseries plots and correlation coefficients between each of the spatial reconstructions against ERA-Interim anomalies at select grid points across the spatial domain, it was found that during DJF and JJA, the highest correlations coefficients were observed (original for DJF and pseudo for JJA; similar results to Fogt et al. 2016a). During these two seasons, correlations were almost all above 0.7 over the continent, with slightly weaker correlations across the Amundsen Sea region. The transition seasons of MAM and SON were less skillful, but this outcome was expected as expressed above in regards to the results / evaluation of Fogt et al. (2016a) station-based reconstructions.
Figure 4.26: DJF timeseries of ERA-Interim anomalies and each of the spatial pressure reconstructions during the period of overlap (1979-2013). Also shown are the correlation coefficients between each spatial reconstruction and ERA-Interim anomalies.
Figure 4.27: Same as Fig. 4.26 except now for JJA.
Figure 4.28: Same as Fig. 4.26 except now for MAM.

Anomaly (hPa)


-8 -4 0 4 8 12

a) Amundsen Sea (65°S 113°W)  
Original: 0.560  Pseudo: 0.517  Era-Int: 0.648

b) Oates Coast (70°S 160°E)  
Original: 0.651  Pseudo: 0.771  Era-Int: 0.954

c) Ronne Ice Shelf (75°S 65°W)  
Original: 0.578  Pseudo: 0.726  Era-Int: 0.952

d) East Antarctic Plateau (78°S 50°E)  
Original: 0.745  Pseudo: 0.761  Era-Int: 0.952

e) East Antarctic Plateau (80°S 2°E)  
Original: 0.703  Pseudo: 0.780  Era-Int: 0.959

Legend:
- Original Reconstruction
- Pseudo Reconstruction
- ERA-Int Reconstruction
- ERA-Int Anomalies
Figure 4.29: Same as Fig. 4.26 except now for SON.
4.6.2 Automatic Weather Station Grid Point Evaluation

Nine Automatic Weather Stations (AWSs) located across the continent will be used here to evaluate the spatial reconstructions against *in situ* observations that were not used in the production of these spatial reconstructions. The stations with the most complete and longest records were compiled here for this evaluation, with also taking into consideration to sample each geographic location across the continent as best/complete as possible. Even with (sometimes) sparse AWS data, it is very crucial to use these observation stations to help evaluate the spatial reconstructions as ERA-Interim is only a reanalysis, and it is best to compare with direct observations.

Each of the nine AWSs used in this study can be visually seen in a spatial sense in Fig. 3.1 (purple dots). Note that these nine stations cover distinct geographic locations across the continent and that they are located far away from the staffed research stations used to produce the spatial reconstructions. Two stations (Larsen Ice Shelf and Butler Island) are located on the Antarctic Peninsula. It is important to note that the majority of staffed research stations lie along the northern most tip of the peninsula, while the AWSs used here to help evaluate the spatial reconstructions are located farther inland toward the continent. The remaining seven stations lie on the continent itself, with the exception of Gill. Gill sits on the Ross Ice Shelf, so this will be an important station to use to see how well the spatial reconstructions capture the pressure variability over the ice shelf. Two stations are located in West Antarctica, which is important since Byrd station was the only West Antarctic station used in the production of the spatial reconstruction. Russkaya lies along the coast, while Theresa lies halfway between the South Pole (Amundsen-
Scott) and Byrd station. It would be helpful if more stations could be used in West Antarctica for this evaluation, but unfortunately no other stations exist with usable observational records. Lastly, four AWS are located in East Antarctica, all of which fall far away from any staffed research stations used in the spatial reconstructions: Leningradskaya is a coastal station, while Dome C II, LGB35, and Relay stations are all located far inland from the coastal East Antarctic stations. However, even with the inclusion of these AWSs, there are large gaps that still exist across the continent where no in situ observations are taken, making a full spatial evaluation a challenge. Therefore, the previous section using ERA-Interim anomalies at select grid points proves a valid evaluation method.

Figures 4.30 – 4.37 are set up in a similar way as the previous figures using ERA-Interim select grid points for evaluation, but are divided into seasons by geographic location, meaning that for each season, a timeseries plot is given for the five East Antarctic AWSs and another for the four West Antarctic AWSs. Correlation coefficients are again given for original and pseudo spatial reconstructions against the direct observations as each AWS. Note that the AWS observations are given on an alternative y-axis (right y-axis). The spatial reconstruction anomalies for the nearest grid point to the AWS is given on the left side y-axis. The reason for using raw observations and not using anomalies for the AWSs is due to record length. As it can be seen in the timeseries plots, these AWSs do not have long records, therefore a climatological 30-year period to develop anomalies could not be used, making it necessary for raw observations to be used in place of anomalies. This does not affect the calculation of correlation coefficients.
Furthermore, the spatial reconstructions based on weights from observations rather than ERA-Interim grid point data, are also examined here, labeled ‘Obs_wgts’ in the legend.

Figures 4.30 – 4.31 represents the DJF East Antarctic and DJF West Antarctic AWS timeseries, respectively. The most noticeable feature in both of these figures are the high correlation coefficients. All correlation coefficients are above 0.8 except for Relay station in East Antarctica (original = 0.791 and pseudo = 0.592). What is more profound and promising to see are the very high correlation coefficients at the two AWSs in West Antarctica (Figs. 4.31 c-d), as only Byrd station was used to constrain the kriging model here. Also of importance to note in Figs. 4.30 – 4.31 are the two different sets of spatial reconstructions. By changing the way that the kriging weights are defined does not have an influence of the outcome of the spatial reconstructions; the black and dark green lines (original) and red and blue lines (pseudo) mirror each other almost perfectly. Due to these results of the two different sets of spatial reconstructions basically mirroring each other, only the correlation coefficients are given for the spatial reconstructions using ERA-Interim data to define kriging weights.

Similar to the evaluation using ERA-Interim select grid points, JJA correlation coefficients are much higher for the pseudo spatial reconstructions for the AWSs (Figs. 4.32 – 4.33). All of the pseudo spatial reconstruction correlation coefficients with AWS data are above 0.69, with many greater than 0.8. The most surprising yet promising result in the JJA AWS timeseries evaluation comes from the West Antarctic AWS Theresa. The pseudo correlation was 0.954, even higher than the correlation seen in DJF (the overall most skillful season).
As expected, the transition seasons of MAM and SON experienced slightly weaker correlation coefficients when comparing AWSs to each of the spatial reconstructions. Figures 4.34 – 4.35 represent MAM East and West Antarctica, respectively. The interior and coastal stations during MAM had much more year-to-year variability that was not fully captured by the spatial reconstructions. The pseudo reconstructions generally did better (and in a few instances much better) than the original spatial reconstructions. The most promising result in MAM is again the AWS of Theresa in West Antarctica. The pseudo correlation coefficient is 0.839 over a period of 19 years.

Likewise, Figs. 4.36 – 4.37 represent SON East and West Antarctica, respectively. This season also experiences slightly weaker correlation coefficients, but now the original and pseudo spatial reconstructions do roughly similar. Many of the lower correlations are a result of not capturing the full extent of the interannual variability. This can be seen very clearly in Fig. 4.36a during the years 1981-1982. The observations at Leningradskaja indicated a large decrease in pressure, however all of the spatial reconstructions indicated a slight increase in pressure, with overall very weak (near zero) anomalies. Many other instances of why low correlation coefficients are seen is due to not capturing the anomaly magnitude. During many years, observations show very large observational anomalies while the spatial reconstructions do not capture the magnitude fully. However, there may be errors induced into some of these AWS records by having missing months and/or data collection errors, especially when creating seasonal means.

The AWS evaluation has allowed for several additional conclusions on reconstruction skill. First, the two different sets of spatial reconstructions presented here
(i.e., regarding how the kriging weights were defined) were very similar to each other. This suggests that ERA-Interim data is very similar to *in situ* observations, not allowing for much deviation between each spatial reconstruction set. This observationally driven kriging weight spatial reconstruction set was also used to help evaluate the ERA-Interim select grid points examined in section 4.6.1 above, but the figures were omitted for brevity and repetitiveness; these results were very similar to those shown here. Second, the pseudo spatial reconstruction generally had higher correlation coefficients in all seasons (except DJF) when compared to the original spatial reconstruction. Lastly, with the evaluation of these timeseries plots, it is concluded that the most skillful spatial reconstructions seem to be during DJF and JJA. Therefore, these are the two seasons that will be examined in most depth in the following chapter. Nonetheless, it is remarkable that several locations in West Antarctica still displayed high skill in both MAM and SON.
Figure 4.30: DJF timeseries of East Antarctic AWS anomalies and each of the kriging spatial reconstructions during the period of overlap (1979-2013). Also shown are the correlation coefficients between each spatial reconstruction and AWS anomalies.
Figure 4.31: Same as Fig. 4.30 except now for West Antarctica.
Figure 4.32: Same as Fig. 4.30 except now for JJA.
Figure 4.33: Same as Fig. 4.30 except now for West Antarctica JJA.
Figure 4.34: Same as Fig. 4.30 except now for MAM.
Figure 4.35: Same as Fig. 4.30 except now for West Antarctica MAM.
Figure 4.36: Same as Fig. 4.30 except now for SON.
Figure 4.37: Same as Fig. 4.30 except now for West Antarctica SON.

SON West Antarctic & Peninsula Stations 1979-2013

- a) Larsen Ice Shelf
  - Original: 0.755
  - Pseudo: 0.884

- b) Butler Island
  - Original: 0.706
  - Pseudo: 0.797

- c) Theresa
  - Original: 0.756
  - Pseudo: 0.691

- d) Russkaya
  - Original: 0.781
  - Pseudo: 0.767

Legend:
- Green: Observations
- Black: Original Reconstruction
- Red: Pseudo Reconstruction
- Blue: Pseudo Reconstruction (Obs wgts)
- Green: Original Reconstruction (Obs wgts)
4.7 Low-Frequency ERA-Interim Timeseries Evaluation

Low-frequency, 11-year Hamming filter timeseries plots of the five geographically selected ERA-Interim grid points were also evaluated. Specifically, an 11-year Hamming filter was used instead of a running mean in order to give the greatest weight to the center year over the averaging period and to also help highlight decadal-scale variability. Each figure below is identical to Figs. 4.26 – 4.29, except now representing low-frequency variability over the 11-year smoothing, which may be better represented than interannual variability, and its accuracy is important for trends and long-term changes.

Figure 4.38 shows the DJF 11-year smoothed ERA-Interim anomalies and spatial reconstructions. Except for the Amundsen Sea, all correlation coefficients are above 0.9, which when compared to Fig. 4.26 are much higher than the correlation coefficients for the interannual (high frequency) variability. For each location, the smoothed ERA-Interim anomalies closely resemble each of the plotted spatial reconstructions (except during the early and late portion of the Amundsen Sea timeseries). However, only in the Amundsen Sea is the interannual variability is better captured when compared to the low-frequency variability, which is due to subtle differences in the timing of mean pressure differences, as stated in Fogt et al. (2016a). This can be seen in Fig. 4.26a where during the early and late portion of the record, the ERA-Interim anomalies are generally much greater or smaller than the spatial reconstructions. There are also several instances where the timing of pressure changes does not match the variability that the spatial
reconstructions produced, which are all highlighted in the smoothed correlations, making them lower than the interannual correlations.

The JJA low-frequency comparisons are shown in Fig. 4.39, and the two transition seasons, MAM and SON, follow respectively (Figs. 4.40 – 4.41). For JJA, the high frequency timeseries (Fig. 4.27) generally have higher correlations than the low-frequency smoothed timeseries. In other words, the interannual variability is generally better captured, again due to subtle differences in the timing of mean pressure changes. When smoothing the data, this creates notable differences in the low-frequency correlations. This is especially seen in Figs. 4.28a – 4.29a, where ERA-Interim anomalies deviate from year to year, while the spatial reconstructions have a weak magnitude that is generally around zero. When these are smoothed, (Figs. 4.40 - 4.41), the ERA-Interim anomalies look much different than the spatial reconstructions. The spatial reconstructions have smoothed anomalies that are nearly zero while the ERA-Interim smoothed data rises and falls at much greater magnitudes (due to the high interannual variability). This is especially seen over the Amundsen Sea in SON. The interannual variability was captured at $r = 0.799$ and 0.775 for the original and pseudo spatial reconstruction, respectively. However, when the data were smoothed, the low-frequency (decadal-scale) variability was significantly hindered at $r = 0.462$ and -0.234 for the original and pseudo spatial reconstructions, respectively.

While the interannual variability correlations are generally higher than the decadal-scale variability correlations, there are several instances where this isn’t true. For MAM (Fig. 4.40), the decadal-scale variability is much higher for the Oates Coast and
over portions of the East Antarctic Plateau. This is also the case over the Ronne Ice Shelf in SON (Fig. 4.41). However, it should be noted that very large differences between the interannual and decadal-scale variability correlations (between ERA-Interim anomalies and each spatial reconstruction) are rare. They generally are similar to one another, and very large differences occur only in a few instances. It is encouraging to see some high correlation coefficients for decadal-scale variability, since the Fogt et al. (2016a) station-based reconstructions (and the spatial reconstruction conducted here) were only calibrated to capture interannual variability, and no constraints were given to capture decadal-scale variability. However, these results regarding 11-year smoothing are slightly different than the results found in Fogt et al. (2016a). Generally, the low-frequency variability was captured just as well, if not markedly better than the interannual variability, at each station and during each season for the station-based reconstructions, but not necessarily for the spatial reconstructions. These select grid points whose low-frequency variability is evaluated here are located far away from the staffed research stations, and some over regions of very high interannual variability not sufficiently captured in the spatial reconstructions, which is seen in the smoothed correlations. The only season where all locations (except over the Amundsen Sea; location of high interannual variability) of low-frequency variability correlations were greater than interannual variability correlations was DJF.
Figure 4.38: Low-frequency 11-year Hamming filter (smoothing) of select ERA-Interim grid points and each spatial reconstruction. Correlation coefficients between each smoothed spatial reconstruction and the smoothed ERA-Interim data is given. The year is the center of the 11-year period.
Figure 4.39: Same as Fig. 4.38 except now for JJA.
Figure 4.40: Same as Fig. 4.38 except now for MAM.

- **a)** Amundsen Sea (65°S 113°W)
  - Original: 0.401
  - Pseudo: 0.298
  - Era-Int: 0.549

- **b)** Oates Coast (70°S 160°E)
  - Original: 0.869
  - Pseudo: 0.931
  - Era-Int: 0.977

- **c)** Ronne Ice Shelf (75°S 65°W)
  - Original: 0.591
  - Pseudo: 0.698
  - Era-Int: 0.904

- **d)** East Antarctic Plateau (78°S 50°E)
  - Original: 0.650
  - Pseudo: 0.744
  - Era-Int: 0.977

- **e)** East Antarctic Plateau (80°S 2°E)
  - Original: 0.899
  - Pseudo: 0.969
  - Era-Int: 0.997

**Legend:**
- Original Reconstruction
- Pseudo Reconstruction
- ERA-Int Reconstruction
- ERA-Int Anomalies
Figure 4.41: Same as Fig. 4.38 except now for SON.
4.8 Uncertainty Testing - Ensemble Standard Deviation

To help test for reconstruction uncertainty, a modified, basic approach was taken to examine the ensemble spread. There were a total of 12 different station-based reconstructions at each station produced in Fogt et al. (2016a). Eight methods used original data (i.e. only midlatitude predictor stations; 5% and 10% networks, raw and detrended data, and ending in 2011 and 2013) and four set used pseudo data (i.e. original midlatitude predictors plus pseudo data from gridded pressure products; 5% and 10% networks using HadSLP2 and 20CR; all ended in 2011 and used raw/trended data). Recall, all reconstructions that originally ended in 2011 as presented in Fogt et al. (2016a) were extended here to 2013, so all 12 sets of station-based pressure reconstructions now end in 2013 to make them all comparable to one another. In this evaluation, the original and pseudo reconstruction sets are held separate from one another. The larger sample of spatial reconstructions allows to test for error at each grid point in the reconstruction, and evaluate the similarity between each of these spatial reconstructions and the ensemble spread will serve as the uncertainty estimates for the spatial reconstruction which will vary spatially.

The standard deviation represents how much a group of data deviates from the mean of the group. High values of standard deviation indicate great deviation and likewise in this case, high uncertainty (or greater sensitivity of the reconstruction skill at each location used for kriging). Low values of standard deviation indicate little deviation and likewise in this case, low uncertainty and / or sensitivity. Figure 4.42 represents the seasonal ensemble standard deviation of the eight original spatial reconstructions from
1979-2013, while Fig. 4.43 represents the seasonal ensemble standard deviation of the four pseudo spatial reconstructions from 1979-2013. These ensemble standard deviations are computed at every grid point and for each year and then the time mean is calculated. The time mean calculation results in the mean ensemble standard deviation across all years at every grid point.

When using the eight original reconstructions to produce eight different spatial reconstructions, all standard deviations are below 1.25 hPa, and generally below 0.75 hPa across the entire continent with the exception of a few locations (Fig. 4.42). Across the entire spatial domain during DJF low ensemble deviations exist, except for near the station Vostok, where the standard deviations are ~1 hPa. This higher ensemble standard deviation in this region is likely indicative of a lower-quality station-based reconstruction at Vostok. For MAM and JJA, there is also a small region on the northern peninsula that has a slightly larger ensemble standard deviation, again possibility indicative of a less reliable station-based reconstruction in this region, or at least larger differences / sensitivity in the station-based reconstruction approach. Furthermore, during JJA and SON, a region of higher standard deviation (~0.75) is seen over Byrd station in West Antarctica. This is not surprising though due to that station’s known challenges it posed in the Fogt et al. (2016a) station-based reconstruction. Similarly, the differences in most East Antarctic coastal stations can also be seen during JJA due to slightly higher ensemble standard deviations. This was expected due to the known nature of how variable each station-based reconstruction is when using original data. However, all
previous figures used the overall best (original and pseudo kept separate) station-based reconstructions.

When comparing Fig. 4.42 to Fig. 4.43, it is very noticeable how fewer blue regions (higher ensemble standard deviations) there are in the pseudo ensemble standard deviations. This isn’t surprising giving the known fact that the station-based pseudo reconstructions were of comparable skill to the original station-based reconstructions in DJF and outperformed the original in every other season. The pseudo station-based reconstructions also had a much smaller range between each method, as indicated by the skill statistics in Fig. 2.14. During DJF, results are much improved over East Antarctica (near Vostok in particular) as now the entire spatial domain has ensemble standard deviations of ~0.5 or less. A similar story is seen during MAM. JJA and SON in Fig. 4.43 are the only seasons where there are several regions of ensemble standard deviations of ~0.75-1.0 hPa. For both seasons, the Ross Ice Shelf near McMurdo/Scott Base stations stands out. Again, this is likely due to a slightly weaker pseudo station-based reconstruction at McMurdo/Scott Base. Similar to DJF in Fig. 4.42, Vostok also likely has a slightly less skillful pseudo station-based reconstruction during JJA. However, the most promising result in Fig. 4.43 is the improvement in West Antarctica ensemble standard deviations when using the pseudo reconstructions due to the known issues with the Byrd observational record.

These results indicate that across the spatial domain and across all 12 different reconstruction methods, there is little spread between the spatial reconstructions. The highest ensemble standard deviations were ~1 hPa and the area this encompassed was
small. Given that measurement uncertainty in some barometers throughout the early twentieth century was around 1 hPa, these small mean standard deviations are well within this range and are acceptable levels of error / uncertainty. This gives confidence in the spatial reconstructions as there is little difference in the spatial reconstruction produced between each different method of input data for the kriging model; the results are not overly sensitive to which station-based reconstruction data were used as input to the kriging model. These ensemble standard deviation plots prove that by using the overall best reconstruction was not a case of cherry picking to make the results look more reliable than they should be; each method performs well with only a few instances where a station-based reconstruction might be performing subpar.
Figure 4.42: Time mean ensemble standard deviation using only the eight original station-based reconstructions from 1979-2013 to produce eight new original spatial pressure reconstructions.
Figure 4.43: As in Fig. 4.42, but for pseudo spatial pressure reconstructions.
4.9 Chapter Summary

An evaluation of each of the seasonal spatial reconstructions was performed in this chapter. Spatial footprints of atmospheric pressure across the Antarctic continent were first evaluated at each of the 19 staffed research stations used to produce the seasonal pressure reconstructions. It was found that large spatial footprints at each of these 19 stations exist; the most pronounced footprints are seen in DJF and JJA, while smaller footprints are seen during the transition seasons. Due to these large footprints, it allows for spatial pressure reconstructions to be performed even with the limited number of observations going into the reconstruction across the large Antarctic domain.

The first spatial reconstruction evaluated was the ERA-Interim spatial reconstruction. This reconstruction method used ERA-Interim station data to produce the spatial reconstruction, and it was found that it produced a very similar pressure field across the domain as seen in the raw / full ERA-Interim (i.e., model-based) anomalies, the latter which were constrained by far more observations. This was evaluated by using multiple different skill statistics; examining grid point correlations (also squared correlations to see how much of the variance was captured), RE, CE, and MAE from 1979-2013 by season. This evaluation was another measure taken to prove that the kriging model was an acceptable model to use as it replicated ERA-Interim anomalies almost perfectly.

A similar approach was taken to evaluate the remaining spatial reconstructions produced (i.e. spatial reconstructions produced using the best station-based original and best station-based pseudo reconstructions). However, multiple versions of these spatial
reconstructions were performed. They were each performed using ERA-Interim defined kriging weights and also using observationally driven kriging weights; the results were nearly identical allowing for the conclusion that ERA-Interim data does not vary much from in situ observations across the continent. The evaluation of these spatial pressure reconstructions revealed that DJF was the most skillful reconstruction season, but JJA also had high skill in the pseudo spatial reconstruction. The skill of the spatial reconstructions was dampened in both transitions seasons and across the surrounding oceans, especially across the Amundsen Sea in all seasons.

Spatial anomaly correlations and spatial MAE calculated for each year during 1979-2013 also indicated that during multiple years, very low (or negative) spatial correlations were seen. However, this was found to be the case primarily due to the fact of capturing the wrong pattern, but often with low MAE. During the years of low anomaly correlation, the opposite signed anomalies were often replicated because anomalies were very weak or near zero. For instance, ERA-Interim may have had very weak positive anomalies but the spatial reconstruction may have provided for a very weak negative anomaly across the continent. Therefore, spatial correlations were low (because the patterns were different) but MAE was also low. The spatial domain was also shrunk to examine the influence of the surrounding oceans (regions of high variability and no input observations for the kriging model) on the spatial reconstructions. Generally, the correlations and MAE improved due to the spatial reconstructions not capturing the high variability across the Southern Ocean, but usually only modestly so.
Timeseries plots (low- and high-frequency) were also evaluated during the period of overlap between ERA-Interim/AWS observations and the spatial reconstructions. The ERA-Interim select grid point timeseries plots were useful to see if the magnitude of anomalies were captured across the spatial domain. Generally, high to moderate correlations were seen at all locations sampled, including locations with AWS data, with the exception of over the Amundsen Sea. Due to high interannual variability in this region not captured by the spatial reconstructions, the correlations were dampened. It can be seen across all four seasons that in this region, the spatial correlations did not capture the magnitude of ERA-Interim anomalies. However, some of these extreme ERA-Interim anomalies could be exaggerated, but overall the spatial reconstructions were least skillful in this region across all evaluation methods.

Lastly, the ensemble spread between eight different original spatial reconstructions and four different pseudo spatial reconstructions were evaluated. It was found that generally, the ensemble spread is low across the spatial domain, but a few regions do exhibit regions of higher standard deviation. These regions of higher standard deviation are likely indicative of a less skillful and/or more variance between the individual station-based pressure reconstructions from Fogt et al. (2016a) at any given location. Furthermore, this method of evaluation also reinforced the general theme that, usually, the pseudo reconstructions outperform the original reconstructions, and that the results are not overly sensitive to which method of station-based reconstructions were used for input to the kriging model.
After completing the evaluation of the seasonal spatial pressure reconstruction in this chapter, it is concluded that spatial pressure reconstructions across the Antarctic continent are not only doable, but also reliable, especially during the summer and winter seasons. This evaluation has helped answer the first research question of this thesis, but not all seasons and spatial reconstructions are of equal reliability. Summer original and winter pseudo spatial reconstructions are the most skillful, as indicated by how well these specific spatial reconstructions match ERA-Interim anomalies and AWS observations across the continent. The transition seasons and surrounding oceans pose more challenges as the skill at these locations is less reliable (spatial reconstructions do not correlate as strongly to AWS observations or ERA-Interim anomalies as in the other two seasons). Due to this evaluation and these reasons mentioned here, much of the analysis in the next chapter will focus on austral summer and winter.
CHAPTER 5: ANTARCTIC SPATIAL PRESSURE VARIABILITY AND TRENDS THROUGHOUT THE 20TH CENTURY

5.1 Introduction

Throughout this chapter, atmospheric pressure variability and trends will be discussed using a suite of gridded pressure datasets along with the seasonal spatial pressure reconstructions evaluated in the previous chapter to help answer the last two research questions. Specifically, the spatial reconstructions can be compared to each of the gridded pressure products to see how the variability and trends in each dataset differ from each other. Comparing the three gridded pressure products to observations and the spatial pressure reconstructions will serve as a final evaluation of all the 20th century gridded pressure products. Through this analysis, the ultimate goal is to further the understanding of Antarctic pressure variability and trends across the full 20th century, which would be a significant step forward in scientific discovery. The layout of this chapter is as follows: section 5.2 will examine observational and ERA-Interim pressure trends to demonstrate the current scientific understanding of Antarctic pressure changes post-1957 for observations and post-1979 for ERA-Interim and again observations; section 5.3 will examine each season in regards to the full 20th century Antarctic trends and variability (more emphasis given to DJF and JJA); section 5.4 will examine pressure anomaly composite differences and as well as the time sensitivity of pressure trends across the continent over different time periods; and lastly section 5.5 will be the concluding remarks.
5.2 Observational and ERA-Interim Trends

5.2.1 Observational Trends 1957-2013

Observational pressure trends and their 95% confidence intervals (hPa / decade) from 1957-2013 at each of the 19 stations used in the generation of the seasonal spatial pressure reconstructions are shown in Table 5.1. The use of observations is important, as it is the most reliable source of data across the continent. Table 5.1 is broken into three colored categories (rows) and by each season (columns): red represents the seven peninsula stations, green represents the nine East Antarctic stations, and yellow represents the three interior stations. These stations can be visualized geographically in Fig. 3.1. Trends that are significantly different from zero at $p<0.05$ are in boldface.

There are several important characteristics of the observational trends in Table 5.1. First, the season with the greatest number of stations with significant trends is DJF, with MAM also showing many significant observational trends, consistent with Turner et al. (2005) during 1971-2000. During DJF, all trends are negative, with the exception of Orcadas which has a trend of $0.00 \pm 0.43$. It isn’t that surprising to see this station not have a strong negative trend due to its location; Orcadas is located much farther north ($-60.7^\circ$S; closer to the midlatitudes), off the Antarctic Peninsula. The strong negative pressure trends (and many significant) across the Antarctic continent during the 1957-2013 period are also not surprising, as this is consistent with the positive trend in the SAM index during summer (DJF) in the late 20th / early 21st century (Chapter 2; Fig. 2.6). The greatest significant negative pressure trend is observed at the East Antarctic station of Novolazarevskaya (-0.85 $\pm$ 0.51).
During MAM, almost the entire continent is again showing negative pressure trends, with the exception of the Antarctic Peninsula where positive pressure trends are seen (also Byrd station, but very minimal and this record had to be patched due to missing data). As in DJF, the most significant trends are seen across East Antarctica (all negative), with only the positive pressure trends at Orcadas and Marsh / O’Higgins being significant on the Antarctic Peninsula. Observational trends during JJA are mostly negative across the continent, with very few significant negative pressure trends seen. SON is again a different story, where now all pressure trends across the continent are

Table 5.1: Observed pressure trends and 95% confidence intervals (hPa / decade) by season and station (color indicates grouping by geographical region) from 1957-2013. Boldface type represents significant trends at $p<0.05$.

<table>
<thead>
<tr>
<th>Station</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellingshausen</td>
<td>-0.42 ± 0.44</td>
<td>0.34 ± 0.46</td>
<td>-0.34 ± 0.56</td>
<td>0.21 ± 0.48</td>
</tr>
<tr>
<td>Faraday</td>
<td>-0.56 ± 0.51</td>
<td>0.19 ± 0.54</td>
<td>-0.43 ± 0.67</td>
<td>0.17 ± 0.58</td>
</tr>
<tr>
<td>Esperanza</td>
<td>-0.41 ± 0.55</td>
<td>0.30 ± 0.47</td>
<td>-0.18 ± 0.65</td>
<td>0.36 ± 0.60</td>
</tr>
<tr>
<td>Marambio</td>
<td>-0.68 ± 0.52</td>
<td>0.30 ± 0.47</td>
<td>-0.25 ± 0.58</td>
<td>0.38 ± 0.58</td>
</tr>
<tr>
<td>Marsh / O'Higgins</td>
<td>-0.53 ± 0.43</td>
<td>0.43 ± 0.41</td>
<td>-0.32 ± 0.54</td>
<td>0.46 ± 0.50</td>
</tr>
<tr>
<td>Rothera</td>
<td>-0.73 ± 0.57</td>
<td>0.12 ± 0.65</td>
<td>-0.52 ± 0.70</td>
<td>0.26 ± 0.61</td>
</tr>
<tr>
<td>Orcadas</td>
<td>0.00 ± 0.43</td>
<td>0.67 ± 0.40</td>
<td>-0.08 ± 0.47</td>
<td>0.43 ± 0.45</td>
</tr>
<tr>
<td>Halley</td>
<td>-0.79 ± 0.54</td>
<td>-0.30 ± 0.46</td>
<td>0.29 ± 0.53</td>
<td>0.16 ± 0.49</td>
</tr>
<tr>
<td>Novolazarevskaya</td>
<td>-0.85 ± 0.51</td>
<td>-0.54 ± 0.48</td>
<td>-0.56 ± 0.53</td>
<td>0.12 ± 0.44</td>
</tr>
<tr>
<td>Syowa</td>
<td>-0.70 ± 0.45</td>
<td>-0.25 ± 0.49</td>
<td>-0.08 ± 0.55</td>
<td>0.33 ± 0.42</td>
</tr>
<tr>
<td>Mawson</td>
<td>-0.55 ± 0.46</td>
<td>-0.40 ± 0.39</td>
<td>-0.26 ± 0.53</td>
<td>0.10 ± 0.41</td>
</tr>
<tr>
<td>Davis</td>
<td>-0.61 ± 0.46</td>
<td>-0.54 ± 0.40</td>
<td>-0.51 ± 0.55</td>
<td>0.04 ± 0.41</td>
</tr>
<tr>
<td>Mirny</td>
<td>-0.75 ± 0.45</td>
<td>-0.82 ± 0.42</td>
<td>-0.83 ± 0.60</td>
<td>-0.05 ± 0.44</td>
</tr>
<tr>
<td>Casey</td>
<td>-0.43 ± 0.47</td>
<td>-0.36 ± 0.47</td>
<td>-0.18 ± 0.61</td>
<td>0.37 ± 0.42</td>
</tr>
<tr>
<td>Dumont</td>
<td>-0.43 ± 0.46</td>
<td>-0.09 ± 0.49</td>
<td>-0.14 ± 0.54</td>
<td>0.11 ± 0.44</td>
</tr>
<tr>
<td>McMUrdo - Scott</td>
<td>-0.68 ± 0.58</td>
<td>-0.79 ± 0.49</td>
<td>-0.35 ± 0.64</td>
<td>0.11 ± 0.50</td>
</tr>
<tr>
<td>Vostok</td>
<td>-0.27 ± 0.49</td>
<td>-0.21 ± 0.51</td>
<td>0.13 ± 0.63</td>
<td><strong>0.61 ± 0.47</strong></td>
</tr>
<tr>
<td>Amundsen - Scott</td>
<td>-0.41 ± 0.45</td>
<td>-0.26 ± 0.42</td>
<td>-0.07 ± 0.54</td>
<td>0.41 ± 0.42</td>
</tr>
<tr>
<td>Byrd</td>
<td>-0.30 ± 0.55</td>
<td>0.03 ± 0.57</td>
<td>0.23 ± 0.72</td>
<td><strong>0.76 ± 0.48</strong></td>
</tr>
</tbody>
</table>
positive (except Mirny station), but very few being significant. These observational trends align themselves very well with the observational trends calculated in Turner et al. (2005), as seen in Fig. 2.5 with the most significant trends being observed in DJF around the coast of East Antarctica and less significant trends across the peninsula.

5.2.2 Observational Trends 1979-2013

The observational trends during the latter period of 1979-2013 are shown in Table 5.2. There are some important similarities and differences to note throughout the seasons. During DJF, a similar story is seen where all trends across the continent are negative and many of them are significant. However, overall the negative trends in DJF are stronger in magnitude than during 1957-2013. During MAM, East Antarctica and the Antarctic Plateau still show negative pressure trends, but none of which are significant, reflecting that these trends have weakened in comparison to 1957-2013 in MAM. Another notable difference in MAM is that now all pressure trends in the Antarctic Peninsula (except Orcadas) are negative, completely opposite what was seen during the full observational record of 1957-2013. Some of the negative pressure trends in the Peninsula during MAM are quite impressive and significant (i.e., station Rothera with a significant trend of -1.35 ± 1.31 hPa / decade).

Another important difference between the 1957-2013 and 1979-2013 observational trends is during austral winter (JJA). During the full period of observations, almost all stations across the continent had negative pressure trends (a few being significant), but the opposite is seen when examining the latter period of observations. Most stations, especially in East Antarctica and across the Plateau, are now positive,
albeit not significant at $p<0.05$. A similar story is seen in SON between Table 5.1 and Table 5.2, where all observational pressure trends are positive and mostly insignificant (with the exception of a few insignificant negative pressure trends seen across the Antarctic Peninsula during the 1979-2013 time period).

Table 5.2: Same as Table 5.1, except now for 1979-2013.

<table>
<thead>
<tr>
<th>Observations 1979-2013</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellingshausen</td>
<td>-0.73 ± 0.95</td>
<td><strong>-0.88 ± 0.85</strong></td>
<td>-0.41 ± 1.26</td>
<td>-0.04 ± 0.94</td>
</tr>
<tr>
<td>Faraday</td>
<td>-0.59 ± 1.08</td>
<td>-0.98 ± 1.04</td>
<td>-0.27 ± 1.48</td>
<td>-0.08 ± 0.89</td>
</tr>
<tr>
<td>Esperanza</td>
<td>-0.30 ± 1.14</td>
<td>-0.07 ± 0.94</td>
<td>0.64 ± 1.29</td>
<td>0.90 ± 0.18</td>
</tr>
<tr>
<td>Marambio</td>
<td>-0.84 ± 1.09</td>
<td>-0.36 ± 0.95</td>
<td>0.34 ± 1.18</td>
<td>0.23 ± 0.72</td>
</tr>
<tr>
<td>Marsh / O'Higgins</td>
<td><strong>-1.03 ± 0.95</strong></td>
<td>-0.50 ± 0.71</td>
<td><strong>-1.52 ± 1.14</strong></td>
<td>-0.27 ± 0.60</td>
</tr>
<tr>
<td>Rothera</td>
<td>-0.58 ± 1.17</td>
<td><strong>-1.35 ± 1.31</strong></td>
<td>-0.29 ± 1.53</td>
<td>-0.28 ± 0.68</td>
</tr>
<tr>
<td>Orcadas</td>
<td>-0.68 ± 0.90</td>
<td>0.10 ± 0.72</td>
<td>0.38 ± 1.00</td>
<td>0.83 ± 0.07</td>
</tr>
<tr>
<td>Halley</td>
<td><strong>-1.35 ± 1.07</strong></td>
<td>-0.30 ± 0.99</td>
<td>0.29 ± 0.97</td>
<td>0.37 ± 0.48</td>
</tr>
<tr>
<td>Novolazarevskaya</td>
<td><strong>-1.38 ± 0.95</strong></td>
<td>-0.69 ± 1.01</td>
<td>-0.44 ± 1.21</td>
<td>0.45 ± 0.37</td>
</tr>
<tr>
<td>Syowa</td>
<td><strong>-1.08 ± 0.95</strong></td>
<td>-0.37 ± 1.06</td>
<td>0.37 ± 1.25</td>
<td>0.72 ± 0.15</td>
</tr>
<tr>
<td>Mawson</td>
<td>-0.73 ± 0.94</td>
<td>-0.46 ± 0.83</td>
<td>0.46 ± 1.22</td>
<td>0.79 ± 0.08</td>
</tr>
<tr>
<td>Davis</td>
<td><strong>-0.98 ± 0.93</strong></td>
<td>-0.29 ± 0.88</td>
<td>0.39 ± 1.19</td>
<td>0.67 ± 0.15</td>
</tr>
<tr>
<td>Mirny</td>
<td>-0.61 ± 0.93</td>
<td>-0.64 ± 0.95</td>
<td>0.26 ± 1.27</td>
<td>0.73 ± 0.13</td>
</tr>
<tr>
<td>Casey</td>
<td>-0.84 ± 0.93</td>
<td>-0.49 ± 1.09</td>
<td>0.83 ± 1.27</td>
<td><strong>0.94 ± 0.04</strong></td>
</tr>
<tr>
<td>Dumont</td>
<td><strong>-1.01 ± 0.79</strong></td>
<td>-0.08 ± 1.01</td>
<td>0.25 ± 1.23</td>
<td>0.78 ± 0.09</td>
</tr>
<tr>
<td>McMurdo - Scott</td>
<td><strong>-1.35 ± 1.24</strong></td>
<td>-0.76 ± 1.01</td>
<td>0.40 ± 1.42</td>
<td>0.37 ± 0.52</td>
</tr>
<tr>
<td>Vostok</td>
<td>-0.70 ± 1.01</td>
<td>-0.28 ± 1.04</td>
<td>0.45 ± 1.48</td>
<td>1.01 ± 0.06</td>
</tr>
<tr>
<td>Amundsen - Scott</td>
<td>-0.73 ± 0.91</td>
<td>-0.42 ± 0.87</td>
<td>0.50 ± 1.16</td>
<td>0.85 ± 0.06</td>
</tr>
<tr>
<td>Byrd</td>
<td><strong>-1.36 ± 1.06</strong></td>
<td>-0.94 ± 1.19</td>
<td>0.39 ± 1.58</td>
<td>0.33 ± 0.57</td>
</tr>
</tbody>
</table>

Tables 5.1 and 5.2 are important as they indicate how pressure trends have changed over the observational period between the full record and the latter half of the record. Many similarities and differences were discussed, of which the most important being the significant negative pressure trends during DJF and how they have amplified in
magnitude over the latter half of the record. In contrast, during the other seasons, trends have often reversed sign or became statistically insignificant, highlighting the large variability in these seasons and the strong dependence on the time period chosen. To gain a better understanding of full spatial coverage across the Antarctic, the ERA-Interim pressure trends will be examined in the next section, which will be compared to the station observations from 1979-2013.

5.2.3 ERA-Interim Spatial Pressure Trends 1979-2013

Figure 5.1 depicts the seasonal spatial pressure trends in ERA-Interim from 1979-2013 (shading and contouring, background fill), while the stippling indicates statistically significant pressure trends at $p<0.05$. Each of the dots / circles on the plot indicates one of the 19 stations used in this study for the generation of the spatial pressure reconstructions. The fill color of the dots at each station indicates that station’s observational pressure trend, and significant observed pressure trends at $p<0.05$ are outlined with a thick black circle. As seen across all seasons, the ERA-Interim spatial pressure trends align very well with the observational pressure trends, not only in terms of trend magnitude but also with regards to where the significant trends are located.

During DJF (Fig. 5.1a) from 1979-2013, the entire continent of Antarctica has experienced negative pressure trends, with the greatest magnitude of these negative pressure trends seen across the Ross Ice Shelf, through portions of West Antarctica, and across the Weddell Sea. Many studies have shown how ozone depletion plays an important role in determining the Antarctic surface pressure change in summer, so this negative pressure trend in DJF is likely an external forcing mechanism response and not
caused entirely or even primarily by natural variability (Thompson et al. 2000; Thompson and Soloman 2002; Arblaster and Meehl 2006). Many of the spatial pressure trends in ERA-Interim are significant at $p<0.05$ during DJF, with the exception of the Antarctic Peninsula and across the interior near Vostok. The only significant observational pressure trend in the peninsula is Marsh/O’Higgins, but this record had to be patched and merged together, so this could be an artificial significant trend due to the merging of two nearby records. The SAM plays a weaker role in the climate of the peninsula and is influenced more profoundly by the regional circulation known as the Amundsen Sea Low (ASL). As seen during DJF, much weaker negative pressure trends are seen across the peninsula, and even a positive pressure trend is seen off the coast of the peninsula. Knowing this, it is not surprising to see insignificant pressure trends across the peninsula.

These negative pressure trends seen in DJF are also seen in MAM (Fig 5.1b); however, they are generally weaker in magnitude across much of the continent and insignificant. This is not the story across the Antarctic Peninsula however. During MAM from 1979-2013, the ASL has deepened, with a significant ($p<0.05$) negative trend across the Bellingshausen Sea.

Lastly, during JJA (Fig. 5.1c) and SON (Fig. 5.1d), positive pressure trends are seen across much of the spatial domain. During both seasons, all of West and East Antarctica experience positive pressure trends in both ERA-Interim and in the observations (apart from a weak negative pressure trend at Novolazarevskaya in JJA), most of which are insignificant at $p<0.05$. The only location of significant positive pressure trends occurs in SON across portions of East Antarctica, with the observational
trend at Casey also significant. Across the western portion of the Antarctic Peninsula
during both seasons, most of the observational and ERA-Interim pressure trends are
negative, opposite of the rest of the continent, but very weak in magnitude and
insignificant.

Figure 5.1: ERA-Interim spatial pressure trends from 1979-2013. Shading and contouring
(background fill) indicates the ERA-Interim spatial pressure field. Stippling indicates
significance at p<0.05. Dots represents the 19 stations used to produce the spatial
pressure reconstructions. Dot fill color represents the observational trends from 1979-
2013 and a thick black outline indicates a significant observational trend at p<0.05 from
1979-2013.
As seen in the previous subsections, the season with the strongest negative pressure trends is DJF, many of which are statistically significant. In the most recent 35 years, the observational trends in MAM are becoming less negative (when comparing the full observational record to the latter half of the observational record), but the opposite is true for DJF, where the negative pressure trends have amplified in magnitude in recent years. Positive pressure trends were seen across much of the continent in JJA and SON from 1979-2013, but the opposite is seen during JJA when looking at the 1957-2013 observational trends. The ERA-Interim spatial pressure field from 1979-2013 has also shown the same results of the latter half of the observational record, but now in a spatial context.

5.3 Full 20th Century Historic Antarctic Pressure Trends and Variability

Throughout this section, pressure trends and variability will be examined during the 20th century. Each subsection will represent a different season, starting with DJF, JJA, MAM, and concluding with SON. The first analysis technique to be analyzed are spatial pressure trends from each spatial pressure reconstruction generated in this research for DJF and JJA. These reconstructed spatial pressure trends will also be compared with each of the gridded pressure products that extend throughout the entire 20th century. After several different time periods are examined in regards to spatial pressure trends, several different timeseries plots will be analyzed to help further understand those trends seen and to help understand the range and scope of the 20th century pressure variability across the continent; 30-year running trends will also be analyzed for each season.
5.3.1 DJF

5.3.1.1 DJF Spatial Pressure Trends

The first season examined is DJF. This is the season where the most skillful (reliable) spatial pressure reconstructions were seen, and is a very interesting season when speaking of Antarctic climate. Both the original and pseudo spatial pressure reconstructions were of comparable skill, with the original slightly outperforming the pseudo spatial reconstruction. Figure 5.2 represents the DJF spatial pressure trends across the entire domain of 60°S – 90°S from 1905-2013. Plot a) and b) are the original and pseudo spatial pressure reconstructions, and c), d) and e) are the gridded pressure products of 20CR, ERA-20C, and HadSLP2, respectively. Shading / contouring represents the pressure trend while the stippling indicates the significance of those trends at \( p<0.05 \) at each grid point.

As seen in both spatial pressure reconstructions, mostly negative (albeit weak) pressure trends are seen across the entire spatial domain. The pseudo spatial reconstruction shows a few areas of weak positive pressure trends (i.e., Syowa station for example), and this is due to the input station data. The pseudo station-based pressure reconstruction had a weak positive trend while the original station-based pressure reconstruction had a weak negative pressure trend over the full record for Syowa. The original and pseudo reconstructions also differ in areas of significance; this is due to very subtle differences in the magnitude of some years in the two reconstructions and is very time sensitive (to the pressure magnitudes at the beginning and end of the time period, especially). Generally, the original reconstruction had greater magnitudes of pressure
anomalies, therefore resulting in a slightly more negative trend and making it significant at the $p<0.05$ level of significance. When comparing the reconstructions to the three century long gridded pressure products, they also agree with a negative pressure trend over the continent during this time. However, these products demonstrate much different results in terms of the magnitude of the trend. HadSLP2 and 20CR align themselves much better with the reconstructions, except still slightly higher negative trends are seen. ERA-20C shows extreme negative pressure trends across the continent during this time period, but is likely artificial and is an outlier when compared to the other products. This hypothesis will be evaluated in more detail in Fig. 5.8.

Figure 5.3 is identical to Fig. 5.2, except now only looking at 1905-1956 (before the observational period). When doing so, the spatial reconstructions both show positive pressure trends with many areas significant across the continent. The three gridded pressure products show very different results from the spatial reconstructions. 20CR and ERA-20C show negative pressure trends across the entire spatial domain, with ERA-20C showing the largest and most significant negative pressure trends across West and East Antarctica of -2hPa / decade or less in magnitude. HadSLP2 aligns better with the spatial reconstructions, where the Antarctic Peninsula shows positive pressure trends and much weaker negative pressure trends across the rest of the continent. Remember that these gridded pressure products are mostly constrained by observations, which are essentially non-existent during this time period in the high-southern latitudes. More confidence is given to the reconstructions as these are constrained by Southern Hemisphere midlatitude observations, unlike these gridded pressure products.
Figure 5.2: Spatial pressure trends from 1905-2013. Shading and contouring represents the trend and stippling indicates significance at p<0.05. Figures a) and b) represent the spatial pressure reconstructions, original and pseudo, respectively. Figures c), d), and e) are the three gridded pressure products that span the entire 20th century.
Figure 5.3: Same as Fig. 5.2, except now from 1905-1956.
Figures 5.4 and 5.5 are again identical to Fig. 5.2, except now from 1957-2013 and 1979-2013, respectively. Since these spatial trends are taken over the observational period, the station observations are overlaid on each plot in a similar fashion to Fig. 5.1. The spatial reconstructions in each figure both show negative pressure trends, with the magnitude of the negative trend being amplified in the latter period (Fig. 5.5). Station observational trends also align very well with the reconstruction trends, which again gives confidence that these reconstructions are reliable during DJF. The strongest negative pressure trends seen in the reconstructions (and observations) occurs along the South Atlantic, across the southern peninsula, through West Antarctica, and extending into the Ross Ice Shelf / Sea region where trends in the latter period are around -1.5hPa / decade. Figure 5.1(ERA-Interim) can also be compared to Fig. 5.5. When doing so, it is seen that the reconstruction spatial pressure trends match the trends in ERA-Interim very well. Looking at the original reconstruction, the strong negative pressure trends that extend from the Weddell Sea down through West Antarctica and into the Ross Ice Shelf region, mirror the same regions of the strongest negative pressure trends in ERA-Interim (Fig. 5.1). However, the original reconstruction overestimates the trend through much of the interior of the continent, especially so around Vostok when compared to Fig. 5.1a. The pseudo reconstruction aligns better with ERA-Interim and the observational trend in this region. Overall, the reconstructions match ERA-Interim spatial pressure trends very well in DJF.
Figure 5.4: Same as Fig. 5.2, except now from 1957-2013.
Figure 5.5: Same as Fig. 5.2, except now from 1979-2013.
When comparing to the three gridded products, ERA-20C aligns best with the spatial reconstructions in the latter period, while 20CR aligns best during the 1957-2013 period. During 1979-2013, 20CR quite drastically underestimates the negative pressure trends in the reconstructions and observations; ERA-20C does a much better job. However, during the full 1957-2013 period, ERA-20C overestimates the pressure trend across much of the continent. Furthermore, HadSLP2 shows irregularities across much of the continent in both figures, hence the regions of very tight gradients from one extreme to another (a quick switch from positive to negative pressure trends not seen in any other product, observation, or reconstruction). This is likely due to the fact that limited observations are going into this product across the continent, and it struggles to capture the correct pressure trend in recent years, but it could also be tied to errors associated with the reduction to sea level pressure over the Antarctic interior, as the other gridded datasets are based on surface pressure.

5.3.1.2 HadSLP2 Timeseries

To help explain why HadSLP2 is showing the trends as seen in Fig. 5.5, a timeseries plot for four different selected gridpoints across the continent was constructed (Fig. 5.6). These four locations were chosen because they are in or very near regions of extreme pressure trends in HadSLP2. The timeseries plots only shows DJF (black line) and JJA (red line), but the other two seasons are very similar. As seen in this timeseries plot around 1960, the pressure sharply decreased and hovered around zero (no large spikes in pressure from 1960-2000). However, at all four of these locations, between 2005-2013, there were very noticeable pressure changes across the continent, as depicted
by HadSLP2. For instance, plot a) and b) represent locations of extreme negative pressure trends. From 1979-2000, the trend is essentially zero (very minimal at most), however, in both DJF and JJA, very large pressure decreases were seen in the last few years of the record, which has a very profound effect on the trend in these locations, especially the latter half of the observational trend of 1979-2013. A similar story is seen in plots c) and d). Here, instead of pressure decreases, large pressure increases have been seen in these regions in the last several years, especially in JJA. For example, at grid point 5 and Relay station during JJA, large positive pressure anomalies of +13hPa were seen, which drastically influences the trends in these regions. Due to these large changes in the HadSLP2 mean sea level pressure field in the last 10 years, absurd and unreliable spatial trends are seen in all four seasons from 1957-2013 and especially so in 1979-2013.
Figure 5.6: Timeseries plot of select grid points across the Antarctic continent during DJF and JJA to highlight the trends seen in Figs. 5.4 and 5.5.

5.3.1.3 DJF Spatially Averaged Timeseries

The timeseries of DJF spatially averaged (across East Antarctica, West Antarctica, the Antarctic Peninsula, and the entire continent) pressure reconstructions and reanalyses from 1905-2013 are presented in Figs. 5.7 and 5.8. In each figure, the black and red lines represent the original and pseudo spatial pressure reconstructions, respectively. The blue line in each figure represents ERA-Interim. Also included in Fig. 5.8 are the reanalyses of 20CR and ERA-20C. For uncertainty / error in the reconstructions, the gray shading represents the maximum and minimum extent of the
95% confidence intervals about the original and pseudo spatial pressure reconstructions. This confidence interval was calculated as 1.96 times the standard deviation of the residuals from the spatial averages of ERA-Interim from 1979-2013. Correlations between the original / pseudo reconstruction and ERA-Interim from 1979-2013 are also given in each figure. For Fig. 5.7, \( r_o \) is the correlation between the original reconstruction and ERA-Interim while \( r_p \) represents the correlation with pseudo reconstruction and ERA-Interim. In Fig. 5.8, only correlations using the original reconstruction are given with respect to ERA-20C and 20CR over the full record and then again only during the latter period. For example, \( r_{05\,20CR} \) indicates that the correlation is between 20CR and the original reconstruction from 1905-2013. Likewise, \( r_{79\,20CR} \) is the correlation between 20CR and the original reconstruction but now only from 1979-2013. Correlations are also given using ERA-20C (below the 20CR correlation in each plot).

In Fig. 5.7, many interesting features stand out in the summer spatial pressure averages, but first it should be noted that high correlations between the reconstructions and ERA-Interim are seen across all regions, with slightly lower correlations in East Antarctica. One of the most important features in Fig. 5.7 is the fact that observations and ERA-Interim are not good indicators of full length 20th century pressure variability in the Antarctic. Historically, the pressure variability across the continent is much more variable than observations and ERA-Interim suggest. From 1905 – 1960, pressure variability is strongly characterized by strong interannual variability. Since approximately 1965, a strong downward trend is seen across all regions (least in the peninsula). This downward pressure trend has not been seen before in the summer season in the 20th century. Many
of the pressure anomalies in the 1990s and 2000s across these regions are among the lowest ever seen in the 20th century. This negative pressure pattern is consistent with previous studies showing how the SAM index (pressure trends in the Antarctic) in the latter half of the 20th century is influenced by ozone depletion (Chapter 2). These spatial averages align very well with the conclusions from Fogt et al. (2016b) where a strong downward trend in pressure in the latter half of the 20th century was seen at all stations reconstructed. This research indicates that spatially across the continent, those same negative pressure trends seen in Fogt et al. (2016b) dominate the end of the 20th century pressure records. Prior to 1960, pressure was much more variable across the continent.

Figure 5.7: Timeseries (and their correlations) of spatially averaged pressure from the two reconstructions with ERA-Interim across the three main geographical sectors and the entire continent.
Figure 5.8 is identical to Fig. 5.7, except now with the inclusion of two other century long reanalyses, ERA-20C and 20CR. This figure demonstrates a few new key points. First, it shows how extreme ERA-20C is throughout the early portion of the 20th century: this reanalysis shows pressure anomalies upwards of 15 - 20hPa across the continent, which is known to be an extreme bias in this reanalysis. Second, it also shows that large positive pressure anomalies are seen across the continent in 20CR, many of which fall outside the 95% confidence interval generated from the spatial pressure reconstructions as noted above. Due to these known deficiencies in the early period of both ERA-20C and 20CR reanalyses, a false negative trend throughout the entire record is produced in DJF (Fig. 5.2). It is clearly seen from the reconstructions this is not the case, and only post-1965 is there a strong negative trend observed, whose magnitude has never been seen before in the 20th century. Lastly, note how the correlations are very low over the entire record, but greatly improve in the latter period (1979-2013) between the reanalyses and original spatial reconstruction. This again shows that the skill of these reanalyses is highly time dependent (see Fig. 3.2), and altogether they have a much better agreement with the spatial pressure field across the continent in the latter half of the 20th century. Keeping this in mind, it gives confidence that the spatial reconstructions are now more reliable than these reanalyses back through the 20th century, as the reconstructions are observationally constrained.
5.3.1.4 DJF 30-year Running Trends

Another important analysis technique is to examine 30-year running trends (Fig. 5.9). Here, the black line represents the original reconstruction and the red line indicates the pseudo reconstruction. These are spatially averaged over East Antarctica, West Antarctica, the Antarctic Peninsula, and the entire continent. The gray shading represents the 95% confidence interval generated from the standard error of the slope over the 30-year period and using the maxima and minima confidence interval from the two reconstructions.
Interestingly, the DJF pressure trends seen beginning around 1965 are unique over the last century across much of the continent. In East and West Antarctica, the 30-year running trends show that since approximately 1965, the upper bound of the 95% confidence interval never crosses the zero line, indicating statistically significant pressure trends (95% confident that the trend is not zero) in these locations; this is a new scientific advancement when taking the full 20th century and area-averages of the Antarctic continent into consideration. This is also the same story when examining the entire continent; however, when looking specifically at the Antarctic Peninsula, the 30-year running trends do not become significant and unique until the last several years of the study.

These strong negative pressure trends across the continent seen throughout this section (season; DJF) are likely indicative of external forcing mechanisms driving these negative trends, and that they are not primarily driven by natural or internal climate variability since the significant trends occur only recently and are unique over 100+ years. Previous work (as noted in Chapter 2) has shown how summer pressure over Antarctica responds to ozone depletion, which is consistent with the work shown here where negative pressure trends have been seen across the continent since around the development of the ozone hole (Thompson et al. 2000; Thompson and Solomon 2002; Arblaster and Meehl 2006). During the early half of the 20th century, before ozone began to rapidly deplete and have a strong influence on Antarctic summer pressures, the timeseries and 30-year running trends shown above indicate that the continent was mostly
influenced by natural variability and that a forcing mechanism response is absent from these timeseries until around 1965.

The remaining seasons are structured in a similar manner presented here. Upcoming figures are identical to figures presented here, but now with a different seasons pressure reconstruction. Due to this and for brevity purposes, figure structure / layout will not be explained again.
Figure 5.9: 30-year running trends of the original and pseudo spatial pressure reconstructions spatially averaged over a) East Antarctica, b) West Antarctica, c) the Antarctic Peninsula, and d) the entire continent. The gray shading represents the maximum / minimum 95% confidence intervals from both the original and pseudo spatial reconstruction trends, based on the standard error of the regression coefficient.
5.3.2 JJA

5.3.2.1 JJA Spatial Pressure Trends

In winter (JJA), the pseudo reconstruction was deemed more reliable than the original reconstruction through multiple different evaluation techniques as shown in Chapter 4 which is similar to Fogt et al. (2016a) as shown in Fig. 2.14. Due to this, more emphasis will be given to the pseudo reconstruction than the original reconstruction for this season. Figures 5.10 – 5.13 show spatial pressure trends of the two reconstructions and the three gridded pressure products from 1905-2013, 1905-1956, 1957-2013, and 1979-2013, respectively. Over the full period (Fig. 5.10), very weak positive and negative pressure trends are seen across the continent in the reconstructions, with more significant trends in the pseudo reconstruction. Coastal East Antarctica primarily contains positive pressure trends, while the Antarctic Peninsula shows weak negative pressure trends. The areas where the reconstructions do not match are over the Ross Ice Shelf, West Antarctica, and near the South Pole. These trends are all weak however, and likely indicative of a slightly different trend in the station-based reconstruction used to generate the spatial reconstruction. In contrast, all three gridded pressure products show negative pressure trends over then entire spatial domain. This is likely due to the early period only having minimal observations going into the gridded products to constrain them, unlike the reconstructions.
Figure 5.10: Same as Fig. 5.2, except for JJA.
When examining the early portion of the record (Fig. 5.11; before observations), the reconstruction trends do not change drastically from those over the entire 20th century. The pseudo reconstructions now show a trend between 0.25 – 0.50hPa / decade across much of East Antarctica and a slightly weaker positive trend across the peninsula. In both the original and pseudo reconstruction, the Ross Ice Shelf shows opposite trends, but both reconstructions agree with a negative pressure trend across much of West Antarctica. However, all these trends are again relatively weak and insignificant. Unsurprisingly, the three gridded pressure products do not align well with one another in the beginning of the 20th century. HadSLP2 matches the pseudo reconstruction the best, which could potentially be due to the fact that the station-based pressure reconstructions were derived in a similar fashion as the methods used to generate HadSLP2. Similar to DJF, ERA-20C seems to have a large bias in the record where large (but insignificant) negative pressure trends are seen across the continent.
Figure 5.11: Same as Fig. 5.3, except for JJA.
During the observational period (Fig. 5.12), the most promising results lie in the pseudo reconstruction, although the original reconstruction trends also match fairly close. In particular, the observational trends agree well with the pseudo reconstruction trends across the continent; even the weak positive trend in West Antarctica is captured correctly with the Byrd station observations. Another promising feature is the significant observational trend at Mirny station along the coast in East Antarctica, which was also captured in both sets of reconstructions. Overall, both reconstructions show negative pressure trends across the continent (with the exception of West Antarctica), where significant negative trends are seen across the Ross Ice Shelf and around portions of coastal East Antarctica. The only instance in the pseudo reconstruction where an observational trend isn’t captured correctly is Vostok station, but the trends in this region are essentially zero. The three gridded products also mostly show negative pressure trends across the entire continent, with HadSLP2 showing some outlying results that were previously discussed in Fig. 5.6. During the observational period of 1957-2013, 20CR seems to align best with the reconstructions and observational trends.
Figure 5.12: Same as Fig. 5.4, except for JJA.
Lastly, the late period of 1979-2013 can be examined in Fig. 5.13. Here, the reconstructions show most of East Antarctica having a positive pressure trend between 0.25 – 0.75hPa / decade. Through West Antarctica and the Ross Ice Shelf region, the trends are negative; however, they are all insignificant. Unfortunately, HadSLP2 is again showing outlying results, but as explained, this is due to errors in HadSLP2 during the last several years. Both ERA-20C and 20CR agree with the reconstructions and observations, showing a positive pressure trend in East Antarctica. Comparing Fig. 5.13 to Fig. 5.1, it is seen that the pseudo reconstruction aligns very well with ERA-Interim. The only instance of different trends between the two occurs across the Ross Ice Shelf, where the trend deviates by about 1hPa / decade. This difference occurs because the observations from 1982-1986 show moderately strong negative anomalies (-4hPa) where both reconstructions show anomalies near zero in the record, ultimately generating a positive trend in the observations (and ERA-Interim) and a negative trend in the reconstructions (not shown).
Figure 5.13: Same as Fig. 5.5, except for JJA.
5.3.2.2 JJA Spatially Averaged Timeseries

The JJA spatially averaged pressure of the reconstructions and ERA-Interim over East, West, the Antarctic Peninsula, and the entire continent is shown in Fig. 5.14. When comparing JJA to DJF (Fig. 5.7), there are many different characteristics between the two. First, there is not a clearly defined trend, as was the case in DJF in that latter half of the 20th century. This was also seen in Figs. 5.10 – 5.13, where only small, non-persistent trends were seen and were all insignificant across the continent. Also unlike in DJF where an external forcing mechanism likely attributed to the trends seen across the continent, JJA is strongly characterized by natural variability throughout the entire reconstructed record with strong interannual variability. The interannual variability in the peninsula seems to be strongest during the time of observations (1957-2013) and this is consistent with Fogt et al. (2016b). The Antarctic Peninsula also is the region with the strongest correlations between the reconstructions and ERA-Interim during the period of overlap, so considerable confidence is placed in this result.

As with DJF, the two century long reanalyses have a strong positive bias compared to the reconstructions in the early period of the 20th century (Fig. 5.15). This again leads to exaggerated negative pressure trends these products (Figs. 5.10 and 5.11). Since the reconstructions are observationally constrained throughout the entire reconstructed record, these new reconstructions should now be given more trust than these reanalyses that have very minimal observations to constrain their solutions across the high southern latitudes prior to ~1960. The correlations are also provided, and it is
seen that when more observations go into the reanalyses (post 1979) the correlations greatly improve across all regions (less so in West Antarctica).

**Figure 5.14**: Same as Fig. 5.7, except for JJA.
5.3.2.3 JJA 30-year Running Trends

Lastly, JJA 30-year running trends are analyzed in Fig. 5.16. Over the last century, the recent trends seen in observations and reanalyses data previously do not appear to be unique; similar trends have occurred throughout the last 100+ years as this season is characterized by strong interannual and multi-decadal scale variability with pressure trends varying from weakly positive to weakly negative pressure trends throughout the century. The early portion of the 20th century was characterized by
negative trends changing to positive trends until about 1935. After 1935, the continent saw negative trending pressure until about 1970, after which positive pressure trends characterized this season. This aligns with the observations and reconstructions quite well, as the recent period is dominated by positive pressure trends, albeit insignificant.

Figure 5.16: Same as Fig. 5.9, except for JJA.
5.3.3 MAM

In these last two sections, the two transition seasons of MAM and SON will be analyzed. Both of these seasons were determined to have slightly weaker skill than those of DJF and JJA, however both seasons still outperformed climatology as shown in Chapter 4. Due to this weaker skill of these reconstructions, less emphasis will be given here. However, important features will still be discussed for both seasons as similarly done for DJF and JJA. Specifically, timeseries plots of the spatial pressure averages and the 30-year running trends will be shown.

Figure 5.17 shows the spatially averaged pressure during MAM. Several interesting characteristics stand out in this timeseries. First, the greatest skill and therefore correlations with ERA-Interim exist in the Antarctic Peninsula, while the correlations are much lower elsewhere across the continent. Also note the original and pseudo reconstructions align very well with each other in the peninsula; this cannot be said for East or West Antarctica. In these two locations, the pseudo reconstruction was deemed more reliable from the evaluation in Chapter 4. Note that there is no large pressure trend as was seen in DJF. Much of the record is characterized by strong interannual variability.

Another interesting feature in Fig. 5.17 is the prominence of decadal scale variability in the Antarctic Peninsula. This region is strongly characterized by time periods where negative pressure anomalies are seen followed by a period of positive pressure anomalies. This can also be seen in the 30-year running trends in Fig. 5.18. Here in Fig. 5.18c, a persistent pressure pattern appears, where there is an oscillation between
positive and negative trends across different time periods. This is not only seen in the peninsula, but this same pattern is also seen in East Antarctica. For example, from 1960 until very recently, these regions were characterized by a negative pressure pattern; however, in recent years, this pattern is changing and a positive pressure pattern is seen. This pattern is not seen in West Antarctica, which may be due to the known problems of the reconstructions in this region.

Figure 5.17: Same as Fig. 5.8, except for MAM.
Figure 5.18 also shows where significant pressure changes have been seen throughout the 20th century. In East Antarctica, the negative pressure trends that characterized the region from the late 1960s through late 1990s are significant, as discussed with ERA-Interim and observations previously. An interesting prolonged dip in pressure across this region in the late 1990s can also be seen in Fig. 5.17a, which influences the 30-year running trend. ERA-Interim mirrors the reconstructions during this period, so it does not seem to be an issue within the reconstructed data. This same prolonged dip in pressure in the late 1990s is also present in West Antarctica, but much less pronounced and in the peninsula region. Overall, this season is characterized by decadal scale variability (especially so in the peninsula) over the 100+ year reconstructed record.
Figure 5.18: Same as Fig. 5.9, except for MAM.
5.3.4 SON

The last two figures in this section show the spatially averaged timeseries of pressure (Fig. 5.19) and the 30-year spatially averaged running trends (Fig. 5.20). As before, the correlations between the reconstructions and ERA-Interim in MAM are highest in the peninsula and weakest over East Antarctica. The correlations are likely weakest over East Antarctica due to the fact that this is a vast amount of land with few interior stations (that have smaller spatial footprints) which therefore hinders the spatial reconstruction. Another interesting feature in SON is the fact that the full century record is characterized by strong interannual variability (strongest during the period of observations, which is similar to MAM), where no significant trends in the pressure field are seen, as was the case in DJF.

In Fig. 5.19a, there are a few interesting features of the low-frequency pressure pattern. Prior to ~1980, the interannual variability is much weaker, with the exception of the 1940s. During this time, some of the strongest interannual variability in East Antarctica is seen. Another interesting feature leading up to the 1940s is the prolonged period of lower than average pressure in the 1930s. This period of lower pressure is also seen in West Antarctica and in the peninsula, but much less pronounced. In Fig. 5.20, both periods of these interesting features in East Antarctica are missing when considering 30-year running trends.
Figure 5.19: Same as Fig. 5.8, except for SON.

Figure 5.20 helps to place the trends observed today in a historical context. Over the 100+ year record, there are no significant regionally averaged pressure trends; all recent changes in pressure have been observed before across the continent. One interesting feature in Fig. 5.20 is the recent positive pressure trends across the peninsula and West Antarctica. These positive pressure trends / anomalies in Figs. 5.19b,c and 5.20b,c are among the highest ever over the 100+ years. However, in the last few years of the 30-year running trends, a downward trend in pressure across the entire continent is
being seen. This pattern is similar to MAM where there is an oscillation of high and low pressure patterns across the continent, except less profound in SON than in MAM.

Figure 5.20: Same as Fig. 5.9, except for SON.
Lastly, the MAM and SON spatially averaged pressure timeseries plots that include ERA-20C and 20CR (not shown) are quite similar to Fig. 5.8 and Fig. 5.15. In the early portion of the reanalyses record, large positive anomalies are seen, upwards of +15.0hPa / decade. These products again have a large positive bias in the early 20th century, when they are constrained by minimal observations. This large positive bias, similarly to DJF and JJA, create strong negative pressure trends over the full record and early 20th century. Not until ~1960 do the reanalyses agree much better with the spatial reconstructions and ERA-Interim (same story was seen in DJF and JJA). Due to this, it again gives confidence that the seasonal spatial pressure reconstructions produced in this thesis are of much better quality and reliability than any of the full 20th century reanalyses / gridded pressure products.

5.4 Pressure Anomaly Composites and Time Sensitive Trend Analysis

5.4.1 Seasonal Pressure Anomaly Composites Within the Last 60 Years

Another method to further examine the pressure trends seen in recent decades is to analyze pressure anomaly composite differences, as outlined in Chapter 3.4.5. This method is commonly used to compare two different groups of data, and to see if the two means are significantly different from one another. Importantly, this method is not as time sensitive to the chosen beginning and ending periods as regression analysis can be, so this is a good method used to check to see if the pressure changes in the last 30 years are significantly different from the previous 30 years. Both the original and pseudo spatial pressure reconstructions will be examined during each season.
Figure 5.21 and Fig. 5.22 are the comparison of means plots using the original and pseudo spatial reconstructions, respectively, by season. Here, the two 30 years of data to be explored are the last 30 years of the reconstructed record (1984-2013; most recent) and the previous 30 years (1954-1983). The first 30 years of data (1954-1983) were subtracted from the last 30 years (1984-2013) to give a better perspective as what is happening in more recent decades. The differences of means are shaded and contoured, while the significance at $p<0.05$ is stippled. The significance indicates that there is at least 95% confidence that the difference between the two means is not zero.

During the summer season, the composite differences confirm that the pressure over the continent in the last 30 years is much lower than it was in the previous 30 years. The only exception to this is the station of Orcadas located off the northern peninsula where a slight increase in pressure in the last 30 years has been seen. Throughout the Antarctic Peninsula, across the South Atlantic, and throughout the Ross Ice Shelf region, the two reconstructions align very well. In these locations, the difference of means is around -2hPa and lower which is significant in all regions. A similar conclusion is reached throughout all East Antarctica with significant differences, except the magnitude of the difference is slightly higher in the original reconstruction. In West Antarctica, the two reconstructions generally show that pressure has been lower in the most recent 30 years when compared to the previous 30 years, however this change is insignificant in the vicinity of Byrd station. Between the timeseries plots shown previously and Figs. 5.21a – 5.22a, it is concluded that during the summer season, the pressure field has seen impressive decreases in pressure across the entire continent.
Figure 5.21: Seasonal anomaly composite differences (comparison of means) using the original reconstruction between two 30 year groups of pressure data (spatial mean of 1984-2013 minus spatial mean of 1954-1983).
Figure 5.22: Same as Fig. 5.21, except now using the pseudo reconstruction.
During JJA, the composite analysis between the two reconstructions generally tells the same story, but a few discrepancies do exist. First, the reconstructions agree that over East Antarctica and across much of the peninsula, the most recent 30 years have seen lower than average pressure than the previous 30 years, albeit insignificant in most locations. The region of greatest negative mean difference is located across the Ross Ice Shelf and through the Oates Coast. However, this was the same region as explained in section 5.3.2 where McMurdo observations and ERA-Interim anomalies show a weak and insignificant positive pressure trend in this region, which is likely indicative of complications with the McMurdo station reconstruction in both the original and pseudo reconstructions. The most interesting feature of mean difference between the two reconstructions is in West Antarctica. During JJA, the pseudo reconstruction was deemed much more reliable, so Fig. 5.22c is likely more trustworthy than Fig. 5.21c. The composite analysis using the pseudo reconstruction in West Antarctica shows a pressure increase in the last 30 years, which is opposite of the original reconstruction. The Byrd station observational trend was positive in both Figs. 5.12 – 5.13, garnering further confidence that the composite analysis using the pseudo reconstructions is likely more accurate than the original reconstruction in West Antarctica. Generally, during the winter season, the entire continent has experienced insignificantly lower than average pressure across the continent in the last 30 years, when compared to the previous 30 years, with the exception of West Antarctica.

The two transition seasons of MAM and SON also have an interesting story to tell across the continent. Generally, the original and pseudo reconstructions match fairly well
in regards to the sign of the difference and even the difference magnitude in most instances. In MAM, both sets of reconstructions show that across West and East Antarctica, lower than average pressure has been seen in the last 30 years compared to the previous 30 years. The composite analysis reveals that none of the mean differences between the two time periods are significant in West Antarctica, while much of East Antarctica shows a significant difference, especially in the original reconstruction. This can also be seen in Figs. 5.17 – 5.18, where a downward pressure trend is seen across East Antarctica in the late 20th century. In contrast, pressure increases are seen in the Antarctic Peninsula, as described in Tables 5.1 – 5.2 and Fig. 5.18. This is the only location of positive pressure trends and differences across the continent in MAM.

During SON, both sets of reconstructions agree that around the coast of East Antarctica and the Ross Ice Shelf, the 1984-2013 mean pressure was lower than the mean pressure during 1954-1983, with the mean pressure difference along the coast between 60ºE and 90ºE being significant at $p<0.05$. Outside of these regions, especially in the interior of the continent and in West Antarctica, the mean pressure difference is significantly greater in the last 30 years than it was prior during 1954-1983. Both sets of reconstructions also agree that mean pressure increases have been seen across the Antarctic Peninsula as well; however, only in the original reconstructions is this shown as being significant.

In conclusion, the composite analysis has revealed and confirmed many interesting features of the changing pressure pattern across the Antarctic continent. First, during DJF, the mean pressure from 1984-2013 has been significantly different than the
mean pressure from 1954-1983. The only region of insignificant negative mean pressure differences were in West Antarctica. Second, during MAM and JJA, all of East Antarctica has seen a mean pressure decrease in the last 30 years, but only significant in MAM; nonetheless in a historical context similar differences in this season have occurred in earlier portions of the 20th century. Lastly, in both transition seasons, the peninsula has seen positive mean pressure differences, indicating rising pressure in this region when compared to the previous 30 years of data. The next section will take another look at the pressure trends across the continent, now to examine time sensitivity using differing lengths to calculate linear trends.

5.4.2 Sensitivity of the Reconstructed Pressure Trends to Starting and Ending Period

Up until this section, the main analysis techniques used to examine the reconstruction pressure trends have been to use least squares linear regression and composite analysis. Unlike least squares linear regression, composite is much less sensitive to the starting and ending periods chosen by the analyst, but still has its limitations as only a portion of the time period is examined. To fully understand the pressure trends in the reconstructions and how time sensitive they are, Fig. 2.23 examines the spatially averaged reconstruction pressure anomalies over East and West Antarctica over various time periods, by season. A minimum of at least 30 years of data needed to calculate the trend in order to remove strong influence of outliers. The starting year of the trend is given on the y-axis and the ending year is given on the x-axis. Shading represents the pressure trend (hPa / decade), while hatching and stippling indicates the $p<0.10$ and $p<0.05$ significance levels, respectively, to help show how the statistical significant
trends change with time. From the upper left moving to the lower right of each plot, the length of time increases; the diagonal moving from the lower left to upper right where the shading starts indicates trends calculated with exactly 30 years of data.

During DJF, the same significant negative pressure trend across East and West Antarctica is seen when taking the last several decades into consideration. The strongest negative pressure trends are seen over the recent shorter time periods, as seen by the darker blues in the top right corner of plots (a) and (e). Importantly, this negative pressure trend seen during DJF in the last several decades plays a large role in the long-term trends, as seen here in plots (a) and (e). If the last half of the 20th century is excluded from the trend calculation, mostly positive pressure trends are seen across the continent, with the strongest and most significant positive pressure trends occurring in West Antarctica during the early to mid 20th century. This positive pressure trend during the early half of the 20th century in East and West Antarctica can be seen in Fig. 5.7 also. Overall, during DJF, the most interesting feature is the strong negative pressure trend over the short-term trends (indicative of an external forcing mechanism), and its influence on century long trend calculations. Prior to the late 20th century, the continent mostly experienced positive pressure trends during DJF.

The winter season is also an interesting season in the Antarctic, as multiple switches in pressure trends and variability have been seen (Figs 5.23c, 5.23g, and 5.16). During the shorter time periods (recent and beginning of the record), negative pressure trends across both East and West Antarctica are seen (however the trend is becoming positive in West Antarctica in the last several years). Strong negative trends were seen
across East Antarctica in the very early period of the record; this can also be seen in the
timeseries plot (Fig. 5.14), while much weaker negative trends are seen during this same
time period in West Antarctica. Strong and significant negative pressure trends also
characterize the pressure record in East and West Antarctica from the mid-to late 20th
century also (and continuing up until the end of the record in East Antarctica). However,
outside of the early and late portion of the reconstructed record, strong (and very strong
in East Antarctica) and significant positive pressure trends characterized these regions
through much of the mid 20th century, as indicated by the warm colors in plots (c) and
(g). Altogether this highlights the presence of strong multi-decadal scale variability in
terms of Antarctic pressure in winter.

East and West Antarctica experience a similar story in the recent trends during
MAM; both regions show negative pressure trends, but only significant in East
Antarctica, which shows a much stronger negative trend. However, outside of recent
decades, West Antarctica has experienced positive pressure trends, most of which were
significant across all time periods. The strongest positive pressure trend in MAM over
West Antarctica occurred from the 1920s to 1950s.

The season with the least amount of significant pressure trends occurs in SON, as
previously seen in observations and the reconstructions. Over both East and West
Antarctica in the recent short-term trends, positive pressure trends are seen. The greatest
of these positive trends occur in West Antarctica, while the rest of the West Antarctic
pressure trends remain weak and insignificant. This was also gathered from the SON
timeseries and 30 year running trends, as discussed earlier where this season is strongly
characterized by strong interannual variability, and no long-term or persistent changes. In East Antarctica, the mid 20th century was characterized by relatively strong (for this season) positive pressure trends, with a switch during the mid-to-late 20th century to a weak negative pressure trend. However, in recent years, both East and West Antarctica has been seeing positive pressure trends, as earlier indicated in Fig. 5.22.

Figure 5.23: Temperature trends calculated at different time periods (minimum of 30 years) using the original reconstruction. The trends for DJF, MAM, JJA, and SON are shown left to right, and for East Antarctica on the top, and West Antarctica on the bottom. Shading represents the trends, while the hatching and stippling indicates the significance at p<0.10 and p<0.05, respectively.

5.5 Chapter Summary

Throughout this chapter, each season was analyzed separately using several different techniques to examine the observational, gridded pressure products, and
reconstructions trends and variability. More specifically, the full 20\textsuperscript{th} century Antarctic pressure trends and variability could be examined using the reconstructions produced in this work, which was the ultimate goal: to further understand full 20\textsuperscript{th} century Antarctic pressure trends and variability. The spatial reconstructions were also compared to the gridded pressure products that span the full 20\textsuperscript{th} century, and it was found that during the early 20\textsuperscript{th} century, the gridded datasets not only deviate from the reconstructions, but also with each other. This indicates that these products are highly time dependent, as shown in Fig. 3.2. It was also found that the gridded products show very large positive biases in early 20\textsuperscript{th} century Antarctic pressure that the reconstructions do not. Therefore, an important conclusion made from this research is that these gridded pressure products need to be used very cautiously in the high southern latitudes in the early 20\textsuperscript{th} century. This can be concluded because of the results seen here; the reconstructions are observationally constrained throughout the entire reconstructed period, while the gridded products are only observationally constrained during the time of observations, which are significantly lacking in the high southern latitudes in the early 20\textsuperscript{th} century.

Some of the most interesting discoveries of this research came in the summer season. During the observational period (1957-2013) and also that of ERA-Interim (1979-2013), a very strong negative and significant pressure trend is seen across the continent, of which only amplifies in the latter portion of the observational period. A major conclusion produced from the reconstructions is that this negative pressure trend seen in DJF is unique over the last 100+ years and is primarily externally driven. This can be said as other studies have shown how ozone depletion influences the pressure pattern over the
continent in DJF (Thompson et al. 2000; Thompson and Solomon 2002; Arblaster and Meehl 2006), and this negative pressure pattern begins around the time of ozone hole development. In the reconstructed record, nowhere across the continent has a negative pressure trend of this magnitude and significance been seen before in the 20th century; the early 20th century was characterized by weak positive pressure trends and mostly interannual variability.

Another season with interesting results was JJA. Here, across East Antarctica (and West Antarctica at a weaker magnitude) a very strong positive pressure trend characterized the early to mid 20th century, which was significant (Fig. 5.23). This positive pressure trend during this season now warrants future research. However, during the late 20th / early 21st century across the continent in JJA, mostly negative pressure trends are seen. Over the last century, the recent trends seen in observations and reanalyses data previously do not appear to be unique; similar trends have occurred throughout the last 100+ years as this season is characterized by strong interannual and multi-decadal scale variability with pressure trends varying between positive and negative throughout the reconstructed record.

Lastly, the transition seasons were both characterized by interannual variability, with no clear long-term and persistent pressure trend. The 100+ year record in MAM is mostly characterized by decadal variability in the peninsula and in East Antarctica, as revealed by the reconstructions. Not until recently have strong negative pressure trends been seen across East Antarctica; much of the 20th century was characterized by strong interannual variability. This is similar to SON, where the entire record is characterized by
interannual variability, with no significant trends in pressure seen over a persistent time period.

The final conclusions of this analysis are the following:

- The recent negative pressure trends seen across the continent in DJF are significant and unique over 100+ years of reconstructed data.
- This negative pressure trend seen in the late 20th / early 21st century is (at least primarily) driven from an external forcing mechanism.
- Observational and ERA-Interim spatial pressure trends / variability in recent decades are not good indicators of early 20th century DJF pressure variability / trends over Antarctica.
- MAM, JJA, and SON are characterized by strong interannual variability throughout the entire reconstructed record that is driven by natural and internal climate variability; DJF is characterized by interannual variability during the early 20th century (up until the development of the ozone hole).
- 20th century gridded pressure products are not good indicators of early 20th century pressure trends and variability in the high southern latitudes. These products are highly time dependent. Due to this, the reconstructions generated in this research are deemed more reliable.
CHAPTER 6: CONCLUSIONS

This thesis developed a seasonal spatial pressure reconstruction that extends back to 1905 across a spatial domain of 60° - 90°S. The purpose of this research was to examine 20th century pressure trends and variability throughout the Antarctic, especially to examine if recent trends are unique in comparison with the full 20th century. Since observations are very sparse across Antarctica prior to the International Geophysical Year (IGY) of 1957-58, this work was important in beginning to understand the full 20th century pressure variability and trends. As discussed in Chapter 2, many studies have shown how identifying atmospheric pressure patterns and circulations are necessary to understanding other climate / meteorological variables, such as temperature, wind fields, and sea ice extents.

Turner et al. (2005) examined annual and seasonal mean sea level pressure/surface pressure trends using observational data from 16 stations across the continent. These results found that all the stations examined have negative pressure trends in the annual mean, and that the most significant negative pressure trends are located in the interior of Antarctica and in East Antarctica in DJF. Yet this and other previous studies are plagued with short time scales, only dating back to the IGY and not spatially complete; many large data gaps exist both historically and presently across the continent. Due to this, it is important to examine these recent changes back throughout the entire 20th century and in a spatially complete manner. Therefore, this thesis was built upon three main research questions:
1) What is the skill (reliability) of an Antarctic continent-wide pressure reconstruction based on long-term station reconstructions?

2) Using a 20th century spatially complete gridded reconstruction of pressure, what changes in the Antarctic circulation appear to be unique over the last century, especially at locations away from the reconstructed stations?

3) What is the range and scope of natural variability in pressure across Antarctica over the last century?

To begin to fully understand 20th century pressure variability and trends across the Antarctic, the Fogt et al. (2016a) station-based pressure reconstructions were used to develop multiple different sets of spatial pressure reconstructions; however, ERA-Interim station data were used first for method evaluation / reliability. The first step taken was to prove that the geostatistical interpolation method of kriging used to generate the spatial reconstructions was reliable. To do so, ERA-Interim station data (seasonal means) were used to reproduce the ERA-Interim spatial pressure field from 1979-2013. It was found that the kriging interpolation when using ERA-Interim station data produced very similar results as those in the full (original) spatial pressure field of ERA-Interim itself in all four seasons, with DJF and JJA being the most skillful (reliable). The main reason that this kriging approach works well in Antarctica when only using 19 input stations (very few when compared to the entire continent itself) lies in the fact that each station’s pressure is remarkably similar to the pressure across a wide area (what are termed here as ‘spatial footprints’; homogeneous nature of pressure across the continent). The pressure field across the continent is very continuous in nature, unlike temperature and wind fields that
are more modified by local features. This is especially true in DJF when the entire continent experiences 24 hours of daylight. Given the large area of the spatial footprints within ERA-Interim across the continent, even with only 19 stations used in the interpolation algorithm, kriging can still be used in a meaningful manner. Further, with the very similar results between the raw ERA-Interim pressure field and the reconstructed ERA-Interim pressure field, it was deemed that kriging is a reliable interpolation method and could therefore be used to produce spatial reconstructions that extend back to 1905 using the Fogt et al. (2016a) station-based pressure reconstructions.

After the seasonal spatial pressure reconstructions were generated using the original and pseudo station-based pressure reconstructions, a thorough evaluation was conducted to examine the reliability of these reconstructions. To investigate this, multiple different techniques were used to compare the original and pseudo spatial pressure reconstructions to the ERA-Interim reanalysis, including: $r^2$, reduction of error, coefficient of efficiency, mean absolute error, spatial anomaly correlations, grid point correlations, and 11-year smoothing with hamming filters. From these various evaluation measures, it was easily concluded that spatial pressure reconstructions in DJF and JJA were the most reliable, with MAM and SON being slightly less reliable. Similar seasonally varying pressure reconstruction skill was observed in Fogt et al. (2016a). The original spatial reconstruction was the most reliable in DJF, while significant improvement was seen in the pseudo spatial pressure reconstruction in JJA. Overall, the spatial pressure reconstructions were all deemed reliable enough to provide useful
information on historic pressure variability throughout the 20th century, due to how well they matched ERA-Interim after 1979.

More specifically during DJF, impressive $r^2$ values above 0.7 were seen across the entire continent, which gives strong confidence that this season’s spatial original reconstruction is a good representation of the pressure field over the years 1979-2013. Furthermore, mean absolute error across the continent fell below 1.5hPa during DJF when using the original reconstruction, which again shows a good comparison with ERA-Interim. During the winter season (JJA), the pseudo reconstruction was deemed most reliable, with mean absolute error across the continent less than 1.75hPa and $r^2$ values almost all above 0.7 across the continent. Notably, the reduction of error and coefficient of efficiency values were also always positive over the continent in all four seasons from 1979-2013, further indicating a more skillful spatial reconstruction than if the climatological mean were to be used. Overall, this evaluation answered the first research question, proving that it is possible to have a reliable Antarctic continent-wide pressure reconstruction based on long-term station reconstructions.

To investigate the final two research questions, multiple different analysis techniques were used: trend analysis, 30-year running trends, correlation, composite analysis, and timeseries analysis. The spatial pressure reconstructions were also compared to observations and several different gridded pressure products, namely ERA-Interim, 20CR, ERA-20C, and HadSLP2. First, pressure trends in observations (1979-2013 and 1957-2013) and ERA-Interim (1979-2013) revealed that a strong negative pressure trend that is significant at $p<0.05$ in summer is seen across the continent during
1957-2013, and only amplifies in magnitude during 1979-2013 in both observations and ERA-Interim. During MAM, pressure trends in the peninsula region were positive, but became negative in the latter portion of the record. Again, East and West Antarctica contained negative pressure trends, similar to DJF but mostly insignificant. During JJA, the observational trends during 1957-2013 were negative across the continent, but became mostly all positive during 1979-2013. Lastly, SON had shown generally positive but insignificant pressure trends across the continent.

To fully understand the historical significance of these trends, pressure trends across the entire Antarctic continent during DJF were first examined over four different time periods, 1905-2013, 1905-1956, 1957-2013, and 1979-2013. When the spatial pressure reconstructions are compared to the gridded pressure products covering the early 20th century, considerable differences are seen, not only between the reconstructions and gridded products, but also between the gridded pressure products themselves. The gridded pressure products are constrained by observations only during times when observations are available. Due to this, these products often show drastically different results in the spatial pressure field in the Antarctic prior to the IGY due to minimal observations. Since this is a known deficiency, the reconstructions, which are statistically (and indirectly, observationally) constrained throughout the entire reconstructed record, are given more emphasis as they are likely more reliable.

During DJF, the strong negative pressure trend seen in the late 20th century is entirely absent from the early 20th century. This thesis is therefore among the first research demonstrating that the recent negative pressure trend in summer is unique in the
100+ year record. The reconstructions show that the early 20th century in DJF was characterized by interannual variability, and that an external forcing mechanism is likely responsible for the negative pressure trend in the late 20th century. This negative trend is likely the result of ozone depletion, as it is known to have pressure effects in the Antarctic summer season (Thompson et al. 2000; Thompson and Solomon 2002; Arblaster and Meehl 2006). During the winter, the Antarctic ozone hole develops and when sunlight returns, much less radiation is absorbed in the stratosphere due to decreased ozone, effectively increasing the stratospheric midlatitude/polar temperature gradient. This increase in the stratospheric temperature gradient will therefore increase the westerlies to maintain thermal wind balance, and will eventually propagate downward to the troposphere by the summer season. Therefore, the increased westerlies around the continent will lower pressure across the continent and this can be seen in the negative pressure trends as shown previously. The gridded pressure products also show a negative pressure trend in the late 20th century, but this strong negative pressure trend is strongly amplified due to a large positive bias in the early 20CR and ERA-20C data (this is not seen in the reconstructions). Therefore, these gridded products are not good representations of early 20th century Antarctic pressure variability and trends.

In contrast, the other three seasons are dominated by interannual variability that is strongly tied to natural and internal climate variability. No long-term or persistent pressure trends are seen in the reconstructed record like what was seen in DJF. JJA and MAM both consist of decadal-scale variability, with prolonged periods of higher than average pressure across the continent followed by lower than average pressure
throughout the 20th century. The Antarctic Peninsula also often experiences slightly different pressure trends and variability than the rest of the continent outside the summer season. This is likely due to the known regional atmospheric pressure circulation, known as the Amundsen Sea Low, that influences the climate of the peninsula, while the rest of the continent is often influenced by large-scale, hemispheric-wide atmospheric circulation patterns.

There are implications on Antarctic (Southern Hemisphere) climate that need to be explained pertaining to this work. The greatest implication occurs in the summer season. Recently, Antarctica has essentially escaped the larger implications of global climate change. Studies have shown that temperatures (especially outside of the peninsula and West Antarctica) have been cooling across the continent, or at least have a minimal warming trend. This is opposite of much of the rest of the continent. These cooling trends across East Antarctica are likely a result of decreased ozone and increased westerlies, as previously explained. The increased westerlies (positive SAM) essentially lock in the cold air over the polar cap and doesn’t allow for heat transfer. However, a recent study by Soloman et al. (2016) suggests that a reversal is likely to be seen in coming decades due to ozone recovery. Therefore, if ozone recovery reverses the polarity of the SAM, these current trends of pressure and temperature across the continent are likely to reverse. Therefore, Antarctica is of great concern in the coming decades due to the possibility of great warming, where global climate change will align with Antarctic climate change, further enhancing the warming across the continent.
As a final summary, the three original research questions are directly answered here:

1) An Antarctic continent-wide seasonal spatial pressure reconstruction is not only possible, but also reliable. The summer and winter seasons are the most reliable, due to these seasons being the seasons of greatest correlation of pressure between the Fogt et al. (2016a) Antarctic stations and their midlatitude predictors. The original spatial reconstruction was the most reliable in DJF, while the pseudo spatial reconstruction drastically outperformed the original spatial pressure reconstruction in JJA. The two transition seasons were slightly less reliable than the skill seen in DJF and JJA, but generally the pseudo spatial pressure reconstructions outperformed the original spatial pressure reconstructions and meaningful results are still produced.

2) Only during DJF are atmospheric circulation changes unique over the last century. When examining the three distinct regions (East, West, and Antarctic Peninsula), the recent circulation changes over East and West Antarctica are unique and significant at $p<0.05$; not until very recently do changes in the Antarctic Peninsula become unique and significant. No unique circulation changes were seen in the reconstructed record in any other season.

3) The strong negative pressure trend in DJF is likely caused by an external forcing mechanism and is at least not primarily driven by natural or internal climate variability. This can be concluded for several reasons. First, this trend is unique over the last 100+ years, and the timing of the trend coincides with the onset of
the Antarctic ozone hole. Second, much research has been done on ozone depletion and its influence on Antarctic pressure. Ozone depletion will act to strengthen the circumpolar jet around the continent, effectively lowering pressure across Antarctica. In contrast, the early 20th century during DJF was characterized by interannual variability, driven by natural and internal climate variability. The other three seasons were characterized by strong interannual and decadal-scale variability, with the absence of a long-term and persistent pressure trend, as seen in DJF, indicative of an absent external forcing mechanism during these seasons. Therefore, the other three seasons are primarily driven by internal and natural climate variability.

This thesis has made a significant step forward in the understanding of 20th century Antarctic pressure variability and trends. Since the first research question was answered positively, the reconstructions allowed for new conclusions to be made regarding Antarctic pressure variability during the last century. Future work should begin to examine these 20th century spatial pressure trends and variability in more detail, especially climate model simulations aimed to place causes and sources of internal variability on Antarctic pressure during the full 20th century into perspective. Another interpolation method, RegEM, is another method that was used successfully to reconstruct temperature across the continent (Steig et al. 2009; O’Donnell et al. 2011). Using this method to reconstruct atmospheric pressure across the continent is beyond the scope of this thesis and is for future work. One region of the spatial pressure reconstructions that was slightly subpar was in the Amundsen Sea region, where future
work should include a new spatial pressure reconstruction that can improve the reliability in this region; RegEM may especially be beneficial to use in this region. As more reconstructed pressure datasets become available, it is hoped that they align well with the results presented here and further conclusions can be made about the 20th century pressure trends and variability across the Antarctic continent at even finer spatial and temporal scales.
REFERENCES


