RESEARCH ARTICLE

Antarctic temperature variability and change from station data

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Abstract

Variability and change in near-surface air temperature at 17 Antarctic stations is examined using data from the SCAR READER database. We consider the relationships between temperature, and atmospheric circulation, sea ice concentration and forcing by the tropical oceans. All 17 stations have their largest inter-annual temperature variability during the winter and the annual mean temperature anomalies are dominated by winter temperatures. The large inter-annual temperature variability on the western Antarctic Peninsula has decreased over the instrumental period as sea ice has declined. Variability in the phase of the SAM exerts the greatest control of temperatures, although tropical Pacific forcing has also played a large part, along with local atmospheric circulation variability at some locations. The relationship of positive (negative) SAM and high (low) Peninsula and low (high) East Antarctic temperatures was not present before the mid-1970s. Thirteen of the 17 stations have experienced a positive trend in their annual mean temperature over the full length of their record, with the largest being at Vernadsky (formerly Faraday) $(0.46° \pm 0.15°C \cdot dec^{-1})$ on the western side of the Antarctic Peninsula. The deepening of the Amundsen Sea low as a result of the more positive SAM and changes in the IPO and PDO have contributed to the warming of the Peninsula. Beyond the Antarctic Peninsula there has been little significant change in temperature. The two plateau stations had a small cooling from the late 1970s to the late 1990s consistent with the SAM becoming positive, but have subsequently warmed. During spring there has been an Antarctic-wide warming, with all but one station having experienced an increase in temperature, although the only trends that were significant were at Vostok, Scott base, Vernadsky and Amundsen-Scott. In this season, much of the Peninsula/West Antarctic warming can be attributed to tropical Pacific forcing through the IPO/PDO.

KEYWORDS

Antarctica, climate change, climate variability, temperature

1 | INTRODUCTION

Changes in near-surface air temperature are extremely important for many glaciological, oceanographic, chemical and biological processes over the Antarctic continent and surrounding ocean areas (Scambos *et al.*, 2000; Convey, 2003; Cook *et al.*, 2005; Meredith and King, 2005; Turner *et al.*, 2017). However, determining such changes presents a number of problems. There are very few in situ observations over the Southern Ocean and the estimation of surface temperature using satellite measurements is difficult because of the extensive cloud cover. Similarly, over the Antarctic continent there are problems in estimating surface temperature from infrared satellite imagery because of the comparable temperature and reflectivity of low cloud and the snow surface (Turner *et al.*, 2001). In the remote interior, many automatic weather stations (AWSs) have been installed since the 1980s (Lazzara *et al.*, 2012) and observations from these systems have proved extremely valuable (e.g., Costanza *et al.*, 2016). However, they are unattended for much of the year and instrumental issues and lack of data continuity make utilizing such data for investigations of variability and change problematic.

Meteorological observations from Antarctic staffed weather stations are therefore the most reliable and consistent data available to investigate Antarctic climate variability and change because of the extensive quality control that has been carried out and the near-continuous nature of the records, which in many cases start well before the satellite era. Because of the logistical difficulties of re-supplying the stations, most are located in the coastal region, with only two stations with long records located deep in the interior of the continent. The available temperature data have been used in many meteorological studies over the years. For example, Thompson and Solomon (2002) and Marshall (2007) used the station data to investigate the contribution of changes in the Southern Hemisphere annular mode (SAM), which is the primary mode of atmospheric circulation variability at high Southern latitudes, to Antarctic surface temperature trends. Moreover, the observations have been central in the efforts to estimate the temperature trends in the interior of the continent by using interpolation techniques (Steig *et al.*, 2009; Nicolas and Bromwich, 2014).

Over the last few decades, a number of studies have investigated the inter-annual variability and trends in the surface temperatures using station data. In an attempt to estimate whether Antarctic temperatures were changing, Raper *et al.* (1984) applied an areal weighting to the station annual mean temperatures and found that temperatures had increased by $0.29°C·dec^{-1}$ over 1957–1982, although this trend was dominated by a warming across the Antarctic Peninsula. Jacka and Budd (1991) investigated selected Antarctic temperature data spanning 1956 to the late 1980s and found a mean warming across all the Antarctic station data of $0.28°C·dec^{-1}$. Later, they updated their data base to 1996 and revised their estimate of the warming to $0.12°C·dec^{-1}$ (Jacka and Budd, 1998).

The monthly mean temperatures from the stations (the CLIMAT messages) are distributed over the WMO Global Telecommunications System (GTS) and were brought together by Jones (1995). He examined trends at 16 stations and found that over the period 1957–1994 the mean trend had been $0.57°C·dec^{-1}$ ($p < .05$).

Because of uncertainty over the quality of the various Antarctic temperature data sets, the Scientific Committee on Antarctic Research (SCAR) decided in the late 1990s to produce a new climatology of station data based on the six hourly synoptic observations. This initiative became known as the reference Antarctic data for environmental research (READER) project and eventually involved all the nations that maintained year-round staffed stations in the Antarctic. The details of the READER project are described in detail in Turner *et al.* (2004).

Changes in the near-surface conditions were considered by Turner *et al.* (2005) who used the READER data to examine the trends over the full length of the station data. They highlighted the marked warming at stations on the Antarctic Peninsula, where Vernadsky (formerly Faraday) was found to have warmed during 1951–2000 at an annual rate of $0.56°C·dec^{-1}$ and $1.09°C·dec^{-1}$ for the winter.

Many station records in the READER data base now extend back over 60 years providing the longest detailed temperature time series for the continent, allowing decadal time scale variability and change to be investigated. In this article we therefore present an up-to-date assessment of the temperature variability and trends at the stations with long records and investigate the relationships of the temperatures to the atmospheric circulation, sea ice extent, the major modes of climate variability and tropical sea surface temperatures (SSTs).

Here we have used data from 17 stations (listed in Table 1 and with their locations shown on Figure 1), which all have near-continuous records of more than 30 years in length. We focus particularly on six stations that span the different climatic regions of the Antarctic—Vernadsky and Esperanza are respectively on the western and eastern sides of the Antarctic Peninsula, Orcadas is on a sub-Antarctic island, Mawson is on the coast of East Antarctica, Scott Base is located South of the Ross Sea and Amundsen-Scott is a plateau station located at the South Pole.

We have used data from Scott Base rather than McMurdo on the edge of the Ross ice shelf as the record was found to be more complete. The United Kingdom has operated a station 'Halley' on the Brunt Ice Shelf on the eastern side of the Weddell Sea since 1957. However,

TABLE 1 The stations considered in this study listed eastwards from the Greenwich Meridian

Station name	Operating nation	Period of operation	Latitude	Longitude	Elevation (m)
Novolazarevskya	USSR then Russia	1961–	70.8°S	11.8°E	119
Syowa	Japan	1957, 1959–61, 1967–	69.0°S	39.6°E	21
Mawson	Australia	1954 -	67.6°S	62.9°E	16
Davis	Australia	1957–64, 1969–	68.6°S	78.0°E	13
Mirny	USSR then Russia	1956–	66.5°S	93.0°E	30
Vostok	USSR then Russia	1958–61, 1963–93, 1995, 1997–2002, 2004–	78.5°S	106.9°E	3,490
Casey	Australia	1959–	66.3°S	110.5°E	42
Dumont d'Urville	France	1956–	66.7°S	140.0°E	43
Scott Base	New Zealand	1957–	77.9°S	166.7°E	16
Rothera	United Kingdom	1976–	67.5°S	68.1°W	32
Faraday/Vernadsky	United Kingdom then Ukraine	1950–	65.4°S	64.4°W	11
Bellingshausen	Russia	1968–	62.2°S	58.9°W	16
Esperanza	Argentina	1945–	63.4°S	57.0°W	13
Marambio	Argentina	1970–	64.2°S	56.7°W	198
Orcadas	Argentina	1903–	60.7°S	44.7°W	6
Neumayer	Germany	1981–	70.7°S	8.4°W	50
Amundsen-Scott	United States	1957–	90.0°S		2,835

being on a floating ice shelf with ice breaking away periodical from the edge of the shelf, has resulted in a changing distance of the station from the ocean. In addition, the station has been moved inland five times to maintain a safe distance from the ice edge. The changes in distance of the station from the relatively warm ocean have had an impact on the heterogeneity of the Halley temperature series, with at least one large jump in the record and other smaller changes. For these reasons, we have not used the Halley data in this study.

While many of the surface meteorological records are now 60 years in length, starting around the time of the International Geophysical Year (IGY) in 1957/58, high quality atmospheric analyses are not available for the earlier part of the period. We have therefore only used reanalysis fields for the period from 1979 when satellite sounder data became available and the fields are more reliable.

In Section 2 we describe the data used in this study, with Section 3 considering the mean temperatures at the stations. Section 4 examines the inter-annual and decadal timescale temperature variability and, for the period since 1979, considers the relationships between the temperatures and the sea ice, atmospheric circulation and global SSTs. Section 5 examines the temperature trends over the full length of the records and for the period since 1979 when the changes can be related to various atmospheric and oceanic parameters. Section 6 presents conclusions and discusses how the temperature trends observed at the stations relate to trends in the interior estimated using various techniques.

2 | DATA

Monthly mean near-surface (2 m) air temperatures for the period up to December 2018 were obtained from the SCAR READER database available online at https://legacy.bas.ac.uk/met/READER/. Most of the monthly mean temperatures were computed from the six hourly synoptic observations, however, some of the more recent mean values were taken from the CLIMAT messages. The origin of each monthly mean temperature can be found on the READER web site.

The austral seasons were taken as spring (September–November), summer (December–February), autumn (March–May) and winter (June–August). As the austral summer season spans two calendar years, we have indicated the year that contains the December month, that is, summer 2015 covers December 2015 to February 2016.

Temperature trends were computed using a standard least-squares method, with the methodology used to calculate the significance levels based upon Santer *et al.* (2000). Annual and seasonal means in a given year were only computed when all months of the year or season were available.
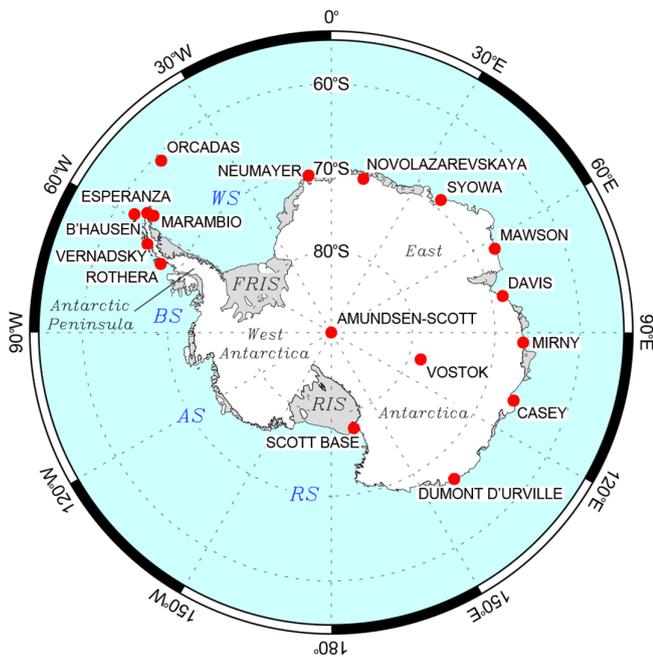
FIGURE 1 The locations of the 17 stations considered in the study. WS, Weddell Sea; BS, Bellingshausen Sea; AS, Amundsen Sea; RS, Ross Sea [Colour figure can be viewed at wileyonlinelibrary.com]

Atmospheric circulation variability and change since 1979 were determined using the ECMWF Interim reanalysis (ERA-Interim) fields (Dee *et al.*, 2011), which have a grid spacing of ~70 km. Several studies have carried out intercomparisons of the various reanalysis data sets and concluded that the ERA-Interim data are the best for depicting recent Antarctic climate (e.g., Bracegirdle and Marshall, 2012).

Fields of monthly mean sea ice concentration (SIC) computed using the NASA Team 1.1 algorithm were obtained on a 25 km resolution grid for 1979–2018 from the US National Snow and Ice Data Center (www.nsidc.org). The UK Hadley Centre's HadISST data set (http://www.metoffice.gov.uk/hadobs/hadisst/) was used to provide ocean conditions over the period. For the computation of the correlations the time series of sea ice data, SSTs and atmospheric fields were all detrended a priori. The index of the SAM covering 1957–2018 came from http://www.nerc-bas.ac.uk/icd/gjma/sam.html and is described by Marshall (2003).

3 | MEAN TEMPERATURES AT THE STATIONS

The annual and seasonal mean temperatures for the 30 year climatological period 1981–2010 for the 17 stations considered, along with the inter-annual variability

are given in Table 2. For the year as a whole, the stations with the highest mean temperatures are on the western side of the Antarctic Peninsula, with Bellingshausen Station on King George Island, South Shetland Islands having the highest annual mean temperature ($-2.1°C$). Bellingshausen also has the highest temperature in each of the four seasons, which can be attributed to its northerly location, lack of sea ice around the island and its exposure to relatively warm climatological northwesterly winds. To the South, on the western side of the Peninsula, Vernadsky station also has a relatively high annual mean temperature ($-2.9°C$) as it is also under the influence of the relatively warm climatological northwesterly flow. Orcadas station on Laurie Island, South Orkney Islands is located to the North of the Antarctic Peninsula, but is only the third warmest station in terms of annual mean temperature ($-3.1°C$) because it can be affected by cold southerly air flow from the ice-covered Weddell Sea.

Esperanza and Marambio stations, although located near the tip of the Antarctic Peninsula, are colder (annual mean temperatures are -4.6 and $-8.1°C$, respectively) than the stations on the western side, since they are more under the influence of the Antarctic Peninsula barrier winds arriving from the South.

The ring of stations around the coast of East Antarctica are all at comparable latitudes and all have similar annual mean temperatures in the range -9 to $-11°C$. They have mean summer temperatures that are below freezing, with mean positive temperatures at that time of year only being found at stations on the Antarctic Peninsula.

Scott Base is at a more southerly location compared to the other East Antarctic coastal stations and this is reflected in the lower mean temperatures throughout the year compared to the other sites.

In the interior of the continent Vostok is colder than Amundsen-Scott by 3–7°C throughout the year, with the smallest (largest) difference in the summer (winter). The differences in temperature between the stations arise as a result of Vostok's higher elevation and greater remoteness from the moderating influence of the ocean.

4 | TEMPERATURE VARIABILITY

The atmospheric and oceanic influences on the near-surface temperatures vary around the Antarctic continent. There are some continent-wide factors that modulate the temperatures, such as the SAM. This can be considered a proxy for the strength of the circumpolar westerlies around Antarctica and in recent decades has become more positive (stronger westerlies) in summer in response to ozone depletion (Thompson and Solomon, 2002). There is a well-documented signature of higher

TABLE 2 Annual and seasonal mean temperatures for 1981–2010

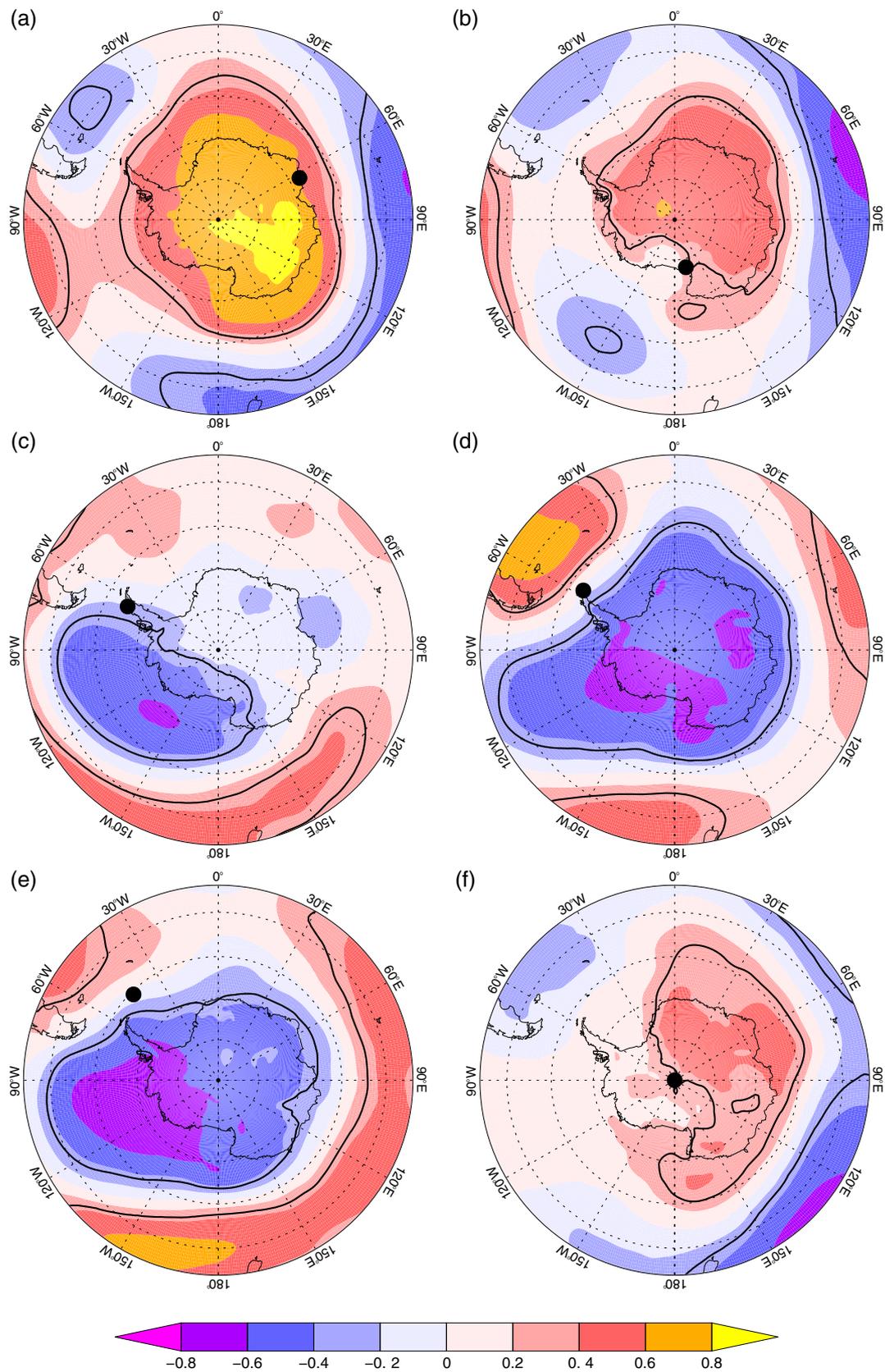| Station	Temperature (°C)				
	Annual	Spring	Summer	Autumn	Winter
Novolazarevskya	−10.1 (0.6)	−11.7 (1.0)	−1.6 (0.7)	−10.9 (1.0)	−16.3 (1.5)
Syowa	−10.5 (0.8)	−12.8 (1.1)	−1.7 (0.7)	−10.0 (1.3)	−17.3 (1.7)
Mawson	−11.3 (0.8)	−12.0 (0.9)	−1.7 (0.7)	−13.8 (1.6)	−17.7 (1.7)
Davis	−10.1 (1.0)	−10.9 (1.2)	−0.4 (0.7)	−12.2 (1.8)	−16.7 (2.0)
Mirny	−11.3 (0.7)	−12.2 (1.0)	−3.3 (0.9)	−13.2 (1.5)	−16.2 (1.6)
Vostok	−55.3 (0.7)	−55.2 (1.2)	−35.8 (1.1)	−62.9 (1.6)	−66.9 (1.9)
Casey	−9.1 (0.9)	−10.2 (1.1)	−1.3 (0.7)	−10.8 (1.7)	−14.2 (1.7)
Dumont d'Urville	−10.8 (0.7)	−11.8 (0.7)	−2.2 (0.7)	−12.8 (1.0)	−16.3 (1.6)
Scott Base	−19.6 (0.8)	−19.9 (1.5)	−6.9 (0.7)	−23.5 (2.0)	−28.2 (2.0)
Rothera	−4.1 (1.1)	−5.1 (1.6)	0.9 (0.5)	−2.8 (1.0)	−9.3 (2.5)
Vernadsky	−2.9 (1.1)	−4.1 (1.6)	0.8 (0.6)	−1.7 (0.8)	−6.3 (2.3)
Bellingshausen	−2.1 (0.8)	−2.6 (0.9)	1.3 (0.5)	−1.5 (1.1)	−5.6 (1.9)
Esperanza	−4.6 (1.1)	−4.0 (1.6)	1.0 (0.8)	−5.5 (2.1)	−10.0 (2.2)
Marambio	−8.1 (1.2)	−7.0 (2.0)	−1.4 (1.0)	−9.8 (2.5)	−14.2 (2.6)
Orcadas	−3.1 (0.7)	−3.0 (1.5)	1.1 (0.5)	−1.9 (1.2)	−8.3 (2.0)
Neumayer	−16.0 (0.7)	−17.2 (1.3)	−5.6 (0.9)	−16.9 (1.3)	−23.9 (1.9)
Amundsen-Scott	−49.5 (0.9)	−49.7 (1.7)	−32.3 (1.4)	−56.5 (1.5)	−59.2 (1.8)

Note: The *SD* is given in brackets.

(lower) temperatures across the Antarctic Peninsula and lower (higher) temperatures over the rest of the continent when the SAM is in its positive (negative) phase (e.g., Marshall and Thompson, 2016). The influence of the SAM on surface temperatures can be appreciated from the spatial figures showing the correlation of the observed annual mean temperature time series at each station with the spatial annual mean sea level pressure (MSLP) from ERA (Figure 2). At stations such as Orcadas and Esperanza higher (lower) temperatures are associated with anomalously low (high) pressure over the Antarctic continent (mid-latitude regions), which is the characteristic signature of the positive phase of the SAM. At Mawson, Scott Base and Amundsen-Scott the SAM-temperature relationship is reversed, with higher (lower) temperatures associated with anomalously high (low) pressure over the Antarctic continent (mid-latitude regions). However, while these spatial patterns depicting the influence of the SAM on Antarctic temperatures appear to predominate, the relationship between temperature and the phase of the SAM is not temporally invariant (e.g., Silvestri and Vera, 2009; Marshall et al., 2013), which can complicate the interpretation of decadal time-scale temperature variability.

Another annular, large-scale pattern of atmospheric variability, known as the baroclinic annular mode, is linked to the amplitude of extratropical eddy activity over much of the Southern Hemisphere storm track and also influences Antarctic surface temperatures, However, while important in some regions, its impact is much less widespread and of smaller magnitude than the SAM (Marshall and Thompson, 2016).

Variability in tropical sea surface temperatures can influence Antarctic air temperatures through quasi-stationary atmospheric wave trains originating in the Pacific (Turner, 2004) and Atlantic oceans (Li et al., 2014). As discussed in the following sections, temperatures at all the Antarctic stations are influenced by the phase of ENSO, but with the greatest impact occurring in West Antarctica and the Antarctic Peninsula. On longer time scales, the Pacific Decadal Oscillation (PDO) and Interdecadal Pacific Oscillation (IPO) also influence atmospheric conditions at high southern latitudes and have been linked to changes in the Amundsen Sea Low (ASL). This is the climatological area of low pressure found between the Antarctic Peninsula and the Ross Sea (Raphael et al., 2015), the depth and location of which affects temperatures across the Antarctic Peninsula, West Antarctica and the Ross Ice Shelf (Clem and Fogt, 2015; Purich et al., 2016). The ASL is particularly important in modulating the temperatures at Vernadsky, and there is a significant anticorrelation between MSLP in the area of the ASL and Vernadsky annual mean temperature (Figure 2c).

FIGURE 2 The correlation of the observed annual mean temperature time series for 1979–2018 with the spatial annual mean MSLP from ERA for the six stations considered in detail. (a) Mawson, (b) Scott Base, (c) Vernadsky, (d) Esperanza, (e) Orcadas and (f) Amundsen-Scott. The black dots indicate the locations of the stations [Colour figure can be viewed at wileyonlinelibrary.com]

The presence or absence of sea ice in the vicinity of a station can have a large effect on the near-surface temperature as the sea ice can markedly limit the flux of heat from the relatively warm ocean into the atmosphere. This effect is most pronounced during the winter months when the air–sea temperature difference is greatest. Sea ice variability is affected by a number of local and broad-scale factors, such as regional wind systems and the modes of climate variability. The phase of the SAM influences the pattern of sea ice distribution with less (more) ice around the Northern Antarctic Peninsula and Weddell Sea and more (less) around East Antarctica when the SAM is positive (negative) (Lefebvre and Goosse, 2008). In contrast, some local wind systems can create regional sea ice anomalies that have a large effect on temperatures over a small region, which can be independent of the large scale variability.

All 17 stations considered here have their largest inter-annual variability of temperature during the winter (Table 2) and the annual mean temperature anomalies are dominated by winter, as positive or negative sea ice anomalies can amplify temperature changes as a result of anomalous atmospheric flow. In the western and north-eastern parts of the Peninsula, this is a result of the large air–sea temperature difference during this season and the large variability in sea ice cover. Winter temperature variability is largest at Marambio (2.6°C) where sea ice is particularly variable close to the station. The SD of winter temperature is also large at Rothera, Vernadsky and Esperanza stations, where SIC variability is large during that season. In addition, the large winter SD of temperature at Vernadsky is also influenced by the 'polynya-like feature' that can develop close to the station in some years (Turner et al., 2013).

4.1 | The Antarctic Peninsula

The stations on the western side of the Peninsula experience some of the largest variability in annual mean temperature (Table 2). This occurs because the stations are to the east of the 'pole of variability', which is a region in the South Pacific where the MSLP and 500 hPa geopotential height are more variable than any other location on Earth (Figure 3) (Connolley, 1997). The high degree of MSLP variability results in large variability in the meridional wind component and SIC to the west of the Peninsula.

The western side of the Peninsula is unique in that it is the only area of the Antarctic (apart from a small part of Victoria Land) where the sea ice moves North–South along the coast during its annual cycle. The anti-correlation between the annual mean temperature and
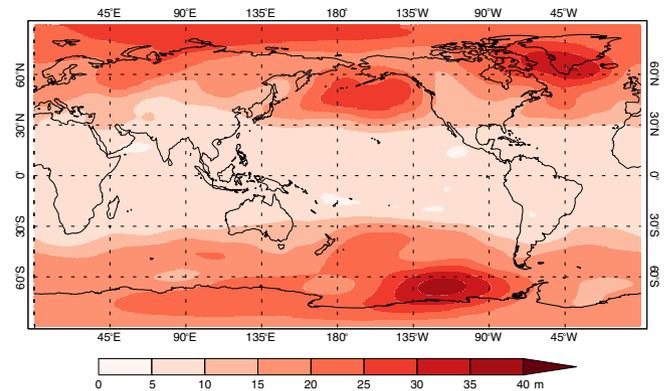

FIGURE 3 The SD of the annual mean 500 hPa geopotential height (1979–2018), illustrating the 'pole of variability' to the west of the Antarctic Peninsula [Colour figure can be viewed at wileyonlinelibrary.com]

annual mean SIC is therefore particularly large close to Vernadsky (Figure 4) and Rothera stations. This results in both stations having SD of annual mean temperature of 1.1°C.

Bellingshausen has a smaller inter-annual variability of annual mean temperature (SD 0.8°C) because of the reduced variability of sea ice in the vicinity compared to Rothera and Vernadsky. Over the north-western part of the Weddell Sea the sea ice is also quite variable and this is an important factor in giving Marambio and Esperanza large inter-annual variability of annual mean temperature of 1.2 and 1.1°C respectively. Another factor influencing temperatures here is the large temperature anomalies associated with Föhn winds that occur during strong westerly wind events (Turton et al., 2018). However, such episodes are relatively rare and short-lived so they will have less of an impact on the long-term temperature variability compared to the sea ice extent and broadscale circulation changes.

The anomalies (from the 1981 to 2010 mean) of annual mean temperature for the Peninsula stations show a high degree of variability (Figure 5a). In some years, there have been very localized temperature anomalies, such as the very warm conditions at Marambio and Esperanza in 2016 (Figure 5a), which were not recorded at other Peninsula stations. The ERA-Interim fields show that these large annual temperature anomalies at the two stations were a result of a very warm winter when strong southwesterly winds advected sea ice away from a relatively small area of the Northwest Weddell Sea around these stations.

In other years all the stations recorded large positive or negative anomalies, for example 1956 (warm), 1989 (warm) and 1980 (cold). These are a result of broadscale atmospheric anomalies that give greater than normal
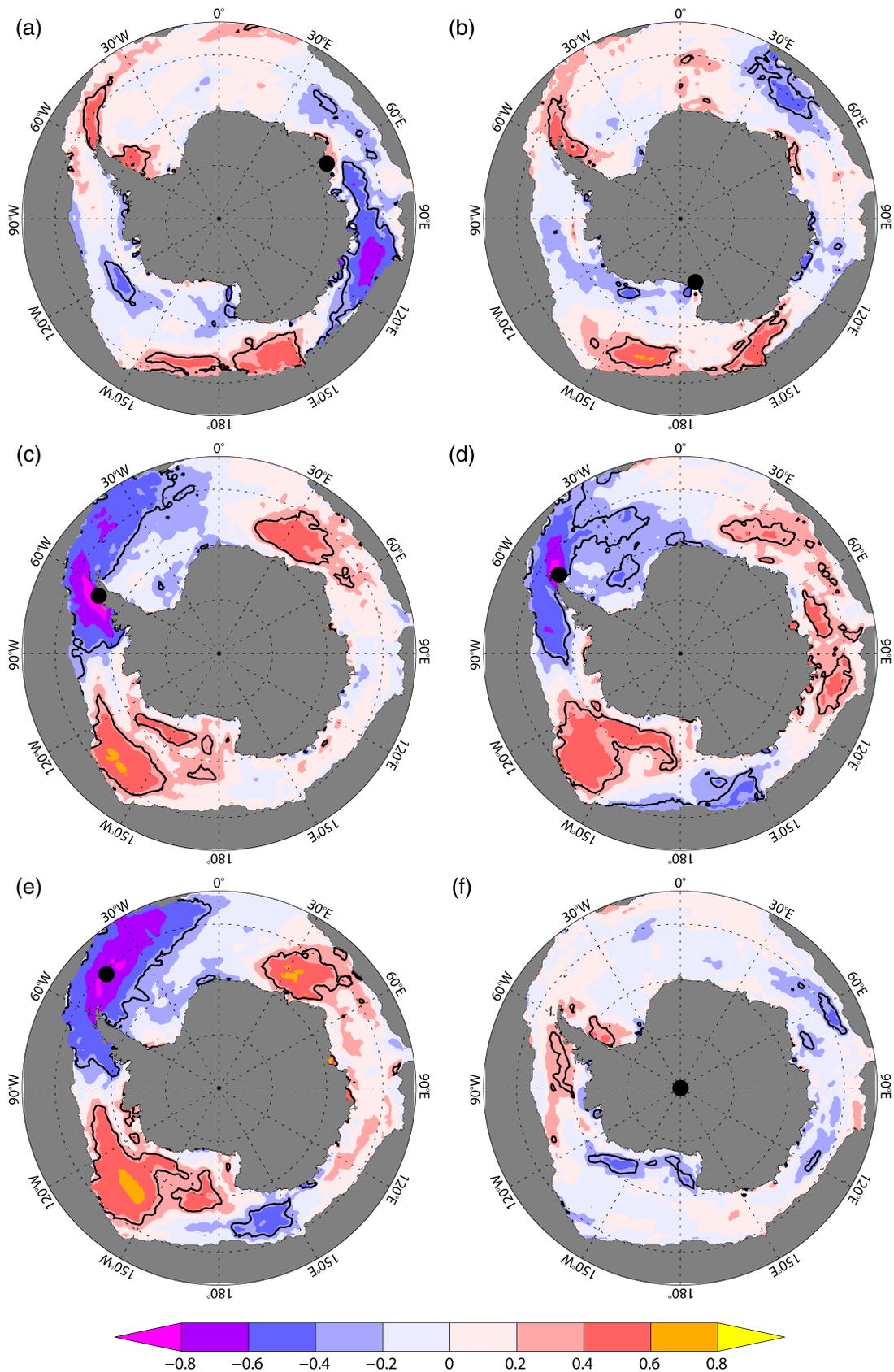
FIGURE 4 The correlation of the observed annual mean station temperatures for 1979–2018 with the annual mean sea ice concentrations for the six stations considered in detail. (a) Mawson, (b) Scott Base, (c) Vernadsky, (d) Esperanza, (e) Orcadas and (f) Amundsen-Scott. The black dots indicate the locations of the stations [Colour figure can be viewed at wileyonlinelibrary.com]
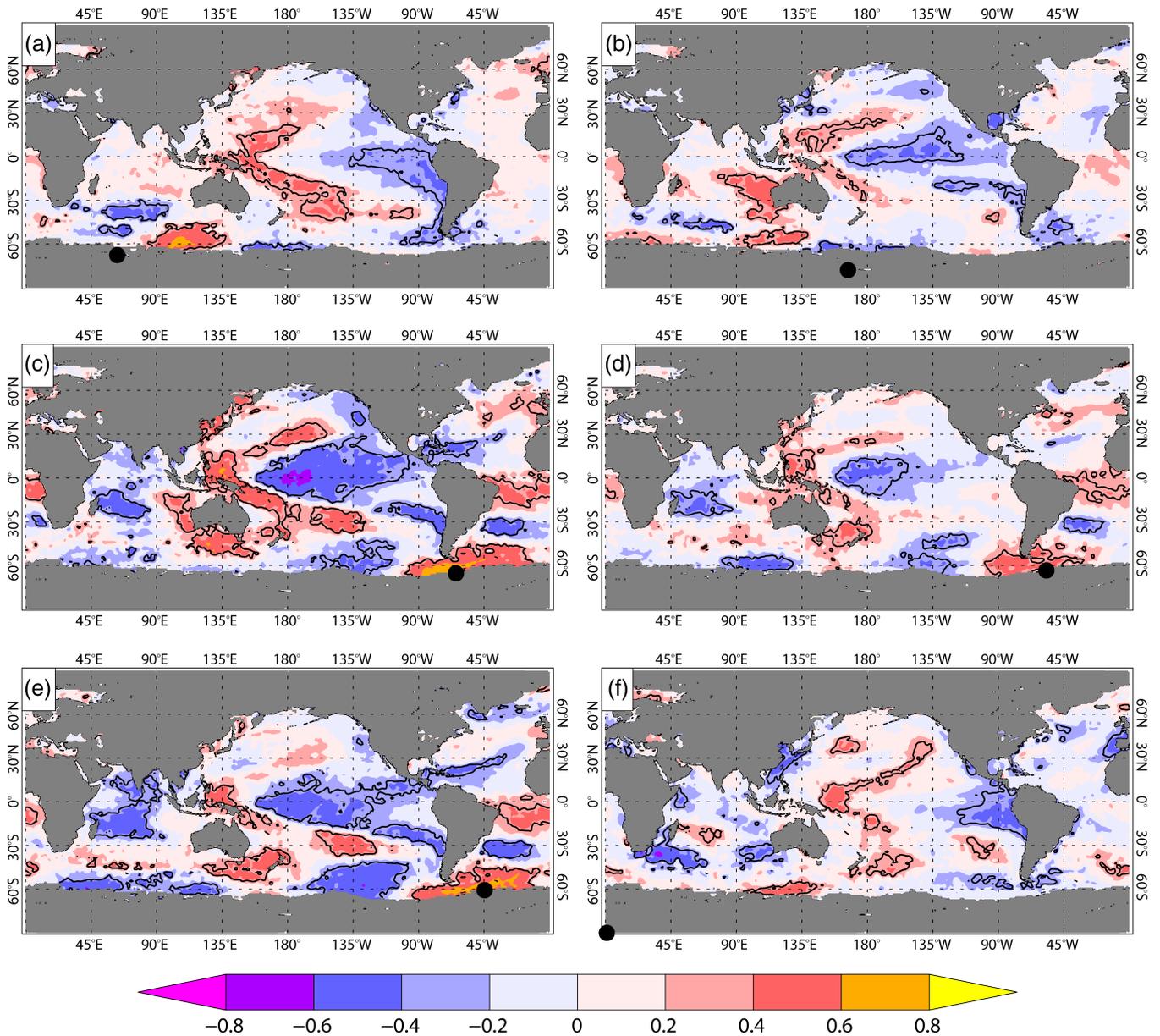
FIGURE 5 The annual mean
station temperature anomalies from
1981 to 2010. (a) the Antarctic
Peninsula, (b) East Antarctic and (c) the
plateau and Ross ice shelf [Colour figure
can be viewed at
wileyonlinelibrary.com]
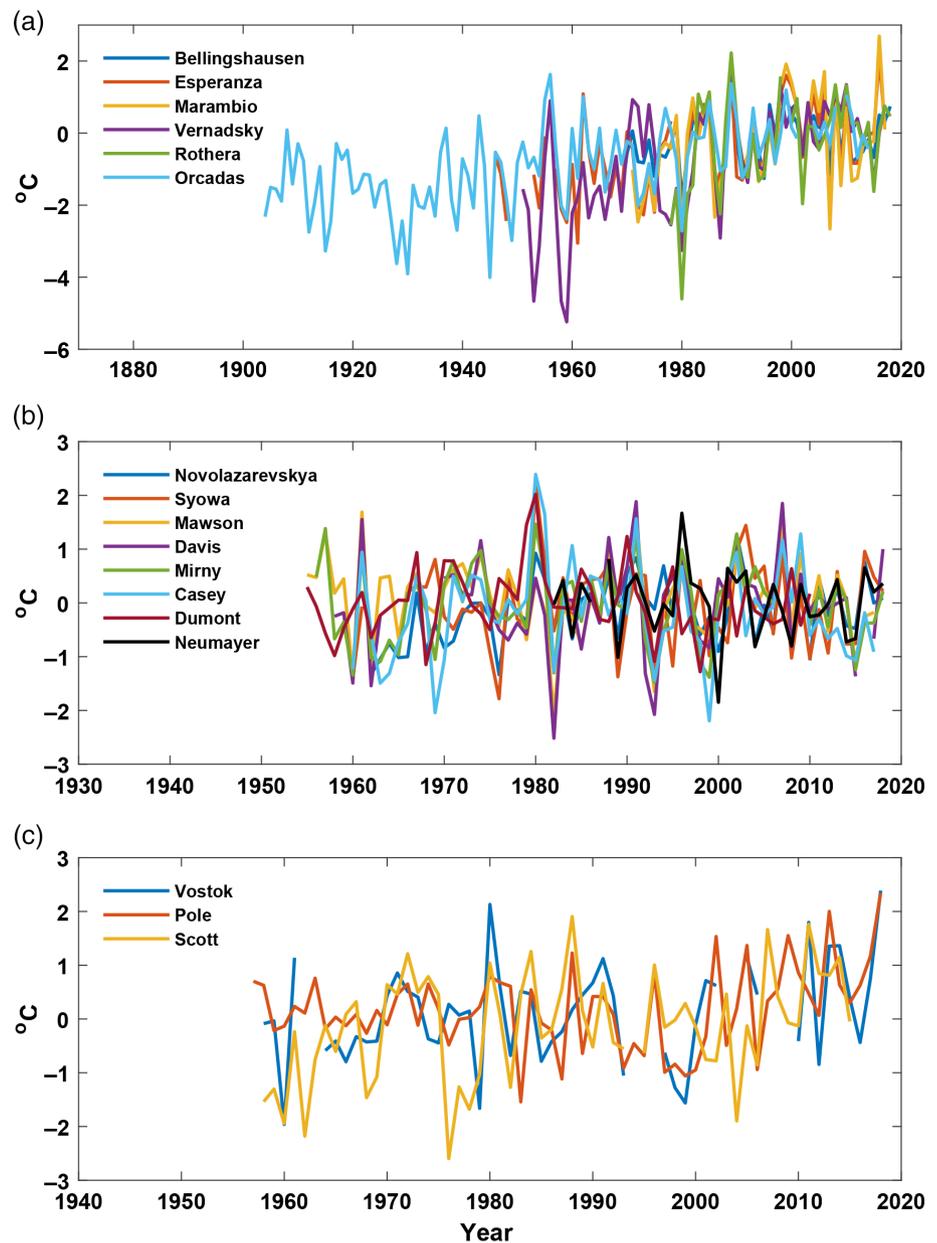
warm or cold air advection across the region. This can be from a very deep ASL, such as in the warm year of 1989, or a couplet of high/low MSLP anomalies across the Peninsula, such as in the cold years of 1980 and 1987. Extreme high winter temperatures on the Peninsula are associated with negative MSLP and upper level geopotential height anomalies over the Bellingshausen Sea, which can in turn be associated with ENSO variability (Marshall and King, 1998; Clem et al., 2017).

The annual mean temperatures at the Peninsula stations are correlated with a pattern of high (low) SSTs over the western (central) tropical Pacific (Figure 6), indicating that higher (lower) temperatures are associated with La Niña (El Niño) conditions. One of the most pronounced patterns of correlation is found at Vernadsky where the deeper ASL associated with the La Niña phase

brings relatively warm air down to the western side of the Antarctic Peninsula (Clem et al., 2016). The magnitudes of the correlations for Orcadas are smaller than for Vernadsky, and are even less for Esperanza on the eastern side of the Antarctic Peninsula due a stronger relationship with zonal wind anomalies associated with the SAM (Marshall, 2007). However, extreme El Niño and La Niña events can give large anomalies in the depth of the ASL resulting in anomalous meridional winds across the Antarctic Peninsula and therefore very warm or cold conditions over the whole region. The tropical Pacific Ocean was characterized by El Niño conditions during 1997 and the ASL was particular weak with greater southerly flow across the Peninsula. All the Peninsula stations had negative annual mean temperature anomalies in this year, with the cold anomalies being particular pronounced

FIGURE 6 The correlation of the annual mean station temperatures for 1979–2018 with the annual mean SST for the six stations considered in detail. (a) Mawson, (b) Scott Base, (c) Vernadsky, (d) Esperanza, (e) Orcadas and (f) Amundsen-Scott. The black dots indicate the locations of the stations [Colour figure can be viewed at wileyonlinelibrary.com]

during the winter months when the tropical—high latitude teleconnection is most pronounced (Karoly, 1989; Harangozo, 2004). However, the high latitude signal of the major El Niño event of 1982 was less clear in the Antarctic Peninsula region indicating the large variability in response to tropical forcing that occurs in the Antarctic to individual events. As noted by Fogt *et al.* (2011), the tropical Pacific—high latitude teleconnection is modulated by the phase of the SAM, which can mask the signal of some ENSO events in the Peninsula. When ENSO and SAM are in phase, the ENSO impacts on the eastern Peninsula are amplified leading to a strong correlation of Peninsula temperatures with ENSO (Clem and Fogt, 2013).

The decadal timescale temperature variability across the Peninsula is examined via the 11 year running mean annual mean temperature (Figure 7a), which shows variability on a range of timescales. The only record that spans virtually the whole of the Twentieth Century is from Orcadas. Here there was a decrease in temperature until around 1930 and then an increase until the end of the 1990s, with the most rapid warming taking place up to around 1960. Temperatures at the station have been positively correlated with the phase of the SAM since the mid-1970s, although the relationship was only significant at $p < .05$ during the 1980s and for short periods subsequently (Figure 8).

Temperatures from the other Peninsula stations increased from the 1950s until the late 1990s, but then decreased slightly in the following years. Since the mid-1970s temperatures at the Peninsula stations have been positively correlated with the phase of the SAM (Figure 8).

Annual mean temperatures at many of the Antarctic Peninsula stations are significantly correlated amongst themselves (Figure 9). The highest correlation (0.98) is between Esperanza and Marambio, which are close together in the Northeast part of the Peninsula. Both stations have relatively high temperatures when the westerlies are strong in response to a positive SAM (Marshall et al., 2006), leading to increased Föhn events (Turton et al., 2018) and a reduction in sea ice along the coast. However, the greatest difference in temperature is found when the winds are weaker and there is less advection of

sea ice away from the eastern side of the Peninsula. Then the greater climatological amount of ice at more southerly latitudes results in colder conditions at Marambio. Annual mean temperatures are also highly correlated between Rothera and Vernadsky (0.94), stations that are ~300 km apart on the western side of the Peninsula. Differences in temperature between the two stations are strongly related to the depth of the ASL. A deep ASL results in less sea ice down much of the western side of the Peninsula and similar temperatures at the two stations. A weak ASL enhances the sea ice gradient down the Peninsula. Under such conditions there is extensive sea ice around Rothera, but often little ice close to Vernadsky because of the polynya-like feature that can form across the Northeast Bellingshausen Sea (Turner et al., 2013). This leads to a greater annual mean temperature
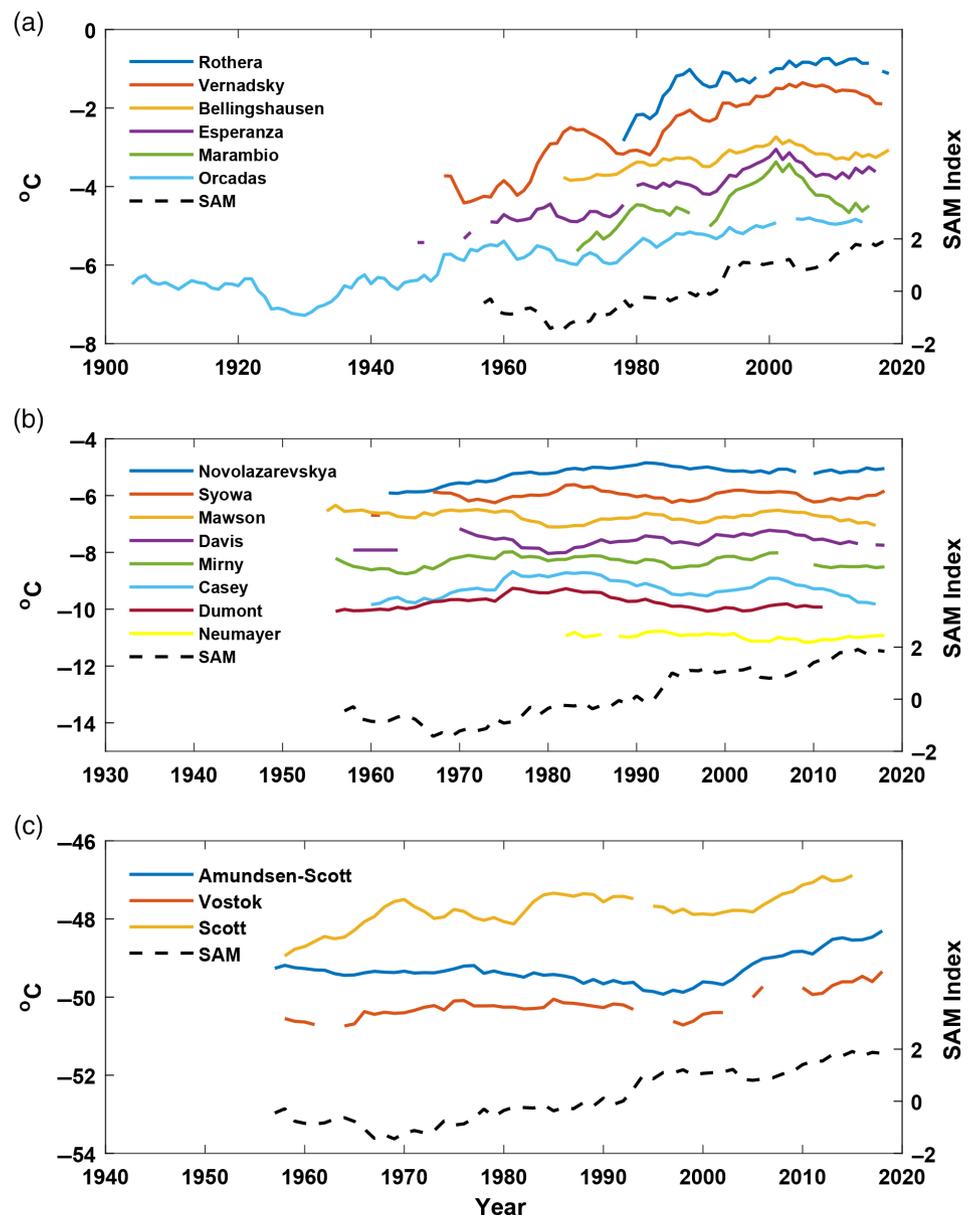
FIGURE 7 The 11-year running mean annual mean temperatures with temperature offsets applied as follows. (a) Antarctic Peninsula/Weddell Sea stations, Rothera (+3°C), Vernadsky (+1°C), Bellingshausen (−1°C), Esperanza (+1°C), Marambio (+4°C) and Orcadas (−2.5°C), (b) East Antarctic stations, Novolazarevskya (+5°C), Syowa (+4.5°C), Mawson (+4.5°C), Davis (+2.5°C), Mirny (+3°C), Casey (+0°C), Dumont d'Urville (+1°C) and Neumayer (+5°C) and (c) Plateau and Ross ice shelf stations, Vostok data (+5°C) and Scott Base (−28°C) [Colour figure can be viewed at wileyonlinelibrary.com]
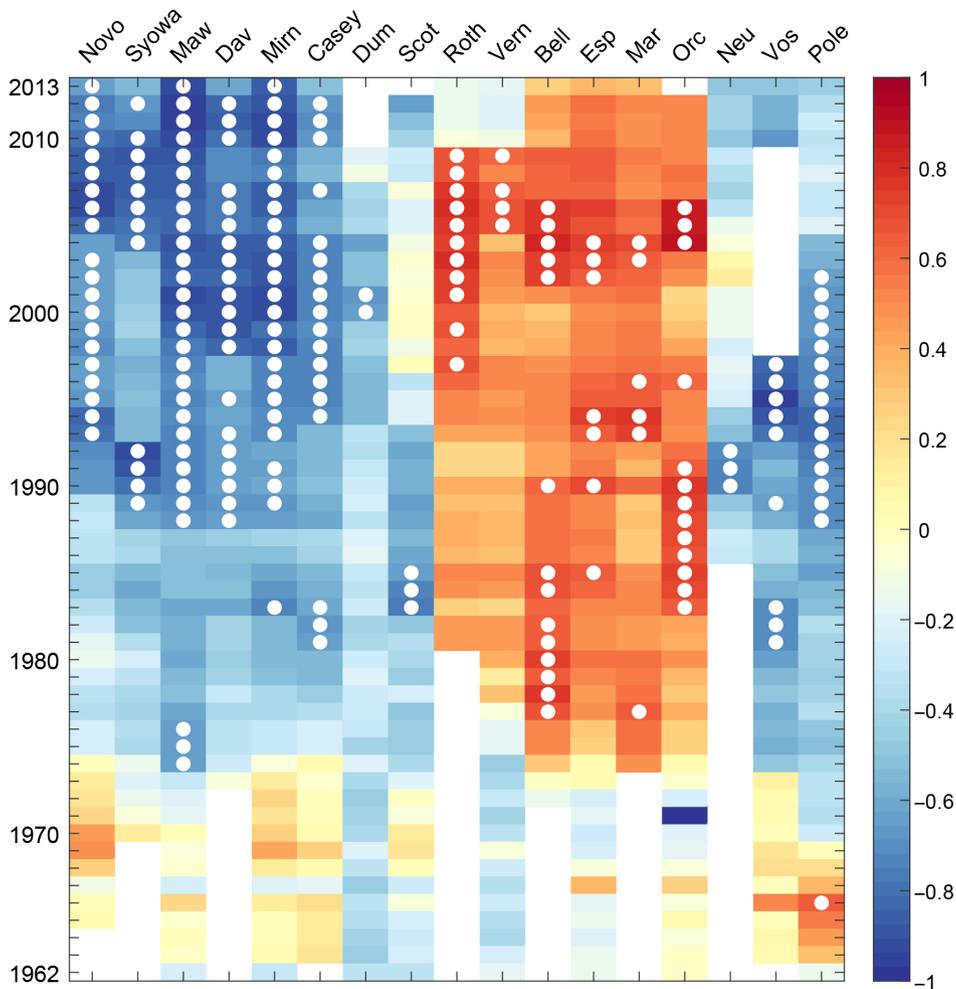
FIGURE 8 The correlations between the 11-year running mean annual mean SAM index and annual mean temperatures at the 17 stations since 1957. The stations are indicated in an abbreviated form eastwards from Novolazarevskya, except for the two plateau stations that are included on the right. Dates on the vertical axis indicate the mid-points of the 11-year running means. The white dots show correlations that are significant at $p < .05$ [Colour figure can be viewed at wileyonlinelibrary.com]

difference between the two stations. The smallest correlation in annual mean temperature (0.47) between stations on the Peninsula is between Marambio and Vernadsky on the east and west Peninsula coast, respectively. Sea ice variability is very important in dictating annual mean temperature at these two stations and the regional processes influencing sea ice variability at the two sites are often decoupled (Turner *et al.*, 2013). Moreover, meridional wind anomalies and thermal advection play a dominant role on the western Peninsula, while zonal wind anomalies and Föhn events are more important on the eastern Peninsula (Clem *et al.*, 2016).

The correlations between the Peninsula station temperatures are largest in the winter and spring (Figure S1) and similar in magnitude to the annual data (Figure 9). During these seasons the sea ice close to the stations has a damping effect on regional temperature variability and therefore increase the importance of Antarctic-wide influences. However, the correlations in summer are much less than the annual values as the lack of sea ice results in a greater influence from local factors and indeed there are weak negative correlations between some Peninsula stations in this season.

The inter-annual variability of the annual mean temperatures at Rothera and Vernadsky has decreased during the instrumental period (Figure 5a) as there has been a loss of sea ice. This has been largest at Vernadsky where the sd of annual mean temperature has decreased from 1.9°C in the 1950s to 0.7°C in the 00s. The greatest decrease in *SD* has been during the winter months.

The warming across the Northern Peninsula from the late 1970s until the late 1990s (Turner *et al.*, 2016) is apparent in the stacked and normalized record for the region (Figure 10a). Of the Peninsula stations examined here, the largest warming trends were at Vernadsky, Marambio and Esperanza (Figure 7a) and the smallest at Orcadas. The 1980s and 1990s were characterized by a trend of the SAM towards its positive phase and a deepening of the ASL, which brought warm air down onto the Peninsula. There was also an increase in MSLP over Southern South America resulting in stronger westerlies that contributed to the warming at Esperanza and Marambio, enhanced by the resultant Föhn effect.

There has been extensive research into the deepening of the ASL and the resultant impact on sea ice and Peninsula temperatures (e.g., Hosking *et al.*, 2013). The two

FIGURE 9 The correlations between the annual mean temperatures at the 17 stations for 1979–2018. The stations are indicated in an abbreviated form eastwards from Novolazarevskya, except for the two plateau stations that are included on the right. The white dots indicate correlations that are significant at $p < .05$ [Colour figure can be viewed at wileyonlinelibrary.com]
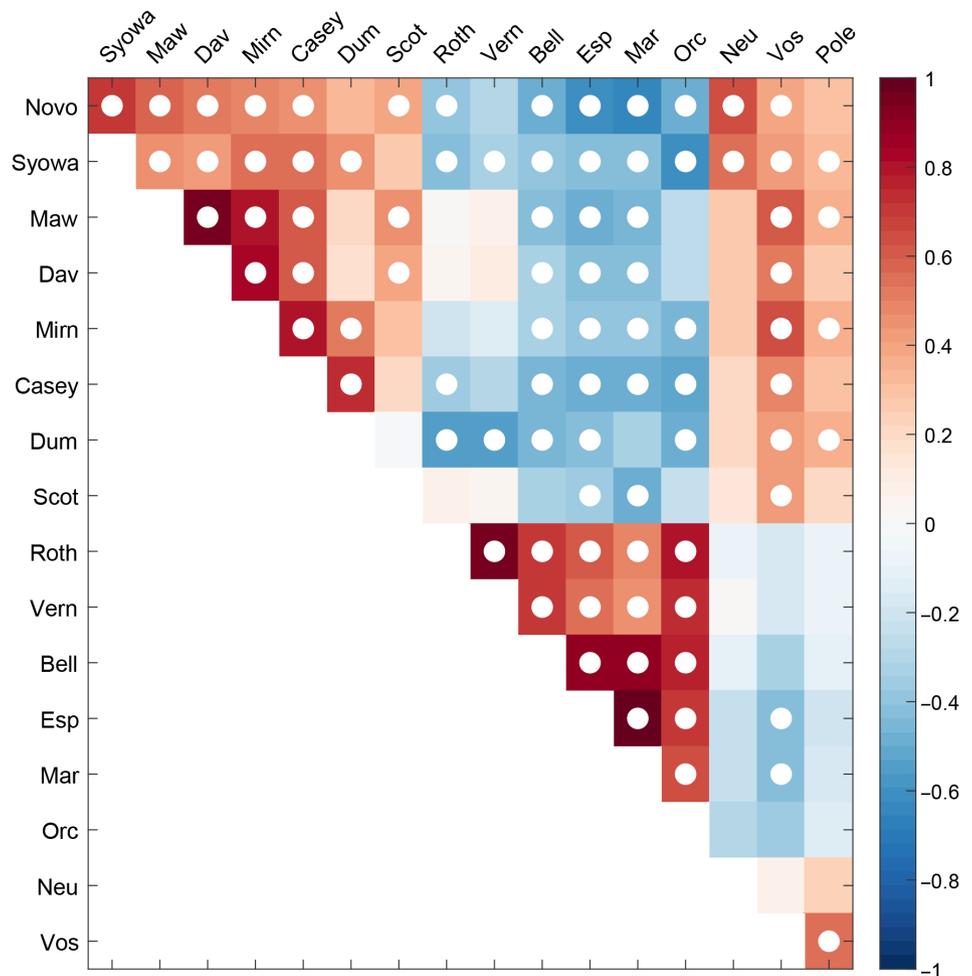

studies by Purich *et al.* (2016) and Clem and Fogt (2015) both suggested that the deepening of the ASL over recent decades was a result of the shift of the IPO/PDO from the positive to the negative phase. Given that the observed shift in the SAM towards its positive phase will have strengthened the ASL (Turner *et al.*, 2009), the deepening is clearly a result of multiple factors.

As discussed by Turner *et al.* (2016), during the 2000s the ASL deepened further, but low MSLP in the Drake Passage brought more easterlies to the Peninsula and greater amounts of sea ice to the tip of the Peninsula, resulting in a small cooling. The Northern Peninsula annual stacked temperature record has shown an upturn with positive anomalies since 2016 (Figure 10a) as a result of negative sea ice concentration anomalies around Esperanza and Marambio since that time, which were also observed off Vernadsky and Rothera during 2017 and 2018.

4.2 | East Antarctica

Variability in the phase of the SAM plays a large part in controlling the temperatures at the stations around the coast of East Antarctica (Figure 8). Here, since the mid-1970s, annual mean temperatures were higher when the SAM was negative, when there was a greater poleward heat flux (Marshall and Thompson, 2016) and less sea ice off the coast (Figure 4a). The switch in the relationship between the annual mean temperatures and phase of the SAM prior to the mid-1970s suggests a change in the atmospheric circulation of high Southern latitudes, and is a subject that is currently under investigation. However, we note that the change in the relationship is not apparent in all seasons. The annual mean temperatures at a station such as Mawson are therefore significantly correlated with a pattern of MSLP that has high (low) MSLP anomalies over the continent (in mid-latitudes) (Figure 2a). However, despite the more positive SAM in recent decades a broadscale cooling at the East Antarctic stations has not been observed. The reasons for this are still unclear, but the impact of a more positive SAM could be masked by the radiative effects of increasing greenhouse gas concentrations or the lack of cooling could be a result of regional atmospheric circulation changes, for example, zonal asymmetries tied to tropical variability (Marshall and Thompson, 2016; Clem *et al.*, 2018a).
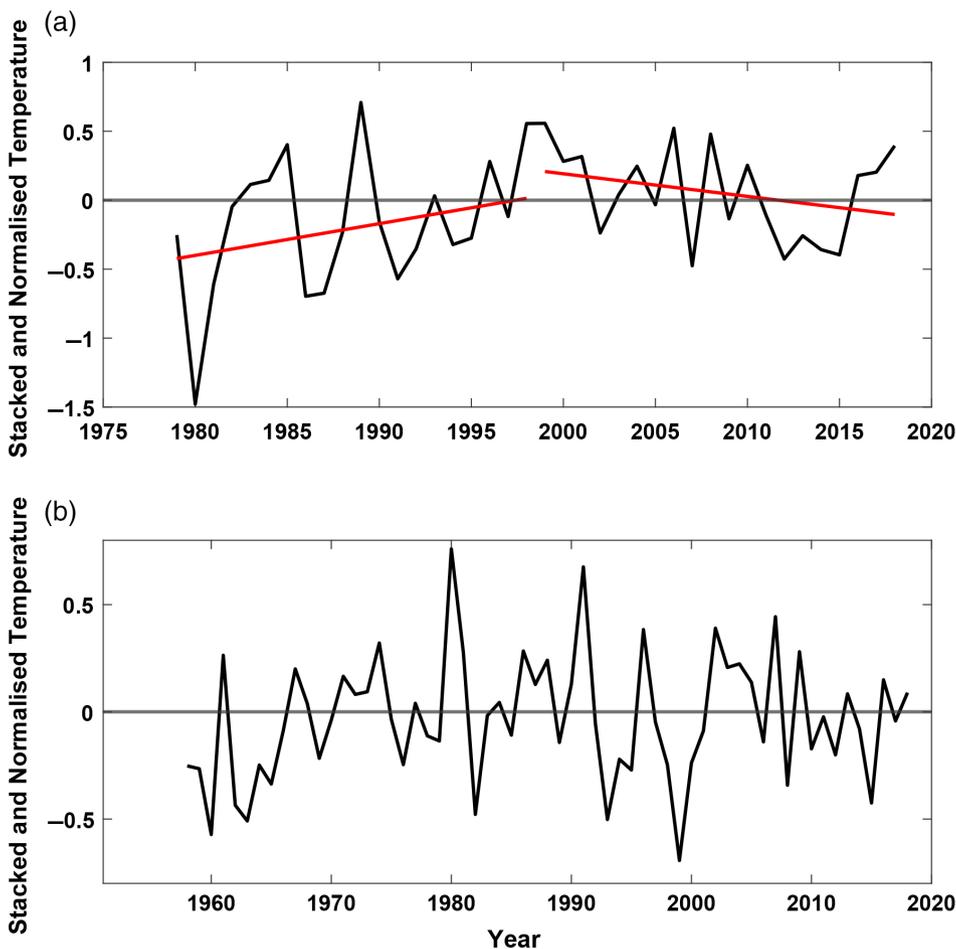
FIGURE 10 The stacked and normalized temperatures for (a) the Peninsula and (b) East Antarctica. The red lines on (a) show the linear trends for the periods 1979–1997 and 1999–2018 [Colour figure can be viewed at wileyonlinelibrary.com]

All the East Antarctic stations have a much smaller inter-annual variability in temperature compared to those on the Peninsula, where sea ice variability can amplify anomalies in the atmospheric circulation. Around the coast of East Antarctica the sea ice extends well North of the coast for much of the year, although individual storms can advect sea ice away or towards the immediate coastal area, opening or closing coastal polynyas. However, large, sustained open water areas, such as those found on the western side of the Antarctic Peninsula even in winter, do not occur close to most stations, limiting the inter-annual variability of surface temperature.

The coastline of East Antarctica is more uniform than other sectors of the Antarctic and the anomalies in annual mean temperature are often of the same sign between these stations (Figure 5b). The largest and most consistent anomalies between stations, such as the warm (cold) anomalies of 1980 (1982) correspond to years when the SAM index was very atypical. In 2016, when there was a large difference between the station anomalies, there was an amplified wave number 3 pattern, which gave large differences in the meridional flow between Syowa/Novolazarevskya and Casey.

Tropical Pacific climate variability influences temperatures at the East Antarctic stations in a similar fashion

to those of the Antarctic Peninsula, with higher (lower) temperatures when tropical Pacific SST anomalies have a signature of El Niño (La Niña) conditions. Similarly, ENSO events can lead to an amplified meridional pattern around coastal East Antarctica that can cause differences in temperature anomalies between Syowa/Novolazarevskya and Mawson/Davis (Clem *et al.*, 2018a). However, the correlations between station temperatures and tropical Pacific SSTs are lower than those for the Antarctic Peninsula stations.

The 11-year running mean temperatures for the East Antarctic stations (Figure 7b) do not show the consistent, broadscale variability apparent across the Antarctic Peninsula. However, adjacent stations around the coast of East Antarctica have a high and significant correlation in annual mean temperature (Figure 9), with the highest correlations being between the temperatures of Davis and Mawson (0.94), Mirny and Davis (0.83), Mirny and Mawson (0.81), and Casey and Mirny (0.80). Some regional trends over parts of the record are apparent in Figure 7b. Mirny, Casey and Dumont d'Urville all experienced a small cooling over the late 1970s to the mid-1990s as the SAM became more positive. But this was not apparent at Mawson, which warmed over this time, especially during the winter

months, when there was an increase in warm air advection. In the first decade of the 21st century the usual negative correlation between East Antarctic temperatures and the SAM reversed in response to anomalously high pressure over the region (Marshall *et al.*, 2013).

The stacked and normalized temperature record for the East Antarctic stations (Figure 10b) is characterized by a small warming trend from the late 1950s to around 1990, followed by a decrease to 2018. However, because of the large variability in the temperatures over these two periods the trends are not significant, nor has there been a significant trend over the whole record.

Neumayer annual mean temperatures have a small, insignificant anti-correlation with the temperatures from Orcadas, Esperanza and Marambio, as the stations are on opposite sides of the Weddell gyre and there are often opposite SIC anomalies across the region. Zonal wind anomalies produce opposite sign temperature anomalies, for example, positive zonal wind anomalies favour Föhn warming on the eastern Peninsula, but a reduction in poleward heat flux and eastward sea ice drift at Neumayer.

4.3 | The Antarctic plateau and Ross ice shelf

The inter-annual variability of annual and seasonal mean temperatures at Vostok is as large as at any of the East Antarctic stations and is especially variable in winter. Temperatures during that season are particularly sensitive to the depth of the mid-tropospheric vortex, with a deep vortex and marked troughing near 135°E bringing relatively warm air to the station. Temperature variability at Amundsen-Scott station is also large during the winter, but also has large variability during the spring. Scott Base is located west of the Pole of Variability and, as a consequence, its annual and seasonal temperature variability is larger than at most of the coastal East Antarctic stations (Table 2).

Variability in SIC has little direct impact on the temperatures at the plateau stations, with the annual mean temperature only having a weak correlation with SIC through the inter-relationship between the SAM, temperature and sea ice. More specifically, higher temperatures on the Plateau are associated with the negative phase of the SAM, which implies a weak ASL and more (less) sea ice around the tip of the Antarctic Peninsula and less (more) over the Southern Amundsen Sea (Figure 4f).

The correlations between the annual and seasonal mean temperatures at Vostok and Amundsen-Scott are significant at $p < .05$, with the correlation being largest in summer when the planetary waves have their smallest amplitude and there are fewer incursions of maritime airmasses on a regional scale. However, Amundsen-Scott and Vostok annual mean temperatures have a correlation of 0.46, which is quite low for two stations of similar geography. Temperature variability at Vostok is strongly influenced by airmasses arriving at the station from the highest part of the plateau, which also affect Amundsen-Scott station. But other factors must play a role. In years of large SAM anomalies, such as 1980 when the SAM was especially negative, Vostok and Amundsen-Scott have consistent, large temperature anomalies (Figure 5c). The correlation between Amundsen-Scott and Scott Base annual temperatures is low at 0.21 because Amundsen-Scott annual mean temperatures are strongly influenced by airmasses arriving from the Weddell Sea, while Scott Base is more affected by air from the Ross Sea (Steinhoff *et al.*, 2009).

The 11-year running mean temperatures show a small cooling at the two plateau stations from the late 1970s to the late 1990s (Figure 7c), consistent with the SAM becoming more positive over this period, which would generally lead to lower temperatures. From the late 1990s all three stations experienced a small warming.

4.4 | Continent-wide variability

The variability of the temperatures on a continent-wide scale can be appreciated from the 5-year running mean temperature anomalies (relative to 1981–2010) for the 17 stations shown on a time—longitude plot (Figure 11). The most striking feature is the low temperatures experienced in the Antarctic Peninsula region up until about 1980. From our understanding of the relationship between temperatures in this region and the broadscale atmospheric circulation in the post-1979 period, this implies a relatively weak ASL and weaker northerly flow around the peninsula (Marshall and King, 1998). This allowed a greater northward extension of the sea ice resulting from more frequent southerly flow, which amplified the cooling by capping the ocean. Some of the largest negative temperature anomalies in the Antarctic records were at Vernadsky during the 1950s and 1960s, with the extensive sea ice during this period confirmed by reports from the station. The 1960s was a unique period when relatively low temperatures were recorded at a number of the stations around the coast of East Antarctica, as well as Vostok, and the correlation between the SAM and temperatures at these stations was negative (Figure 8).

Although the temperatures from the stations around the coast of East Antarctica have a high correlation over the full length of the records (Figure 9), there are periods
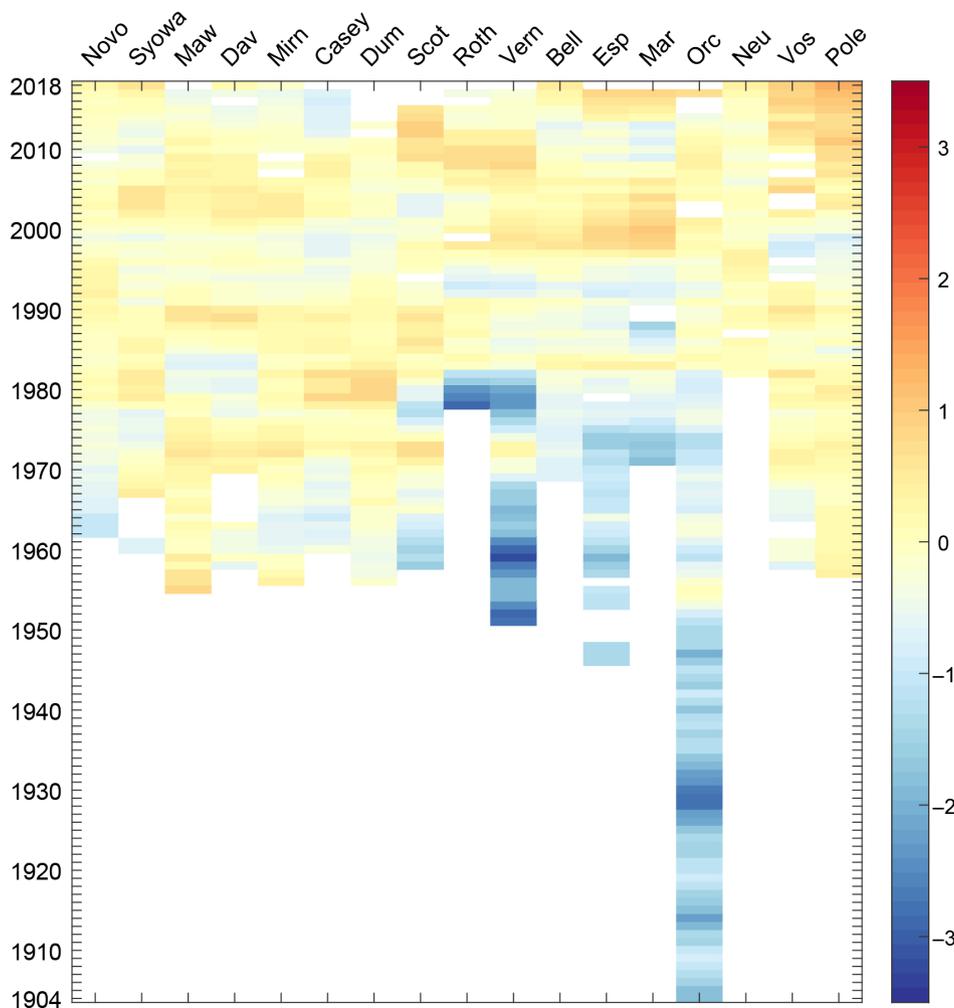
FIGURE 11 The 5-year running mean annual mean temperatures anomalies (from 1981 to 2010) for all the stations examined. The stations are indicated in an abbreviated form eastwards from Novolazarevskya, except for the two plateau stations that are included on the right [Colour figure can be viewed at wileyonlinelibrary.com]

when there are nonuniformities of the temperature anomalies between the stations. For example, in the early 1980s Novolazarevskya/Syowa had high temperatures and Mawson/Davis had low temperatures, pointing to localized meridional wind anomalies. These could be associated with ENSO variability (Clem *et al.*, 2018a); for instance, the strong 1982–1983 El Niño event would favour a weakened ASL/cooling on the Peninsula and increased cyclonic activity over the South Atlantic that would enhance warm northerly flow near Novolazarevskya/Syowa.

The long term warming at Orcadas was observed in all seasons (Figure S2), although the magnitudes of the anomalies were largest in autumn and winter. The warming at the Peninsula stations occurred in all seasons, but with the smallest anomalies in the summer when feedbacks from sea ice anomalies play a small part. Anomalies that span all longitudes around Antarctica are rather rare, as the signals from changes in the phase of the SAM and tropical forcing can result in contrasting temperature anomalies across the Antarctic Peninsula and over the rest of the continent.

5 | THE ANNUAL AND SEASONAL TEMPERATURE TRENDS

Since 1979 we can set the observed temperature trends within the context of changes in the atmospheric circulation and sea ice extent. During this period six of the stations experienced statistically significant ($p < .05$) trends in their annual mean temperatures: cooling at Casey ($-0.26 \pm 0.24°$ deg·dec^{-1}) and Dumont d'Urville ($-0.27 \pm 0.21°$ deg·dec^{-1}), and warming at Vernadsky ($+0.39 \pm 0.28°$ deg/dec), Rothera ($+0.38 \pm 0.34°$ deg·dec^{-1}), Orcadas ($+0.25 \pm 0.23°$ deg·dec^{-1}) and Amundsen-Scott ($+0.29 \pm 0.23$ deg·dec^{-1}) (Table 3). This pattern of change is largely consistent with the positive trend in the annual mean SAM index. However, the warming at South Pole, which is a current topic of investigation, is unexpected considering that the SAM has shifted into its positive phase.

Since 1979 the ASL has deepened (Figure 12), with previous studies suggesting that the development of the ozone hole and the shift of the IPO/PDO to its negative phase, resulting in frequent La Niña conditions, could have contributed to this change (Turner *et al.*, 2009;

Clem et al., 2017). The increase in northerly flow at Vernadsky is linked to the deepened ASL and increased anticyclonic circulation in the South Atlantic resulting from the increase in La Niña conditions after the late 1990s (Ding and Steig, 2013; Clem and Fogt, 2015).

During spring there has been an Antarctic-wide warming, with all but one station having experienced an increase in temperature, although the only trends that were significant at $p < .05$ were at Vostok (+0.60 ± 0.35° ·dec^{-1}), Scott Base (+0.56 ± 0.42° dec^{-1}), Vernadsky (+0.47 ± 0.40° ·dec^{-1}) and Amundsen-Scott (+0.53 ± 0.43° dec^{-1}).

During spring there has been a statistically significant warming across West Antarctica and the Antarctic Peninsula (Clem and Fogt, 2015) with a large part of this attributable to atmospheric circulation changes forced from the tropical Pacific. However, these authors suggested that multiple independent forcing mechanisms were operating making attribution difficult.

The large warming (+0.56 ± 0.42° dec^{-1}, $p < .05$) at Scott Base during spring stands out as the trends in other seasons and the annual data are all insignificant. In their modelling study, Clem et al. (2018b) showed that the spring warming at Scott/McMurdo and Marble Point, Ross Ice Shelf was caused by the cyclonic circulation in the Northern Ross Sea and associated warm air advection. This is consistent with negative IPO/PDO forcing.

Higher temperatures at Scott Base occur when the ASL is deep and located westward of its mean position over the Ross Sea, and warm air is advected from the Bellingshausen Sea and along the coast of West Antarctica into the Ross Sea. Low temperatures occur with relatively high MSLP and a slack pressure gradient across the region, allowing a strong surface inversion to develop and conditions with little cloud. Since 1979 there has been a trend towards the first scenario (Figure 12b) as MSLP in the Ross Sea region has decreased leading to a marked warming at the station, which has been linked to increasing SSTs in the western tropical Pacific associated with the IPO transition to its negative phase in the late 1990s (Clem et al., 2018a).

During summer the only station that experienced a temperature trend at $p < .05$ was Bellingshausen, where temperatures decreased at −0.18 ± 0.15°·dec^{-1}. During this season there has been a large shift of the SAM into its positive phase. However, there has been greater ridging over the Bellingshausen Sea, resulting in more cold air advection along the western side that has contributed to the cooling at Bellingshausen, as well as an insignificant cooling at Rothera.

During the autumn there has been a significant ($p < .05$) decrease in MSLP to the west of the Peninsula (Figure 12d). This was the largest seasonal MSLP trend in

TABLE 3 Annual and seasonal temperature trends for 1979–2018 (1982–2018 for Neumayer)

	Temperature trend (°C decade^{-1})				
Station	Annual	Spring	Summer	Autumn	Winter
Novolazarevskya	−0.04 ± 0.16	+0.11 ± 0.28	−0.13 ± 0.19	*−0.24 ± 0.27*	+0.09 ± 0.43
Syowa	−0.09 ± 0.22	+0.02 ± 0.31	−0.04 ± 0.18	*−0.34 ± 0.35*	−0.01 ± 0.47
Mawson	+0.08 ± 0.21	*+0.27 ± 0.27*	−0.11 ± 0.18	+0.08 ± 0.40	+0.26 ± 0.47
Davis	+0.10 ± 0.25	+0.23 ± 0.32	+0.04 ± 0.17	−0.02 ± 0.50	+0.02 ± 0.54
Mirny	−0.08 ± 0.20	+0.17 ± 0.29	−0.04 ± 0.22	−0.21 ± 0.38	−0.17 ± 0.43
Vostok	+0.21 ± 0.27	**+0.60 ± 0.35**	+0.11 ± 0.28	+0.05 ± 0.43	+0.13 ± 0.60
Casey	**−0.26 ± 0.24**	−0.00 ± 0.30	*−0.18 ± 0.17*	−0.29 ± 0.43	**−0.58 ± 0.51**
Dumont d'Urville	**−0.27 ± 0.21**	−0.04 ± 0.25	*−0.24 ± 0.25*	**−0.41 ± 0.31**	*−0.53 ± 0.52*
Scott Base	+0.11 ± 0.26	**+0.56 ± 0.42**	+0.05 ± 0.19	−0.26 ± 0.55	−0.00 ± 0.60
Rothera	**+0.38 ± 0.34**	+0.29 ± 0.42	−0.08 ± 0.15	**+0.50 ± 0.33**	*+0.68 ± 0.73*
Faraday/Vernadsky	*+0.39 ± 0.28*	**+0.47 ± 0.40**	+0.01 ± 0.16	*+0 .34 ± 0.22*	**+0.75 ± 0.63**
Bellingshausen	+0.09 ± 0.21	+0.11 ± 0.25	**−0.18 ± 0.15**	+0.21 ± 0.26	+0.21 ± 0.50
Esperanza	+0.23 ± 0.32	+0.25 ± 0.47	+0.07 ± 0.21	*+0.51 ± 0.55*	−0.09 ± 0.58
Marambio	+0.21 ± 0.36	+0.26 ± 0.55	+0.12 ± 0.26	+0.53 ± 0.68	−0.10 ± 0.68
Orcadas	**+0.25 ± 0.23**	+0.35 ± 0.42	+0.02 ± 0.17	+0.11 ± 0.35	**+0.58 ± 0.56**
Neumayer	−0.04 ± 0.20	+0.20 ± 0.39	+0.03 ± 0.26	−0.18 ± 0.40	−0.27 ± 0.52
Amundsen-Scott	**+0.29 ± 0.23**	**+0.53 ± 0.43**	+0.30 ± 0.37	+0.14 ± 0.40	+0.24 ± 0.49

Note: Significance is indicated as italic ($p < .10$), bold ($p < .05$) and bold and italic ($p < .01$).
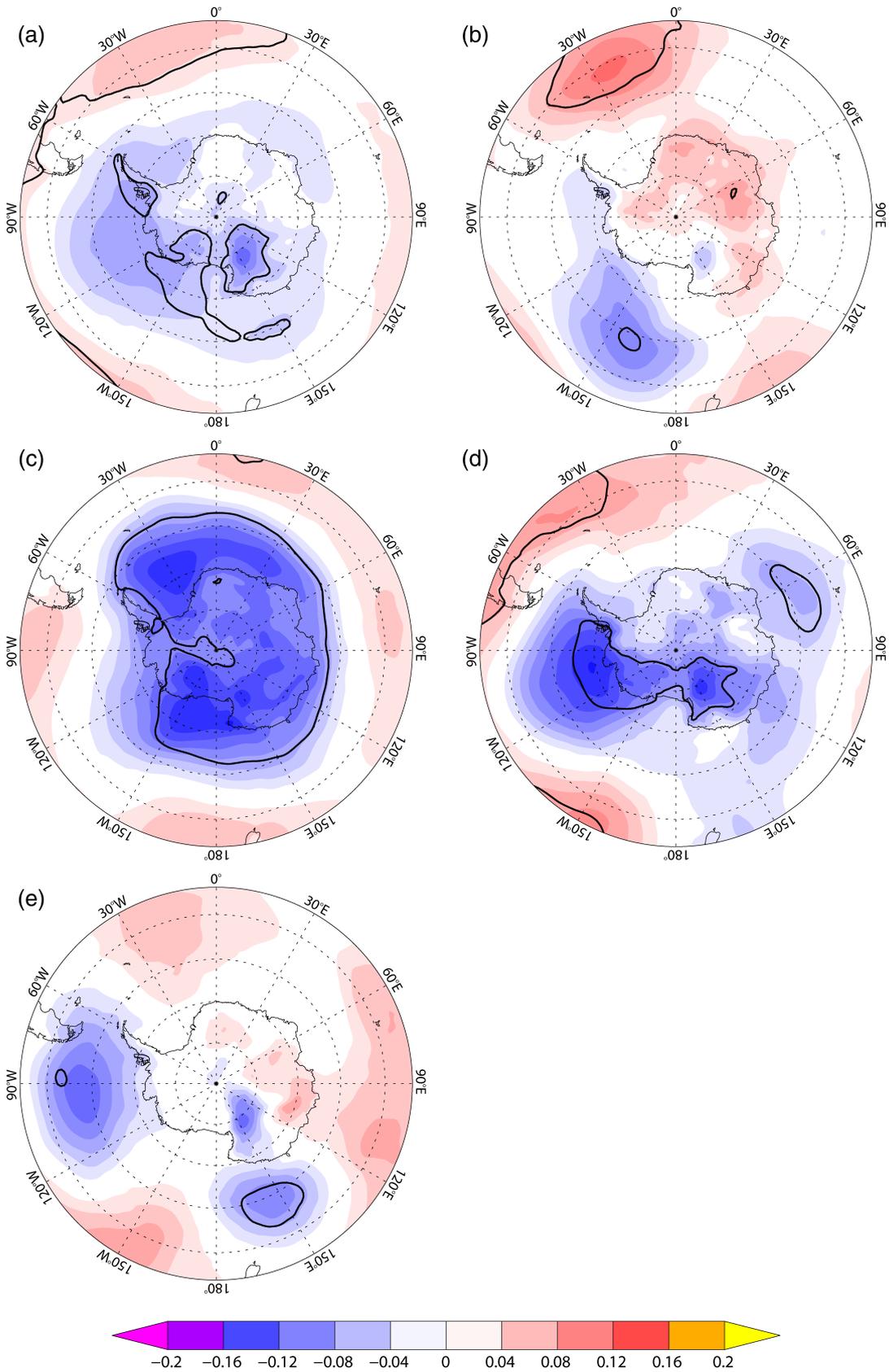
FIGURE 12 The trends in MSLP for 1979–2018. (a) Annual, (b) Spring, (c) Summer, (d) Autumn and (e) Winter [Colour figure can be viewed at wileyonlinelibrary.com]

the region and resulted in a decrease in SIC over the Bellingshausen Sea with a consequent impact on Peninsula temperatures. Vernadsky and Rothera temperatures increased by $0.34 \pm 0.22°\cdot dec^{-1}$ and $0.50 \pm 0.33°\cdot dec^{-1}$ respectively with the other stations warming at less significant rates. The only other station that experienced a temperature trend that was significant at $p < .05$ during this season was Dumont d'Urville. Here the cooling of $-0.41 \pm 0.31°\cdot dec^{-1}$ occurred as a result of greater offshore flow (Figure 12).

In the winter there has also been a decrease of MSLP to the west and northwest of the Peninsula, giving a reduction in sea ice, with Vernadsky and Rothera warming by $0.75 \pm 0.63°\cdot dec^{-1}$, and $0.68 \pm 0.73°\cdot dec^{-1}$ respectively. However, only the trend at Vernadsky was significant at $p < .05$. During this season Orcadas experienced its largest seasonal warming of $0.58 \pm 0.56°\cdot dec^{-1}$ ($p < .05$) when there was a trend to greater northerly flow.

Although no reliable atmospheric analyses are available before 1979 it is possible to infer some factors behind earlier changes, through an understanding of the mechanisms responsible for temperature variability and change since 1979 and a knowledge of the phase of the SAM in the earlier period. The largest significant changes over the full length of the records have been in the Antarctic Peninsula (Table 4), where there has been

a long-term warming at many locations. The six stations around the Peninsula all experienced a significant ($p < 0.05$) increase in their annual mean temperatures over their records, with many of the seasonal trends also being significant. Based on recent studies of the relationship between Peninsula temperatures and the atmospheric circulation, it seems likely that there has been a long-term increase in the northerly component of the wind across the region, leading to a decrease of sea ice over the Bellingshausen Sea. The shift of the annual mean SAM index to more positive values may have contributed to a decrease of MSLP in the Amundsen Sea region, but estimates of the SAM before 1957 vary. Tropical Pacific climate variability also affects the MSLP off West Antarctica and since the 1950s there has been an increase in SSTs across much of the tropical Pacific Ocean, with a greater frequency and intensity of El Niño events. While El Niño conditions are generally associated with higher MSLP in the region of the ASL, recent studies have shown that decadal variability in tropical Pacific SSTs associated with the IPO/PDO has contributed to a deepening of the ASL through a Rossby wave mechanism different from the traditional PSA modes associated with ENSO, which has also been linked to the warming across the Peninsula and at Scott Base (Clem and Fogt, 2015; Clem et al., 2018a).

TABLE 4 Annual and seasonal temperature trends over the full length of the records

Station	Temperature trend (°C decade^{-1})					Period
	Annual	**Spring**	**Summer**	**Autumn**	**Winter**	**Period**
Novolazarevskaya	**+0.13 ± 0.09**	**+0.21 ± 0.16**	+0.06 ± 0.12	0.04 ± 0.17	**+0.24 ± 0.24**	1961–2018
Syowa	+0.03 ± 0.13	+0.03 ± 0.18	+0.04 ± 0.11	−0.08 ± 0.20	+0.10 ± 0.26	1957–1961, 1967–2018
Mawson	−0.05 ± 0.10	+0.10 ± 0.14	*−0.08 ± 0.09*	−0.12 ± 0.18	+0.01 ± 0.23	1954–2018
Davis	+0.05 ± 0.14	+0.15 ± 0.19	+0.06 ± 0.10	−0.06 ± 0.26	−0.04 ± 0.27	1957–1964, 1969–2018
Mirny	+0.00 ± 0.10	*+0.15 ± 0.16*	−0.03 ± 0.11	−0.11 ± 0.20	+0.05 ± 0.22	1956–2018
Vostok	**+0.15 ± 0.13**	*+0.31 ± 0.20*	+0.11 ± 0.15	+0.01 ± 0.24	+0.11 ± 0.32	1958–2018
Casey	+0.00 ± 0.16	+0.12 ± 0.18	−0.06 ± 0.09	+0.00 ± 0.24	−0.03 ± 0.28	1959–2018
Dumont d'Urville	−0.02 ± 0.10	*+0.14 ± 0.14*	+0.00 ± 0.11	**−0.27 ± 0.16**	−0.00 ± 0.24	1956–2018
Scott Base	**+0.22 ± 0.15**	**+0.39 ± 0.25**	+0.08 ± 0.13	+0.12 ± 0.27	+0.16 ± 0.30	1957–2018
Rothera	**+0.44 ± 0.33**	**+0.46 ± 0.42**	+0.02 ± 0.15	**+0.53 ± 0.31**	**+0.83 ± 0.67**	1977–2018
Faraday/Vernadsky	**+0.46 ± 0.15**	**+0.30 ± 0.17**	**+0.16 ± 0.08**	**+0 .47 ± 0.19**	*+0.89 ± 0.32*	1951–2018
Bellingshausen	**+0.17 ± 0.15**	+0.03 ± 0.17	−0.02 ± 0.10	*+0.26 ± 0.18*	**+0.35 ± 0.34**	1969–2018
Esperanza	**+0.29 ± 0.13**	+0.19 ± 0.17	**+0.29 ± 0.09**	**+0.36 ± 0.23**	+0.21 ± 0.26	1945–2018
Marambio	**+0.34 ± 0.25**	+0.15 ± 0.38	**+0.22 ± 0.18**	+0.63 ± 0.50	+0.26 ± 0.52	1971–2018
Orcadas	**+0.19 ± 0.06**	**+0.18 ± 0.08**	**+0.14 ± 0.03**	**+0.19 ± 0.09**	**+0.29 ± 0.13**	1903–2018
Neumayer	−0.04 ± 0.20	+0.20 ± 0.39	+0.03 ± 0.26	−0.18 ± 0.40	−0.27 ± 0.52	1982–2018
Amundsen-Scott	+0.09 ± 0.10	*+0.21 ± 0.22*	+0.11 ± 0.19	+0.09 ± 0.19	−0.01 ± 0.25	1957–2018

Note: Significance is indicated as italic ($p < .10$), bold ($p < .05$) and bold and italic ($p < .01$).

Most of the stations around the coast of East Antarctica have not recorded significant trends in their annual or seasonal mean temperatures since their records began. An exception is the significant increase in the annual ($+0.22 \pm 0.15°·\text{dec}^{-1}$, $p < .01$) and spring ($+0.39 \pm 0.25°·\text{dec}^{-1}$, $p < .01$) temperatures at Scott Base.

6 | DISCUSSION AND CONCLUSIONS

By far the largest changes have been recorded by the Antarctic stations over recent decades have been on the Northern Antarctic Peninsula where there was a marked warming during the second half of the Twentieth Century, followed by a statistically significant cooling in the first decade of the 21st century. The ASL has played a large part in driving change across the Peninsula by altering the meridional component of the wind, which in turn has altered the SIC and consequently the flux of heat from the ocean. Around the Peninsula the long-term shift of the SAM into its positive phase and the increase in the strength of the westerly winds has had a major effect. In recent decades, the loss of stratospheric ozone has contributed to a positive trend in the SAM index during the summer. The stronger westerlies have led to relatively warm air masses crossing the high orographic barrier of the Peninsula and arriving on the ice shelves, with the Föhn effect increasing the temperatures and contributing to their disintegration over the Northern areas. The impact of the deeper ASL has also affected temperatures in the Southern Ross Sea, with Scott Base having experienced a warming that has not been recorded at the other stations around the coast of East Antarctica. The deepened ASL and resultant warming across the Peninsula and at Scott Base has been attributed to tropical Pacific decadal variability, while cooling around the coast of East Antarctica is tied to the shift of the SAM into its positive phase that has reduced the poleward heat flux and contributed to the small temperature trends over recent decades.

The station data, along with satellite observations, reanalysis fields and AWS measurements, have been used in efforts to estimate changes in temperatures in the interior of the continent back to the IGY. These have highlighted a large warming over the interior of West Antarctica that was not apparent from the station data alone. In particular, it is quite distinct from the temperature trends observed across the Antarctic Peninsula and on the Ross Ice Shelf. The patched Byrd record shows one of the largest warming trends in the Southern Hemisphere, which has taken place in spring, summer and winter (Bromwich *et al.*, 2013). The warming has been linked to warm air advection into the interior from the South Pacific.

Recent research has shown that the temperature trends observed at the stations over recent decades have been strongly influenced by the more positive SAM and changes in the tropical Pacific SSTs. However, there are still a number of questions regarding how ocean conditions in various parts of the world influence Antarctic temperatures. There are a number of modes of variability of tropical SSTs and how these interact and influence Antarctic temperatures are still unclear, largely due to the relatively short records. Correctly, representing all these processes within climate models is a high priority and it is essential that the in situ observation programmes continue or are expanded, to allow further investigation of Antarctic climate variability and for model validation and development.

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