Sixty Years of Widespread Warming in the Southern Middle and High Latitudes (1957–2016)

MEGAN E. JONES, a, b, e DAVID H. BROMWICH, a, b, JULIEN P. NICOLAS, a, f JORGE CARRASCO, c
EVA PLAVCOVÁ, d XUN ZOU, a, b AND SHENG-HUNG WANG a

a Polar Meteorology Group, Byrd Polar and Climate Research Center, The Ohio State University, Columbus, Ohio
b Atmospheric Sciences Program, Department of Geography, The Ohio State University, Columbus, Ohio
c Centro de Investigación GAIA Antártica, Universidad de Magallanes, Punta Arenas, Chile
d Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

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ABSTRACT

Temperature trends across Antarctica over the last few decades reveal strong and statistically significant warming in West Antarctica and the Antarctic Peninsula (AP) contrasting with no significant change overall in East Antarctica. However, recent studies have documented cooling in the AP since the late 1990s. This study aims to place temperature changes in the AP and West Antarctica into a larger spatial and temporal perspective by analyzing monthly station-based surface temperature observations since 1957 across the extratropical Southern Hemisphere, along with sea surface temperature (SST) data and mean sea level pressure reanalysis data. The results confirm statistically significant cooling in station observations and SST trends throughout the AP region since 1999. However, the full 60-yr period shows statistically significant, widespread warming across most of the Southern Hemisphere middle and high latitudes. Positive SST trends broadly reflect these warming trends, especially in the midlatitudes. After confirming the importance of the southern annular mode (SAM) on southern high-latitude climate variability, the influence is removed from the station temperature records, revealing statistically significant background warming across all of the extratropical Southern Hemisphere. Antarctic temperature trends in a suite of climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) are then investigated. Consistent with previous work the CMIP5 models warm Antarctica at the background temperature rate that is 2 times faster than that observed. However, removing the SAM influence from both CMIP5 and observed temperatures results in Antarctic trends that differ only modestly, perhaps due to natural multidecadal variability remaining in the observations.

1. Introduction

The polar regions are a main area of focus in the global climate change dialogue, as temperature increases are amplified at higher latitudes (Holland and Bitz 2003; Serreze et al. 2009). However, while the Arctic has persistent warming over the entire region (Steele et al. 2008), temperature trends in Antarctica are more heterogeneous. The continent of Antarctica is typically split into the Antarctic Peninsula, West Antarctica, and East Antarctica, with East and West Antarctica divided by the Transantarctic Mountains. Previous studies have shown that surface temperature is not changing consistently, either spatially across the continent or throughout the annual cycle (e.g., Turner et al. 2005; Monaghan et al. 2008a;
Steig et al. 2009; O’Donnell et al. 2011; Nicolas and Bromwich 2014; Jones et al. 2016). The Antarctic Peninsula and West Antarctica have seen the strongest warming from 1958 to 2012 (Bromwich et al. 2013, 2014; Carrasco 2013; Schneider et al. 2012a) with temperatures in East Antarctica showing no significant long-term trends or even areas of weak cooling during the same time period (Lazzara et al. 2012; Marshall et al. 2013; Smith and Polvani 2017).

One feature of Antarctic temperature changes recently investigated is surface cooling in the Antarctic Peninsula for approximately the past 15 years (Carrasco 2013; Turner et al. 2016; Oliva et al. 2017), which was one motivation for this study. Carrasco (2013) analyzed surface temperature observations from the Peninsula (hereafter, when Peninsula appears alone capitalized, it refers to the Antarctic Peninsula) and South American stations and found a slight cooling at the northern tip of the Peninsula during the first decade of the twenty-first century. Then, Turner et al. (2016) examined annual surface temperature at six stations on the Antarctic Peninsula since 1979, finding an inflection point in 1998 that coincided with the start of the “global warming hiatus” (Trenberth and Fasullo 2013), and determined that the Peninsula cooling was consistent with natural variability influenced by the tropics. Oliva et al. (2017) furthered the Turner et al. (2016) study by adding four more Peninsula stations, discovering cooling trends at 7 of the 10 stations during 2005–15, with the other three warming. However, all 10 stations have a warming trend from the start of their record until 2005, and all but one has a warming trend for the entire time period.

Many factors influence the climate of Antarctica and the southern midlatitudes. A significant mode of climate variability is the southern annular mode (SAM), characterized by opposing pressure and temperature anomalies over the middle and high southern latitudes, respectively (e.g., Marshall 2007). A positive (negative) SAM phase is associated with an increased (weaker) pressure gradient between the polar cap and mid-latitudes and a stronger (weaker) band of westerly winds around 60°S, leading to cooler (warmer) temperatures over the continent and warmer (cooler) temperatures on the Peninsula (e.g., Marshall et al. 2006; Marshall and Thompson 2016). Furthermore, the westerly winds shift poleward (equatorward) during a positive (negative) phase (Limposuvan and Hartmann 2000). Multiple studies have shown that the SAM has the greatest influence on the interannual variability of Antarctic surface air temperature (e.g., Thompson and Solomon 2002; Marshall 2007; Hosking et al. 2013; Marshall and Thompson 2016). In other areas across the Southern Hemisphere, a positive SAM phase is associated with cooling over Australia and warming over Argentina, Tasmania, and southern New Zealand (Gillett et al. 2006). Further, differences exist in the impact of the SAM between seasons; Marshall et al. (2006) found that the SAM contributes most to warming temperatures on the Peninsula in austral summer, while Gillett et al. (2006) indicate the Antarctic mainland cooling and Peninsula warming are largest in austral winter. The SAM has been trending toward a positive phase in recent decades, with a statistically significant trend in austral summer and autumn; this positive trend has been attributed to a combination of stratospheric ozone depletion, increasing greenhouse gas concentrations, and natural variability (e.g., Arblaster and Meehl 2006; Fogt et al. 2009; Thompson et al. 2011; Dätwyler et al. 2017). Medley and Thomas (2019) reconstructed snow accumulation trends over Antarctica by spatially extrapolating ice-core records of accumulation using the spatial variance of precipitation minus evaporation (P − E) fields from global reanalyses. After removing spatially varying but overall negative accumulation impact congruent with the observed positive SAM trend since 1957, they found the residual increasing accumulation could be attributed to temperature changes similar to those observed (e.g., Nicolas and Bromwich 2014).

Other climate modes besides the SAM are known to influence temperature variability in the southern high latitudes. El Niño–Southern Oscillation (ENSO) is a large-scale climate phenomenon linked to sea surface temperatures across the central and east-central equatorial Pacific. The SAM and ENSO are related, and their impacts can sometimes be difficult to separate (Clem and Fogt 2013; Welhouse et al. 2016). The Antarctic climate impacts of these modes are amplified when La Niña occurs with a positive SAM phase and El Niño with a negative SAM phase (Fogt et al. 2011). Additional ENSO connections exist between Antarctica and other regions of the Pacific, such as the central tropical Pacific as discussed in Ding et al. (2011) and Ding and Steig (2013). The two Pacific–South American patterns (PSA1 and PSA2), also related to ENSO, are known to influence temperatures across the Antarctic continent (Mo and Higgins 1998; Marshall and Thompson 2016). During austral spring, significant relationships exist between the West Antarctic/Antarctic Peninsula region and PSA1, whereas East Antarctica is most influenced by ENSO events during austral summer (Schneider et al. 2012b).

In addition to large-scale climate modes, more regional climate features can also impact temperatures across Antarctica and the southern midlatitudes. The Amundsen Sea low (ASL) is a permanent climatological low pressure that strongly influences the climate of West
Antarctica and the Antarctic Peninsula (Baines and Fraedrich 1989; Kreutz et al. 2000). This climatological feature changes not only on its own but in conjunction with the other teleconnections included in this study. The ASL typically shifts south and to the west in the winter, compared to north and to the east in the summer, directly influencing different regions of Antarctica based on the season (Hosking et al. 2013). The ASL has deepened over recent years, increasing the strength of the clockwise flow and advecting more northerly winds across the Peninsula and West Antarctica, causing an increase in temperatures (Turner et al. 2013b; Raphael et al. 2016). This climate feature is also directly related to the SAM phase, as the ASL has negative MSLP anomalies when the SAM phase is positive. Factors influencing the ASL depth include the positive SAM trend in recent years, ENSO (as the ASL is deeper in La Niña compared to El Niño), radiative forcing, tropical forcing, and internal variability (Raphael et al. 2016). The interdecadal Pacific oscillation (IPO) and Pacific decadal oscillation (PDO) both influence temperature patterns in the Antarctic region through tropical sea surface temperature variability (Folland et al. 1999; Newman et al. 2016). Warming sea surface temperatures in the Atlantic Ocean, related to the Atlantic multidecadal oscillation, have been linked to surface pressure around the Amundsen Sea in all seasons but austral summer (Li et al. 2015). Further, the ASL has a minimum in winter, but has deepened the most in the spring and fall seasons (Raphael et al. 2016).

Oceanic factors such as changes in sea ice cover and ocean currents can also influence the climate of Antarctica and the entire Southern Hemisphere. For example, the South Pacific Gyre is a large anticyclonic circulation that acts to transfer heat from the equator to the southern high latitudes; the circulation increased from 1993 to 2014, during which ocean warming was maximized in the top 2000 m at 40°S across all three Southern Hemisphere oceans (Roemmich et al. 2015, 2016). This increasing circulation is supplying warmer ocean waters, correlating with positive air temperature anomalies on the western branch of the circulation around New Zealand. In comparison, the eastern branch is bringing more cold water to the north, leading to negative temperature anomalies along the western coast of South America (Falvey and Garreaud 2009). The strengthening of this gyre circulation can have an influence on coastal stations due to changes in sea surface temperatures caused by the intensification of ocean upwelling off the coast of Chile (Burger et al. 2018).

The present study’s main goal is to expand upon and complement the study by Richard et al. (2013), which reviewed long-term temperature changes in the Southern Hemisphere middle and high latitudes by analyzing records from stations both on and off the Antarctic continent. Their data ended in 2002, therefore an additional 14 years of observations have been added here. Our study also aims to place temperature changes in Antarctica into an almost entire hemisphere-wide perspective. Richard et al. (2013) provides a general overview of the Southern Hemisphere middle and high latitudes for 1958-2002, determining that the largest warming is around the Peninsula, with weaker warming in the midlatitudes and no significant warming recorded in East Antarctica. A distinguishing aspect of this study is that we chose to use updated observational records as our primary source, instead of basing our work on reanalyses or reconstructed gridded data like other studies (e.g., Smith and Polvani 2017). Multiple problems exist when using a reanalysis for the southern high latitudes. One is that the accuracy and temporal consistency of any reanalysis will be affected by the scarcity of data, especially before 1979, which was the start of the modern satellite era (Bromwich and Fogg 2004). This can lead to unreliable trends in the high-latitude Southern Hemisphere before 1979 (Bromwich and Fogg 2004; Bromwich et al. 2007, 2011). Reanalyses also do not have the resolution to accurately portray sharp topography changes, which can be important for regions like the Antarctic Peninsula and the Transantarctic Mountains (Murphy et al. 2004; Nicolas and Bromwich 2014). These problems lead us to focus primarily on observational data and use a reanalysis dataset to investigate pressure trends since 1979 to identify drivers behind the recent temperature trends seen in the observations.

The paper is organized as follows. Section 2 outlines the data and methods used in this study. The station temperature trends are reviewed by themselves and in combination with SST trends (section 3). Section 4 investigates influences of other climate features, including MSLP trends, the SAM, and other large-scale climate modes. Section 5 details the congruence analysis that removes the influence of the SAM from observed temperature and reveals a more homogeneous background warming. Then the ability of climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) to reproduce the observed Antarctic temperature changes is evaluated in section 6. Conclusions and future implications are outlined in section 7.

2. Data and methods

a. Station temperature data

Monthly mean 2-m air temperature records were collected from stations in Antarctica as well as from locations around the Southern Hemisphere, including
South America, South Africa, New Zealand, Australia, and a variety of midlatitude island stations (Fig. 1, Table 1). Stations were selected based on the length of record and the geographical location. Across Antarctica, every station with a record of at least 30 years was used with the exception of McMurdo; Scott Base was used instead because of greater data reliability. Many midlatitude areas had a large number of stations; therefore, we chose a few stations from each region with the longest and most complete records (e.g., in South America and Australia). However, spatial density is inconsistent, as some regions have spatially dense observations (Antarctic Peninsula, South America), while others have few data available (Antarctic interior, southern Pacific Ocean).

Table 2 outlines the specific data sources for each station included in this study, with a large majority of the Antarctic station records from the online Reference Antarctic Data for Environmental Research (READER) archive (Turner et al. 2004). The recent Australian Climate Observation Reference Network–Surface Air Temperature (ACORN-SAT; Trewin 2013) dataset was utilized for Australian-controlled stations and was preferred over the READER archive for its Antarctic stations due to the extent of quality control performed. Monthly temperatures from ACORN-SAT were calculated from the average of the maximum and minimum daily temperatures, compared to other datasets using 3- or 6-hourly observations. Although using only the daily minimum and maximum can cause a slight temperature bias (Bernhardt et al. 2018), we do not believe it will cause a significant difference overall in temperature trends. For Casey, although in the ACORN-SAT dataset, we used the data from READER, as it has a much longer record and the overlapping trends are very similar. We included three stations from the Navy Weather Service of Chile; these records, digitized here for the first time, are available as text files through the PANGAEA Data Publisher (https://www.pangaea.de/). These new stations are especially important when
investigating Peninsula cooling to determine how far north it extended.

Basic quality control was performed visually by using individual monthly time series to remove any extreme outliers (e.g., any value 10°–15°C outside any monthly value). If available, the Global Historical Climatology Network (GHCN) database was also utilized to confirm these anomalous values by being marked missing, as well as to assist in filling any significant gaps in the data that were available in GHCN and not in the data already acquired. GHCN was not used for all stations because many stations had more missing data compared to the original sources. Annual and seasonal means of the monthly temperature observations were calculated at each station if at least 80% of data values were present.

b. Additional datasets

Monthly mean sea surface temperatures, available for 1957–2016, are from the HadISST1 dataset (Rayner et al. 2003). The HadISST1 dataset uses reduced space optimal interpolation (RSOI), an empirical orthogonal function (EOF)-based technique, to reconstruct broad-scale fields of SST. This reconstruction is then blended with quality-improved in situ SST to recapture local variance. The limitations of the interpolation technique lower confidence in data-sparse regions, like areas directly off the coast of Antarctica for the full period of 1957–2016 (Rayner et al. 2003). The SST seasonal observational counts by Fan et al. (2014) in HadSST3 suggests that HadISST1 analyses for all seasons apart from December–February are questionable poleward of 50°S for 1957–2016 because of sparse observations. Monthly mean sea level pressure (MSLP) and 500-hPa geopotential height data were obtained from the ERA-Interim reanalysis beginning in 1979 (Dee et al. 2011); therefore, these parameters will not be included in comparison with the 1957–2016 temperature trends. In addition, the SAM (Marshall 2003), Southern Oscillation index (SOI; NCDC), and Pacific decadal oscillation (PDO; NCDC) indices are used for analysis of the relationship of these three climate factors with temperature variability.

c. Linear trends, confidence intervals, and analysis methodology

Trends were calculated for all stations, seasons, and years for time periods of various lengths. The time periods used (1957–2016, 1979–2016, 1979–97, and 1999–2016) were chosen for a few reasons; as much data as possible needed to be included while balancing the reality of how much Antarctic station data is actually available, using time periods of various lengths and start dates. Many stations on the continent started in or around 1957; therefore, it was adopted as a suitable starting point for the long period, providing 60 years of observations. The year 1979 is the start of the modern satellite era, which is also when most reanalyses begin, so we made the second time period 1979–2016, to have a comparison against reanalysis data. As mentioned earlier, Turner et al. (2016) compared the 1979–97 and 1999–2014 time periods, citing an inflection point in 1998. We decided to replicate this methodology, adding in the two extra years of data now available, making the last two time periods 1979–97 and 1999–2016.

Least squares linear trends were calculated for station temperatures, sea surface temperatures, mean sea level pressure, and 500-hPa geopotential heights. Statistical significance was determined using a two-tailed Student’s t test, with the confidence intervals set at 0.90, 0.95, and 0.99; the degrees of freedom are adjusted for autocorrelation as in Santer et al. (2000). If a trend is referred to as statistically significant, it is significant at 95% unless otherwise noted. Correlations were calculated between detrended seasonal temperature time series and seasonal time series of the SAM, SOI, and PDO indices for the four time periods. We chose to use detrended time series to assume that no link exists between linear temperature trends and trends of the three indices, as discussed in Marshall (2007). In the same way, linear regression coefficients were created for temperature/SAM index and temperature/SOI to better analyze the magnitude of temperature changes linked to these climate modes.

d. EOF analysis

To obtain a concise view of spatiotemporal temperature changes across our array of stations, we performed an empirical orthogonal function (EOF) analysis to extract the main modes of temperature variability. One issue that can negatively affect the results of the EOF analysis is the uneven distribution of the stations across our domain (Karl et al. 1982). To address this issue, we used gridded reanalysis temperature data to extract the EOF spatial patterns using the following three-step method:

1) The first three EOF spatial patterns (eigenvalues) were computed by performing a rotated-varimax EOF analysis on ERA-Interim seasonal and annual 2-m temperature anomalies spanning 1979–2016. The gridded temperature anomalies were weighted by the cosine of latitude and the correlation matrix was used in the EOF algorithm. Eigenvectors were rotated as they are less vulnerable to sampling error compared to unrotated eigenvectors, and because patterns become more separated, which makes for more straightforward analysis (Richman 1986).

2) The values of the gridded spatial patterns obtained in step 1 were interpolated to the stations’ locations.

3) The EOF time series associated with each pattern interpolated in step 2 were derived by calculating the
Table 1. All stations used in this study, sorted alphabetically by region. Numbers in the first column correspond to locations in Fig. 1. Also listed are start year, latitude and longitude, elevation in meters, and percent complete by month through 2016.

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<th>Number</th>
<th>Station name</th>
<th>Start year</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Elevation (m)</th>
<th>Percent complete (through 2016)</th>
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</table>
dot product of the 1957–2016 station temperature time series and the interpolated EOF patterns.

One limitation of this approach is that the period used to extract the spatial patterns (1979–2016) is shorter than the one used to compute the EOF time series (1957–2016). The underlying assumption is that the first three patterns are identical during the two periods. While this may not be totally true, this assumption is supported by the fact that the first two patterns can be linked to leading modes of atmospheric circulation variability (SAM and ENSO), as shown in section 4 of this paper.

e. Congruence analysis

A congruence analysis was performed to determine the SAM contribution to the temperature trends
This is done by first detrending the time series, linearly regressing the detrended temperature time series onto the detrended SAM index, and then multiplying the regression coefficients at each station by the SAM trend to determine the portion of the temperature trend caused by the SAM. This SAM-congruent trend at each station is then removed from the original temperature trend to reveal temperature trends linearly independent of the SAM; this analysis approach was previously employed by Gillett et al. (2008). We call these linearly independent trends the background temperature trends, to describe the trends caused by factors other than the SAM, as the SAM has the most influence over temperature variability. An important assumption made when using SAM-congruent trends is that SAM-temperature relationships are the same when comparing interannual and multidecadal time scales.

3. Temperature trends

a. Station-based observational temperature trends

The 2-m air temperature station observation trends are plotted on spatial maps, along with contoured sea surface temperature trends from the HadISST1 dataset, and will be discussed by period, beginning with 1957–2016 and continuing with 1979–2016 and 1999–2016; 1979–97 is included in the online supplemental information. The focus area is West Antarctica and Antarctic Peninsula, as the goal of this study is to put those two areas into a larger spatial perspective. All seasons and the annual period are included. Values and confidence intervals for all seasons and time periods are in Tables S1–S4 in the online supplemental material.

Figure 2 shows the 1957–2016 annual and seasonal 2-m temperature station trends, where a number of

![1957-2016 Temperature Trends](image-url)
stations are eliminated due to length of record. The 2-m temperature trends are overwhelmingly warming throughout all seasons—not just in the Peninsula and West Antarctica, but for the majority of the extratropical Southern Hemisphere stations included in this study. Stations with statistically significant warming annual trends in the focus area include Byrd (0.29 ± 0.19°C decade⁻¹), Esperanza (0.29° ± 0.16°C decade⁻¹), Faraday (0.49° ± 0.28°C decade⁻¹), and Orcadas (0.22° ± 0.12°C decade⁻¹). The above conclusions also apply to the seasonal temperature trends, but the consistent warming in the 1957–2016 period is most robust in annual trends, with warming damped in East Antarctica (Fig. 2e).

The 1979–2016 trends (Fig. 3) reveal more cooling than the 60-yr period, mostly confined to East Antarctica, which is known from previous literature (e.g., Turner et al. 2005; Nicolas and Bromwich 2014). Austral summer has a few stations in the Peninsula vicinity that are significantly cooling (Fig. 3a): Bellingshausen (−0.20° ± 0.19°C decade⁻¹), Larsen Ice Shelf (−1.05° ± 0.33°C decade⁻¹), and Ushuaia (−0.40° ± 0.22°C decade⁻¹). Byrd is warming in every season but austral fall, although none of those trends are statistically significant (Fig. 3c). East Antarctica has many stations cooling throughout the year, except for austral spring (Fig. 3g), where many stations are warming at a statistical significance of 95%.

In the 1999–2016 trends, strong and statistically significant cooling on the Peninsula is most evident in austral summer (Fig. 4a); there are statistically significant trends at the Peninsula stations of Bellingshausen (−0.76° ± 0.54°C decade⁻¹), Larsen Ice Shelf (−1.38° ± 0.78°C decade⁻¹), and Rothera (−0.57° ± 0.51°C decade⁻¹). This cooling extends north of the peninsula to the southernmost South American stations (−0.64° ± 0.87°C decade⁻¹ at Diego Ramirez and −0.78° ± 1.27°C decade⁻¹ at
Ushuaia), as well as the Falkland Islands (−0.46° ± 0.96°C decade⁻¹) and South Georgia (−0.84° ± 0.64°C decade⁻¹), although South Georgia is the only station with a statistically significant trend. Cooling is also shown at Byrd, the station representing all of West Antarctica, with a small trend of −0.11° ± 1.05°C decade⁻¹ that is not statistically significant. This cooling is evident throughout the other seasons, although not as strong, and with cooler SSTs. The other notable trend is widespread warming throughout East Antarctica most prominent in DJF and SON (Figs. 4a,g), in contrast with typical cooling seen in this region.
An inflection point in 1998 has been found by Turner et al. (2016) due to the shift in temperature trends, as well as some of the pressure patterns (e.g., DJF 1999–2016 MSLP; see Fig. 4b). Recent analysis by Gonzalez and Fortuny (2018) reveals that the long-term warming on the Peninsula is quite robust and indicative of extreme local variability, compared to trends in periods less than 30 years, indicating that the recent strong cooling in the Peninsula region cannot currently be considered as evidence for a shift in the overall warming trend, and is instead attributed to natural variability. Considering the full period of station temperature observations (1957–2016; Fig. 2), the statistically significant, widespread warming is prominent in the mid-latitudes, and even at some Antarctic continental stations in the yearly trends (Fig. 2e), giving high confidence that these warming trends are not caused by natural variability. There is much concurrence in this study that overall, the majority of East Antarctica and the Antarctic interior are not significantly warming with some regions possibly cooling; these regional temperature trends agree with previous research on this topic. Station air temperatures agree with SST trends from HadISST1; ocean surface temperatures have a significant influence on many of the observational trends, due to the majority of the data coming from coastal or island stations. Although widespread warming exists in all seasons during 1957–2016, a shortage of observations occurs past 50°S in HadISST1 during the early part of this period (except for austral summer, Fig. 2a), lowering confidence in the dataset for the earliest years. In the 1979–2016 period (Fig. 3), cooling appears directly around the Antarctic continent, with warming in the midlatitudes; significant warming is largest in the western South Pacific Ocean, possibly due to the South Pacific gyre strengthening since 1993 (Roemmich et al. 2016). The two shorter time periods, 1979–97 (Fig. S1) and 1999–2016 (Fig. 4), show much stronger trends. The period 1979–97 emphasizes the SST pattern associated with the South Pacific gyre, along with warming along the eastern coast of South America and off the southern tip of South Africa, with these trends largest in the austral summer. In comparison, the warming is slightly muted in
1999–2016, with the strongest warming now in the southern Indian Ocean, and present in every season but austral summer. Most noteworthy is the pronounced ocean cooling in the Peninsula region in DJF (Fig. 4a); it correlates well with the negative air temperature trends seen in the station observations.

4. Influence of various climate features

a. Circulation patterns

Seasonal and annual MSLP trends from ERA-Interim are shown with the same station temperature trends as in section 3, to determine common circulation patterns and
their influence on temperatures; two consistent patterns anticipated were the SAM and the Amundsen Sea low, with the SAM normally appearing in the summer season and the ASL present the rest of the year (Arblaster and Meehl 2006; Raphael et al. 2016), albeit in slightly different locations. Trends for 1957–2016 were not calculated as ERA-Interim begins in 1979.

In 1979–2016, the SAM pattern is evident only in DJF (Fig. 3b), with negative MSLP contours directly around Antarctica that transition to positive contours at lower latitudes; this is also seen in austral summer for 1979–97 (Fig. S1b). A strengthening ASL is clear in MAM (Fig. 3d), with negative contours centered off the coast of West Antarctica; this signal is not as prominent in other seasons. MSLP trends in 1999–2016 are quite different, with an uncommonly strong dipole set up on either side of the Peninsula in DJF (Fig. 4b). A positive anomaly on the west side of the Peninsula (Bellingshausen Sea) and a negative anomaly on the east side (Weddell Sea) drive winds from the south through the Peninsula, which is a significant difference from any other time period and season that explains why there has been such strong cooling in this region. Turner et al. (2016) determined the deepening in the Weddell Sea to be caused by a strengthening midlatitude jet. Other seasons in this time period show a deepening ASL, comparable to trends in 1979–2016.

For West Antarctica and the Antarctic Peninsula, the smaller-scale climate feature that is most significant is the Amundsen Sea low, as discussed in the introduction. It appears in many time periods and seasons in the ERA-Interim surface pressure, and due to its proximity to West Antarctica and the Peninsula, it has an important impact on wind patterns and temperature changes. During the summer, the ASL is directly west of the Peninsula; where it will have the most influence, and moves to the west and south during the winter, where it will have a stronger effect on the climate of West Antarctica; in austral fall, Peninsula warming via the ASL is caused by tropical forcing, as discussed in Ding and Steig (2013). This is seen in MAM of 1979–2016 (Fig. 3d), with statistically significant negative anomalies off the coast of West Antarctica and warming across most of the Peninsula. It is also seen in 1979–97 (Fig. S1d), with
warming on the Peninsula in MAM, although this could also be caused by the SAM.

b. The southern annular mode

After analyzing direct observational trends, correlations were calculated between the time series of the temperature data and of the time series for the SAM, SOI, and PDO indices. Correlations between the PDO index and the temperature trends were spatially variable throughout the seasons and time periods, and thus the PDO was not investigated further in this paper. In contrast, correlations between the SAM and the temperature time series are the most consistent and intuitive with prior knowledge of the SAM, as a positive SAM phase is associated with lower pressure and cooler temperatures across continental Antarctica, with opposing characteristics on the Peninsula. Negative correlations exist across the eastern coastal area and interior of Antarctica, as well as in southern Australia (Fig. 5). Positive but weaker correlations exist on the Antarctic Peninsula and continue into South America, stretching across the midlatitudes with the various island stations included in this study. The correlations have slight variations but are overall consistent throughout the seasons and time periods, with statistical significance increasing as the time period increases in length.

![Image of 1957-2016 Surface Temperature and SAM Index Correlation]

Fig. 5. The 1957–2016 seasonal and annual correlations between SAM index and station-based surface temperature observations (circles) with statistical significance outlined at 90% (outline), 95% (one ring), and 99% (two rings). The top inset maps are for southern South America and the bottom for the Antarctic Peninsula.
Regression coefficients were calculated between the temperature trends and the SAM, to put the magnitude of the influence of this climate mode into a better perspective. Coefficients associated with the SAM index are most significant on Antarctica, with positive coefficients for the Peninsula stations and negative coefficients in continental Antarctica. Most stations in the midlatitudes have coefficients of the lowest magnitude (from $-0.15^\circ$ to $0.15^\circ$ decade$^{-1}$), indicating that even if these locations are strongly correlated with the SAM index, the magnitude of the change is small.
Table 3. Seasonal correlation coefficients between the EOF detrended time series and SAM and SOI detrended indices for the 1957–2016 period. Statistical significance at 95% indicated with an asterisk (*).

<table>
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<th>EOF2</th>
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<td>SON</td>
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</table>

An EOF analysis was conducted on the ERA-Interim temperature dataset with the data extracted at each station location for the time periods 1979–2016, 1979–97, and 1999–2016 (more details in data and methods) to further demonstrate the overwhelming influence of the SAM. Using the top three rotated EOFs, the spatial maps and time series of each EOF were both plotted, and the correlation and statistical significance was found between the EOF time series and time series of both the SAM and SOI indices.

Figure 6 shows the top three EOFs calculated for 1957–2016 for each season. The explained variance of each EOF varies through the seasons; MAM, JJA, and SON are dominated by EOF1 (18.93%, 24.14%, and 20.08%, respectively), while DJF has more similar variance for EOF1 and EOF2 (13.97% and 10.90%). The panels in Fig. 6 show the variety each EOF has; however, some patterns emerge, like a strong Peninsula signal in MAM EOF1. The spatial plots also show a frequent connection between the peninsula area and New Zealand and the surrounding islands, shown in EOF1 during MAM, JJA, and SON. This connection ends at the edge of Australia, which is connected more to the east coast and interior of Antarctica, as in EOF1 during JJA and SON. Table 3 shows the correlation magnitude and the statistical significance for the EOF analysis in Fig. 6 (1957–2016). The loadings (colors) of each station in the spatial plot are arbitrary; for example, DJF and SON in EOF1 has a negative correlation with the SAM, but if flipped to positive will then reverse the loadings of the station points, which will match up well with the pattern in MAM and JJA. Throughout the seasons and time periods for the observational EOF analysis, the SAM index is most frequently significantly correlated with all the EOFs (e.g., MAM and JJA for EOF1–EOF3).

Throughout the analysis, it has been consistently seen that the southern annular mode is the most influential climate mode for the Southern Hemisphere high latitudes. It appears in the summer ERA-Interim MSLP and 500-hPa geopotential height figures for 1979–97 (Fig. S1b) and 1979–2016 (Fig. 3b), with the dipole change discussed earlier visible in 1999–2016 (Fig. 4b). The SAM pattern is also shown in the 1979–2016 yearly panel for MSLP trends (Fig. 3j), indicating it is the dominant mode of variability throughout the year. In the EOF analysis, the SOI is significantly less correlated than the SAM, showing it is less influential on the temperature trends when considering multidecadal time periods and continent-wide spatial scales (see Fig. S2 for 1957–2016). Because of this and the lack of a significant long-term SOI trend, ENSO is not investigated further, as the goal of this paper is to focus on large spatial scale and extended temporal trends.

5. Widespread background warming

Because this study has confirmed the significance of the SAM on Antarctic temperature trends, a congruence analysis was performed to determine the exact magnitude of the overall station temperature trends caused by the SAM. Subtracting the SAM-congruent trend from the original trend reveals background temperature trends, caused by forcings other than the SAM (e.g., ENSO, anthropogenic climate change). Figure 7 shows the original temperature trends, the SAM-congruent trends, and the background temperature trends for DJF, MAM, and the annual period for 1957–2016; all other time periods (1979–2016, 1979–97, and 1999–2016) and seasons do not have statistically significant trends in the SAM, and so they are not included.

The SAM-congruent trends (middle column of Fig. 7) are reflective of the SAM increase, with statistically significant negative temperature trends over continental Antarctica and positive trends throughout the Peninsula region. Once these trends at each station are removed from the original temperature trends (left column), the background temperatures (right column) show prominent warming at the large majority of stations included in this study. Many of these warming trends are statistically significant as well, especially in the Eastern Hemisphere midlatitudes. This correlates well with temperature trends seen around the rest of the planet.

This portion of the analysis is vital in summarizing the effects of the SAM and the future of the Southern Hemisphere high-latitude climate. Removing the SAM-congruent trend from the overall temperature trends reveals that without the influence of the SAM, temperatures at almost every station across the extratropical Southern Hemisphere are warming with a high level of statistical significance, especially in the annual trends for 1957–2016. A few exceptions to the warming in the annual long-term trends should be addressed. One station with a cooling trend (although not statistically significant) is Halley, located to the east of the Weddell Sea. It
is the only station on Antarctica that is cooling; the reliability of the temperature trends is suspect due primarily to the number of times the physical location of Halley has changed coupled with the spatial gradients in air temperature on the Brunt Ice Shelf. Initial efforts by British Antarctic Survey to homogenize the Halley temperature time series show warming but the magnitude and statistical significance are yet to be determined (J. Turner and S. Colwell 2019, personal communications); as a result, the temperature data included in this paper are the original observations from the READER archive. The warming at Halley could be damped by the reversal during the 1980s in the relationship between temperatures at Halley and the SAM phase, as discussed by Marshall et al. (2011). Also, stations along the west coast of South America are consistently cooling throughout the year during 1957–2016. This is likely due to the South Pacific gyre, which is associated with cooling sea surface temperatures in this region (Roemmich et al. 2016), influencing the climate of these coastal stations.

**FIG. 7.** The 1957–2016 plots of (left) temperature trends, (center) SAM-congruent trends, and (right) the residual of the SAM-congruent trends for (top) DJF, (middle) MAM, and (bottom) annual data. Trends are in °C decade⁻¹.
6. CMIP5 simulations of Antarctic temperature change

The previous section demonstrated that the Antarctic cooling associated with the positive SAM trend offsets the underlying (background) warming, resulting in muted observed surface temperature change in East Antarctica over the last 60 years while hardly modifying the observed warming over West Antarctica. One question that naturally follows is what relevance does this finding have for projections of future Antarctic climate change as a result of anthropogenic greenhouse gas emissions? One way to consider this issue is to examine whether the climate models used for
the CMIP5 (Taylor et al. 2012) are able to capture past Antarctic temperature behavior and its modulation by the SAM, as a guide to their reliability in projecting future change.

Smith and Polvani (2017) undertook a detailed analysis of the spatial structure of recent Antarctic surface temperature trends as resolved by observation-based reconstructions and CMIP5 simulations, emphasizing the 1979–2005 period and the offsetting observed behavior in March–May compared to September–November. They showed that the CMIP5 models produced an overall uniform annual Antarctic warming, in sharp contrast with the warming over West Antarctica and near-zero change in East Antarctica seen in the reconstructions (e.g., Nicolas and Bromwich 2014). They further argued that this contrast is evidence of the primary role of multidecadal natural variability in recent Antarctic temperature trends.

The CMIP5 model simulations of Antarctic temperature change along with the modulation by the SAM are reconsidered here in a more limited fashion with an emphasis on the period of 1957–2005 (2005 is chosen here as it is the end of the CMIP5 historical experiment). Table S5 lists the 22 evaluated CMIP5 models that have three or more ensemble members with all forcings for the “historical period” of roughly 1850–2005. Three ensemble members were averaged for each model to treat all models in the same manner. For models with more than three members, the three members used for our analysis were randomly selected.

The average of the 22 individual CMIP5 ensemble-mean simulations (multimodel mean or MMM) is used to examine the forced change in Antarctic near-surface temperature (2-m air temperature) in relation to the observation-based reconstruction of Nicolas and Bromwich (2014). Results are spatially averaged for Antarctica because of the highly smoothed character of the MMM temperature field. Figure 8 shows Antarctic temperature anomalies with respect to the 1960–80 mean computed from the MMM (black line) and from the reconstruction (red line). The dashed lines in both black and red correspond to the MMM and the reconstruction respectively but with the influence of the SAM removed through linear congruence analysis. The gray shading around the MMM displays the spread of the ensemble means (±1 standard deviation that incorporates 14 of the 22 model results). Consistent with the findings of Smith and Polvani (2017), the MMM warms twice as fast as observed (Fig. 8e, solid black compared to solid red; see also Table 4). In particular, the MMM does not capture the cooling in DJF and MAM that started in the 1980s (Figs. 8a,b). These are two seasons during which the SAM has notably strengthened. In JJA and SON, during which the observed SAM has little or no trend, the modeled and observed temperature changes are statistically indistinguishable (Figs. 8c,d, Table 4). It is noteworthy that a stronger MMM warming than observed was also found by Monaghan et al. (2008b) and Klein et al. (2018) for a limited selection of CMIP3 and CMIP5 models, respectively, compared to Antarctic-wide temperature reconstructions; this contrasts with the station-based comparison of Gillett et al. (2008) with a selection of CMIP3 models that found agreement.

Can it be determined from the present analysis whether the observed and modeled Antarctic temperature trends for 1960–2005 disagree once the influence of the SAM is removed? The MMM does not contain multidecadal variability because of all the averaging used in its construction but does contain any forced change to the SAM, such as from stratospheric ozone depletion. Smith and Polvani (2017) emphasized the role of multidecadal variability in observed Antarctic temperature trends. Also, Zhang et al. (2019) argued from model simulations that Southern Ocean convection variability could be responsible for the observed oceanic cooling, and for sea ice expansion since the start of the modern satellite era in 1979 (Fig. 3i). The observational results of Fan et al. (2014) imply that modeled
Antarctic temperatures would show little change or even cooling over the same period. By contrast the CMIP5 simulations produced oceanic warming, sea ice retreat, and continental warming (Turner et al. 2013a; Zunz et al. 2013; Mahlstein et al. 2013; Smith and Polvani 2017; Zhang et al. 2019). Figure 8 and Table 4 confirm that the SAM cools Antarctica (dashed black compared to solid black) in the CMIP5 models (Marshall and Bracegirdle 2015; Smith and Polvani 2017). Figure 9 and Table 4 demonstrate that the MMM without SAM (dashed black) differs significantly from the reconstruction with SAM removed (dashed red) in DJF as well as annually; the annual result is strongly influenced by the anomalous observed temperature

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**Figure 9.** As in Fig. 8. The solid red line is the Nicolas and Bromwich (2014) reconstruction for Antarctica for 1960–2005. The dashed lines represent the temperature reconstruction trend line and the CMIP5 trend line with the SAM influence removed through linear congruence analysis (red dashed and black dashed, respectively). Here the gray shading represents the CMIP5 spread of the ensemble means with the SAM influence removed (±1 standard deviation after detrending).
behavior in MAM. Fogt et al. (2009) compared CMIP3 simulations of SAM behavior with the observed SAM and concluded that multidecadal variability in the observations explained the marked difference in MAM. It is possible that important multidecadal variability remains in the observed background temperature trends in Fig. 9 whereas the MMM trends without SAM do not include this variability. It cannot be concluded definitively that, without the SAM influence, the observed long-term Antarctic temperature trends differ from those simulated by the CMIP5 MMM. With all multidecadal variability and the impact of SAM trends removed, the residual observed long-term Antarctic warming likely reflects the impact of greenhouse gas forcing.

7. Summary and conclusions

Our investigation of temperature observations from many different stations in the Southern Hemisphere shows that significant, widespread warming has occurred across much of the southern middle and high latitudes over the past 60 years. For shorter time periods, cooling can be evident regionally, as seen in the 1999–2016 DJF trends (Fig. 4a) and in the 1979–2016 MAM trends for East Antarctica (Fig. 3e). However, the short-term cooling is cancelled out by long-term warming (Fig. 2), with the strongest trends seen on the Antarctic Peninsula and in the midlatitudes. There is a strong asymmetric signal between, on the one hand, the Peninsula and West Antarctica, which have been warming in 1957–2016, and on the other hand East Antarctica, which exhibits more stable temperatures.

Our correlation and regression analyses between the temperature trends and various climate mode indices confirm that the southern annular mode has the strongest influence on Southern Hemisphere climate (in agreement with previous literature), with El Niño–Southern Oscillation playing an overall secondary role. A deepening of the Amundsen Sea low in recent years, associated in part with the SAM trending positive, has led to warmer temperatures over West Antarctica and the Peninsula. The EOF analysis also showed the significance of the SAM, with ENSO being a secondary influence. Correlations between the EOF time series and the SAM and SOI indices aid in proving their relative importance to Antarctic climate.

Congruence analysis showed that the SAM-congruent trends consistently produced cooling trends over continental Antarctica, compared to warming over the Peninsula and most of the midlatitudes. Removing this from the overall temperature trends at each station, a consistent background warming trend is seen over the past 60 years for annual temperature trends, with the exception of western South America and Halley. This background warming fits well into overall global warming patterns.

The CMIP5 simulations consistently overestimate Antarctic temperature trends, producing values that are nearly identical to the background trends obtained through our congruence analysis rather than the observed trends (Fig. 8). A more detailed study of models by Klein et al. (2018) shows that in the 1990s, there is a large difference between the trends in model means compared to the trends in observations, specifically in East Antarctica. The CMIP5 models create a warming trend over East Antarctica, making temperature trends over the entire continent much more uniform compared to the asymmetric pattern seen in the observations. From the comparison of CMIP5 and observed temperature trends over 1960–2005 with SAM removed (Fig. 9, Table 4), there remains the possibility that the observations retain important multidecadal variability, primarily in MAM, that when removed would make two trend depictions more comparable.

A positive SAM trend is linked to increases in stratospheric ozone depletion and increases in greenhouse gas concentrations, as well as sea surface temperature forcing from the tropics (Thompson and Solomon 2002; Arblaster and Meehl 2006; Marshall 2007; Thompson et al. 2011; Fogt et al. 2017). As springtime stratospheric ozone depletion continues to diminish, the SAM could trend less positively (Polvani et al. 2011), leading to less cooling over East Antarctica and revealing the background warming seen in the congruence analysis in this study. By contrast, McLandress et al. (2011) and Arblaster et al. (2011) concluded that the SAM is predicted to retain its positive trend due to the increase in GHG concentrations, although ozone recovery is likely to partially negate this in austral summer. Part of the DJF SAM trend since 1957 is attributed to tropical sea surface temperature variability (Fogt et al. 2017), indicating that a portion of the SAM forcing is due to natural variability, combined with the anthropogenic forcing of ozone depletion and greenhouse gas concentrations. Fan et al. (2014) also inferred that natural variability could be influencing temperatures trends specifically in DJF, but the mechanisms were not investigated. That study also agrees with our results of warming in the Peninsula and West Antarctic region in the long-term period, as does Richard et al. (2013), although that study only included data through 2002. Because the future of the SAM trend is still uncertain but the importance of the SAM to Antarctic climate variability is well understood, it is essential that climate models correctly simulate the surface temperature trends and their modification by the
SAM, and further research is needed to determine whether this goal has been achieved.

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