Chapter

The Climate of the Antarctic Peninsula during the Twentieth Century: Evidence from Ice Cores

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Abstract

The Antarctic Peninsula (AP) is a region of special climatological interest. The late twentieth century has been a period of warming surface temperatures, enhanced mass loss from melting glaciers and increased snowfall, which have a direct and measurable impact on global sea levels. However, the observational period for Antarctica is short. Observational records only began in the 1940s and much of our understanding of the wider spatial climate variability and glacial dynamics is limited to the satellite era (post 1979). Proxy records, such as those from ice cores, provide an invaluable tool to place these recent changes in context of the past few hundred years, allowing us to investigate climate variability over the entire twentieth century and beyond. In this chapter we review the climate of the AP during the twentieth century, as captured by the instrumental records, and extend our understanding of climate variability over the twentieth century based on climate proxies contained in ice cores. For this study we focus on stable water isotopes and snow accumulation and how they are influenced by changes in atmospheric circulation and sea ice conditions.

Keywords: Antarctic Peninsula, ice cores, climate, sea ice, surface mass balance

1. Introduction

The Antarctic Peninsula (AP) is the only landmass that cuts across the sub-Antarctic zone, transecting the circumpolar trough and forming a partial bridge between the Antarctic ice sheet and South America. Moreover, the AP forms a barrier to the strong south-westerly winds in the lower troposphere, separating the maritime climate from the Bellingshausen Sea from the continental climate on the Weddell Sea side [1–3]. These features highlight the AP as a unique observational platform to study the climatic interaction between low and high latitudes in the Southern Hemisphere. Indeed, climate records from this region add valuable information to understand how heat is transferred and how this has varied over time.

Instrumental observations in the AP are sparse and relatively short, only supported by a network of meteorological stations since the late 1940s [4]. The lack of long-term observational records hinders the possibility to put modern observations into a climatic perspective. However, ice cores retrieved from this region offer the possibility to evaluate climate over longer timescales. Chemical constituents and physical properties preserved in ice cores can be calibrated with meteorological and environmental observations to develop climatic reconstructions based on proxy records [5].

In this chapter, we evaluate the climate of the AP in recent decades, as expressed in the instrumental records, and highlight the important contribution that ice cores have made in expanding our understanding of climate variability over decadal to centennial timescales. We focus on two well-established ice core proxies (1) stable water isotopes, a proxy for past surface temperatures and (2) snow accumulation, a proxy for precipitation. We also demonstrate how both of these parameters have allowed us to investigate changes in large-scale atmospheric circulation beyond the instrumental period.

2. Climate of the Antarctic Peninsula during the twentieth century

2.1 Antarctic Peninsula ice cores

The AP is a region of high snow accumulation, capturing the seasonal deposition of chemical species in the ice [15], which when coupled with known volcanic horizons, allow high accuracy in the dating [16]. A significant advantage of the AP is that surface temperatures coincide with air temperature during cloud condensation, allowing a direct reconstruction of surface temperatures using stable water isotopes [17]. The best sites for ice core drilling are located on ice rises on the east coast, on ice domes, or on the central AP ice divide, where ice disturbance by deep flow is minimum [15, 17].

Since the mid-1970s, several ice cores have been drilled in the AP [6, 7, 9–11, 17–19]. The high annual accumulation, especially on the western coast, limits the temporal range of ice cores in this region, with only a few extending beyond the first half of the twentieth century (**Figure 1**; **Table 1**). The significantly different climatic regimes that prevail on each side of the AP makes it necessary to group these ice cores as west-coast regime and east-coast regime. In this chapter, we will focus our study on the ice cores retrieved from the western side of the AP.

2.2 Surface temperature

The surface temperature records are available from instrumental records at manned research stations and automatic weather stations, as global reanalysis data and obtained via remote sensing during the satellite era. In ice cores the stable water isotope record has been used as a proxy for past surface temperatures over centennial to millennial timescales.

2.2.1 Observations

Long-term trends in surface temperatures show that most of Antarctica has been warming since the records began [4]. The largest warming trends in the continent are concentrated on the western and northern parts of the AP [20–22], a region that exhibits the largest inter-annual variability in the whole continent [4]. Temperature measurements in Antarctica began in the early twentieth century [4] with the greatest density of records in the AP. The AP network includes the longest continuous Antarctic temperature record (Orcadas Station, South Orkney Islands), which extends back to 1903 [16]. After the International Geophysical Year (1957–1958), over a dozen permanent stations began to continuously record meteorological parameters. In addition to the station network, since the early 1980s, several Automatic Weather Stations (AWS) have been deployed in the region. These stations have helped to improve the spatial coverage of meteorological observations, as well as providing data from remote locations [4].

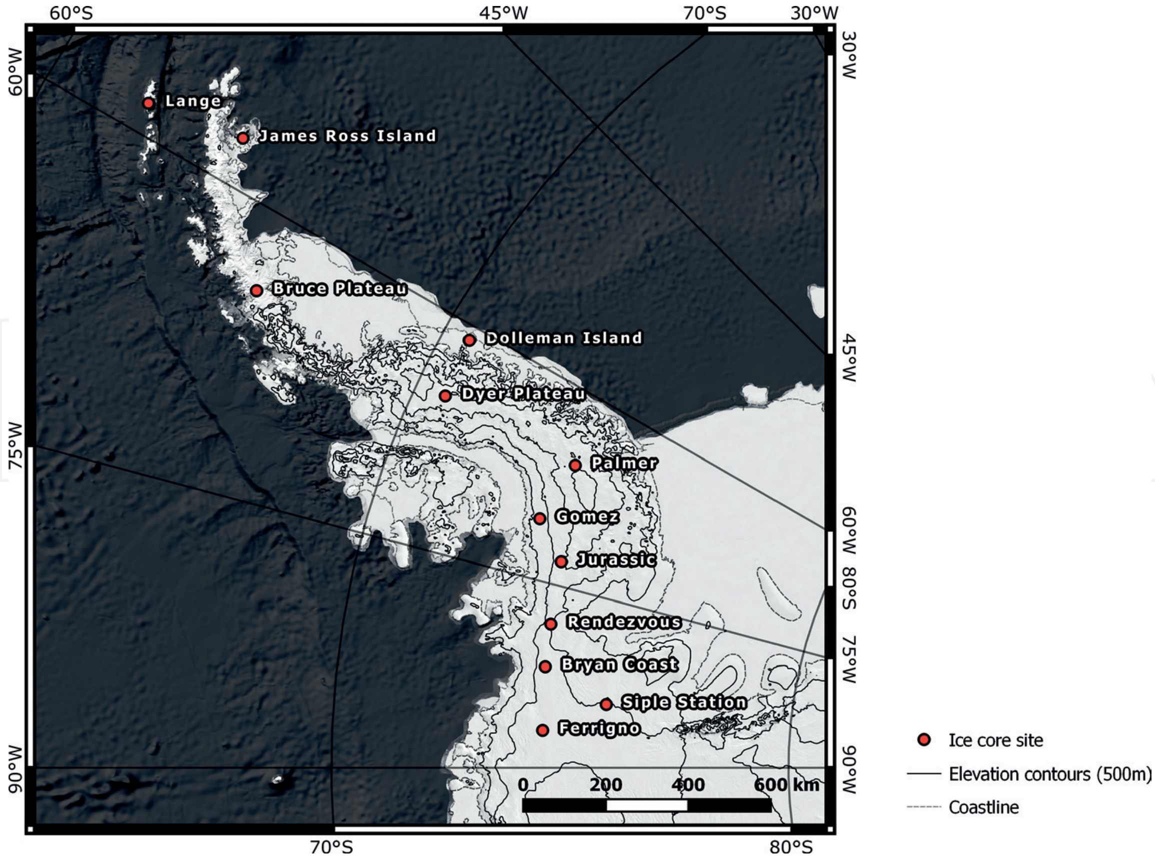

Figure 1.
Map of the Antarctic Peninsula showing the location of ice cores that extend back to the early twentieth century and beyond.

Site name	Longitude	Latitude	Elevation (m a.s.l)	Depth (m)	Data span (AD)	Data source
West coast regime						
Lange	−58.61	−62.11	690	50	1918–1995	[6]
Bruce Plateau	−64.07	−66.03	1976	448	1750–2009	[7, 8]
Dyer Plateau	−64.87	−70.67	2002	190	1504–1990	[9]
Palmer	−65.46	−73.86	1897	–	–	[10]
Gomez	−70.36	−73.59	1400	136	1858–2006	[11]
Jurassic	−73.06	−74.33	1139	–	–	[10]
Rendezvous	−78.16	−74.45	1006	–	–	[10]
Bryan Coast	−81.67	−74.49	1171	140	1712–2010	[10, 12]
Siple Station	−84.25	−75.92	1054	302	1410–1985	[13]
Ferrigno	−86.90	−74.57	1350	136	1703–2010	[10]
East coast regime						
James Ross Island	−57.68	−64.20	1542	364	~14,000 (year BP)–2007	[14]
Dolleman Island	−60.93	−70.58	398	133	1795–1986	[15]

Table 1.
Summary information for ice core sites.

The longest surface temperature record, from Orcadas Station, exhibits a trend of +0.21°C per decade since 1904 [22] with evidence from several stations of a significant warming since the early 1950s [22]. Most notably, the largest statistically significant trend of +0.54°C per decade observed on Faraday/Vernadsky station (1951–2011). Radiosonde data indicates that the largest warming has been confined to the lowest layers of the atmosphere (mainly the lower troposphere) [23]. The largest warming occurs during winter, with trends reaching up to +1.01°C per decade between 1950 and 2011 [24] and the greatest monthly temperature rise has been recorded in July (+1.7°C per decade between 1979 and 2007) [24]. Ultimately, the winter warming has caused an overall decrease in the annual temperature range and a change in the seasonal cycle [4].

Despite the strong regional warming trends measured in western AP in the late twentieth century, the annual mean temperature since the 1990s (1999–2014) has decreased at a statistically significant rate (<5% level), with the most rapid cooling during the summer season [25]. Additionally, Turner et al. [25] suggests that the rapid warming in the AP since the 1950s and subsequent cooling since the late 1990s are part of the large natural decadal-scale climate variability of the region. These findings highlight the need for longer surface temperature records to set the recent changes in a longer-term perspective and to assess the regional climate variability.

2.2.2 Ice cores

Ice cores from western AP provide climate records that extend back up to 600 years (**Table 1**). The linear relationship between local surface temperatures and stable isotopes in precipitation, at middle and high latitudes, allows us to reconstruct past surface temperatures from ice cores [26]. This approach has been applied at several locations in Antarctica over centennial to millennial timescales [27–30].

Isotopic temperature proxy data spanning the twentieth century is available from five ice core sites in the AP region (Bruce Plateau, Dyer Plateau, Gomez, Siple Station and Ferrigno) (**Figure 2**). A strong correlation between surface temperature measurements and temperatures reconstructed from ice cores (except for Dyer Plateau [9]), confirm the use of these records as valid proxies for local and regional temperatures on the west AP. A combination of these five ice cores provides a north–south transect along the AP which can be used to study latitudinal changes in the AP.

The five temperature proxy records do not provide a perfectly consistent picture of climate variability in the AP in the last five centuries. There are periods when most of the cores exhibit a similar temperature trend, but also periods when they show opposing trends. This probably reflects the degree to which ice core sites capture local and regional variability and the imprint of local high-frequency processes that complicate the interpretation [9]. The consistent feature is the recent rapid change in the isotopic composition, likely associated with the twentieth century warming trend measured in the meteorological record. For example, the reconstructed warming from Gomez ice core (+0.055°C per year) is consistent with the warming observed at Faraday/Vernadsky station (+0.054°C per year) (1955–2005) [31].

Overall, temperatures reconstructed from ice cores in the western AP show large inter-annual to inter-decadal variability [22, 31]. In particular, the onset of the warming since the 1950s in the southern cores (Gomez, Ferrigno and Siple Station) is delayed compared to the northern sites (Bruce Plateau and Dyer Plateau) and less pronounced at Siple Station [9, 13]. This could indicate that changes in the conditions in the northern AP did not impact the southern AP until some decades after [8]. Another consistent aspect among these records is a general cooling trend from ~1840/1850 to ~1920/1930 (absent in Siple Station ice core).

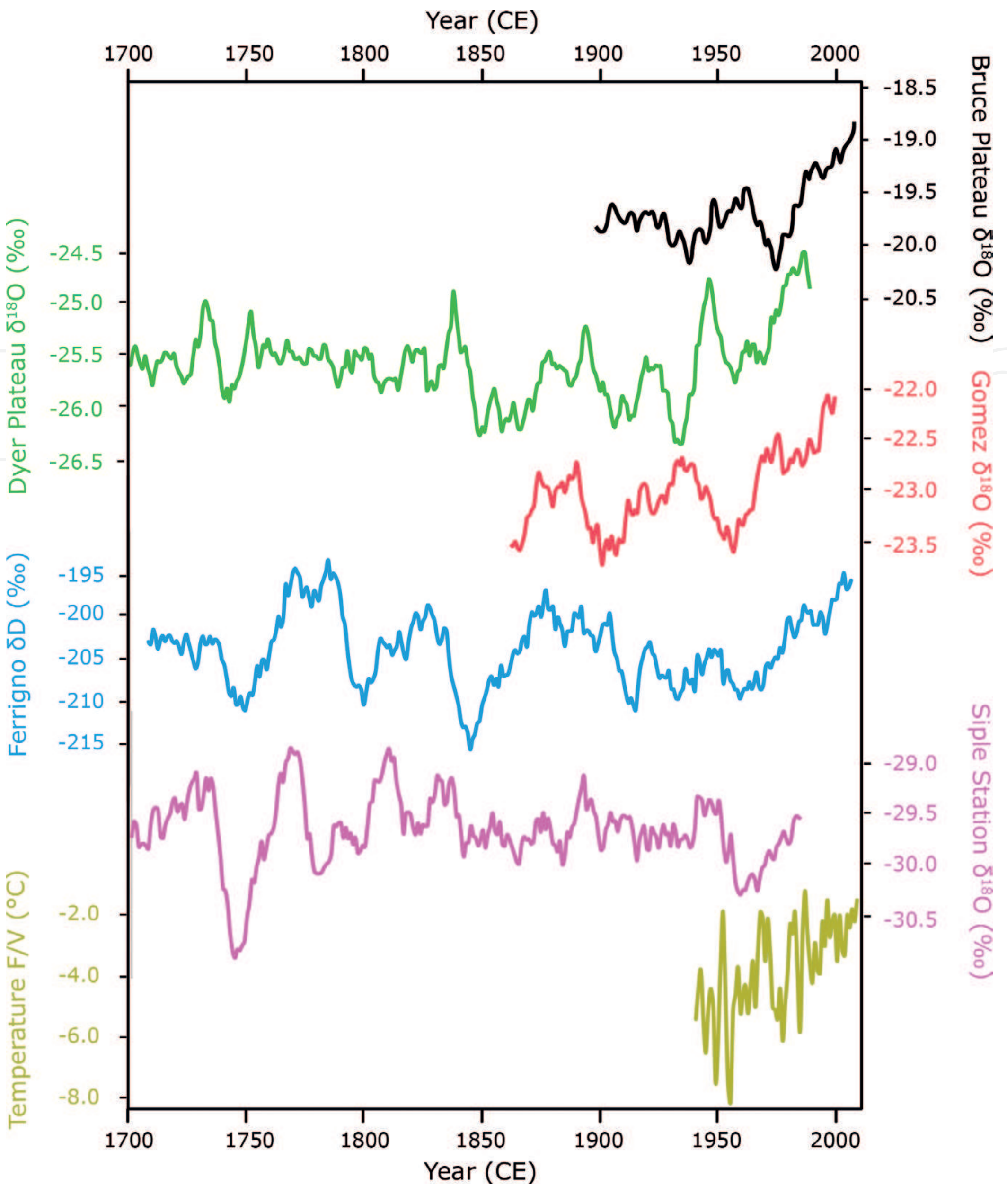

Figure 2.
11-year running mean isotope temperature proxies from ice cores in the AP region and annual mean surface temperature record from Faraday/Vernadsky Station (F/V), between 1700 and 2010.

Even though some records identify the last decades of the record as the warmest of the last centuries (Dyer Plateau and Gomez) [9, 31], others show larger warming trends and warmer decades occurring in the last centuries (Bruce Plateau, Ferrigno, Siple Station) [8, 9, 19]. In particular, in the Ferrigno ice core, Thomas et al. [19] reported larger 50-year warming trends occurring in the middle to late eighteenth century and in the middle nineteenth century. The analysis of the Ferrigno core revealed a reduction in the multi-decadal variability of surface temperatures during the twentieth century and suggested that the warming since the 1950s has not yet taken the system outside the natural range of climate variability [19].

Ice core temperature proxy records from the AP have provided evidence that the warming measured in the instrumental period is not just a local coastal phenomenon, but part of a regional warming trend covering the whole AP and extending back to the early twentieth century. Finally, they have proved that the current warming trends are not unprecedented in the last three centuries, suggesting that in some places the warming still remains within the range of natural range of climate variability.

Several authors have studied the possible drivers of the recent isotopic warming (see [30] and references therein) including the influence of atmospheric circulation and local sea ice conditions (see Section 2.4).

2.3 Snow accumulation

Antarctic surface mass balance (SMB) is the sum of all mass gains (snowfall) and mass losses (drifting snow erosion/deposition, sublimation and melt) from the surface of the Antarctic ice sheet.

2.3.1 Observations

Measuring SMB, in the AP is complicated as high precipitation and complex orography limit the availability of observational data. Remote sensing techniques such as Gravity Recovery and Climate Experiment (GRACE) [32] and radar backscattering struggle to capture the small-scale features of the AP, while inverse methods of calculating SMB, including estimating mass discharge and elevation changes from satellite altimetry [33] require surface observations to correct for firn process.

Regional atmospheric climate models have proved reliable in simulating SMB over the Antarctic ice sheet [34, 35] and over the AP at high (14 km) resolution [36]. In addition, global reanalysis products have been used to approximate Antarctic SMB based on the spatial and temporal variability in precipitation-evaporation (P-E). The European Centre for Medium-range Weather Forecasts (ECMWF) ERA-40 reanalysis, has been shown to correlate with ice core accumulation records from West Antarctica [37], the southern Antarctic Peninsula [38] and across the majority of the Antarctic Peninsula [39]. The updated ECMWF reanalysis product, ERA-interim, has improved model physics with observational data supplemented by ECMWF's operational archives and been shown to represent snow accumulation at several sites across the southern AP and Ellsworth Land [10]. A recent study testing the performance of reanalysis and regional atmospheric climate model products, against over 3265 multiyear in situ observations, concluded that ERA-interim was the most reliable record of interannual precipitation compared with observations across the whole ice sheet [40]. While in terms of absolute snow accumulation observations the Regional Atmospheric Climate Model RACMO2.3 performed best.

RACMO2.3 is forced at its lateral atmospheric boundaries by ERA-interim reanalysis and at its lower ocean boundaries by sea ice fraction and sea surface temperature and been used to reconstruct AP SMB at ~5.5 km resolution for the period 1979–2014 [41]. The model reveals a large accumulation gradient across the AP, with precipitation on the western AP in excess of 3000 mm we year^{-1}, while the eastern AP receives less than 500 mm we year^{-1}. The average ice sheet integrated SMB, including ice shelves is estimated at 351 Gt year^{-1} [41].

During the observational period (1979–2014), there is no significant trend in either the reanalysis P-E data [40] or the modeled SMB from RACMO2.3 [41]. However, a recent compilation of Antarctic ice core snow accumulation records, regressed onto the SMB fields from RACMO2.3, concluded that SMB in this region has been increasing during the twentieth century [42, 43].

2.3.2 Ice cores

Antarctic SMB studies had largely dismissed the influence of the AP due to the lack of observational data. However, recent drilling efforts have greatly improved the spatial coverage in this region and demonstrated its importance in terms of total

Antarctic SMB. A compilation of all available ice core snow accumulation records revealed that SMB in the AP has increased at a rate of 12 Gt year^{-1} since 1900 [42]. This equates to a 138 ± 58 Gt year^{-1} (~20%) increase between the decadal average at the start of the twentieth century (1901–1910) and the decadal average at the start of the twenty-first century (2001–2010).

The dominant moisture source for the AP is the Amundsen Sea [10, 44], a region of high synoptic activity and the largest contributor to the total Antarctic meridional moisture flux [45]. High snow accumulation on the western AP is associated with reduced sea level pressure in the Amundsen Sea, leading to strengthened circumpolar westerlies and enhanced onshore flow of moist air masses originating from the mid-latitudes. Snow accumulation in the AP is related to the frequency of cyclones originating from low-latitudes over the South Pacific Ocean [46].

All AP ice cores reveal an increasing trend in snow accumulation during the twentieth century (**Figure 3**). The largest of which was reported at Gomez, where snow accumulation rates have doubled in the period 1850–2007 [11]. This positive trend is also evident as far south as the Ellsworth Land coast (Ferrigno and Bryan coast), but is not observed in other parts of west Antarctica which reveal little or no trend during this period [12]. The three southern ice core records are highly correlated with each other, and with reanalysis data and modeled SMB [42], suggesting they are representative of regional precipitation and SMB. Using a composite of the three records revealed that after 1919 the running decadal mean exceeds the baseline average and remains there for the entire twentieth century. The trend accelerates after 1984, when annual average snow accumulation values more than double that observed for the previous ~270 years [12]. The Bruce plateau ice core confirmed that the northern AP has also experienced an increase in snow accumulation during the late twentieth century, increasing at a rate of 0.19 mm we year^{-1} since the 1950s [7], but the onset of the increase appears considerably later than that observed at the southern sites.

Prior to 1900 AD, the southern records (Bryan Coast, Ferrigno, Siple Station) suggest a period of relatively stable SMB, with a slight but not statistically significant negative trend (1750–1900). However, contrasting positive and negative trends (1750–1900) are observed at the two northern sites of Dyer Plateau and Bruce Plateau respectively [8].

2.4 The role of atmospheric circulation on AP climate

Atmospheric circulation describes the large-scale movement of air masses around the globe. It creates the winds and, together with oceanic circulation, is responsible for the transfer of the earth's thermal energy. Atmospheric circulation has a number of preferred modes of variability, such as El Nino Southern Oscillation (ENSO), the Southern Annular Mode (SAM) and the Pacific Decadal Oscillation (PDO), all of which influence the climate of the AP.

Major large-scale modes of atmospheric circulation have associated indices, calculated from meteorological data obtained from stations, climate re-analysis and from proxy records obtained from ice cores.

2.4.1 Observed changes in atmospheric circulation

The primary mode of atmospheric circulation in the Southern Hemisphere high latitudes is the SAM. This is a circumpolar pattern of atmospheric mass displacement which describes how the strength and location of the mid-to-high meridional pressure gradient change through time. These changes occur in a non-periodic way,

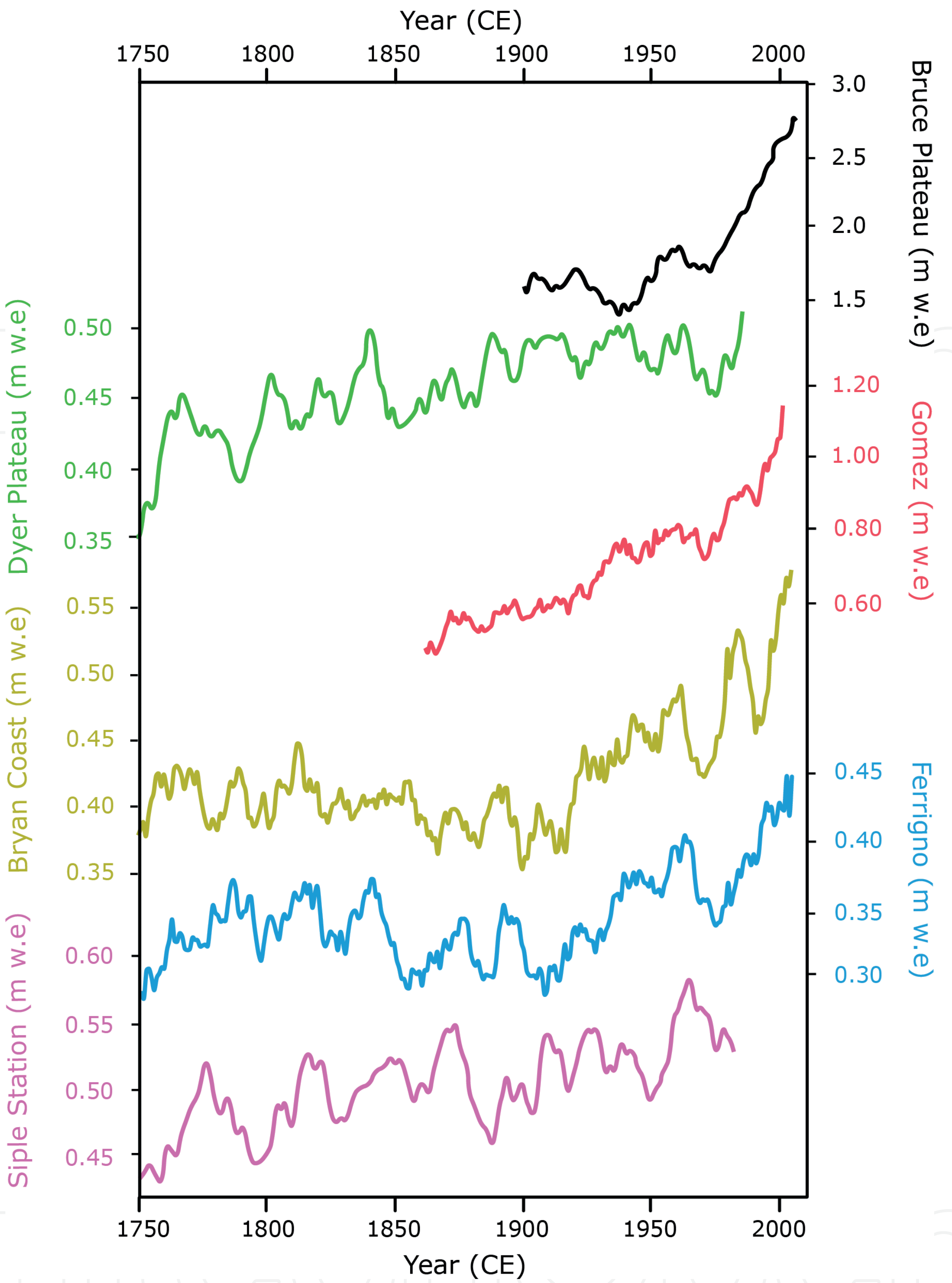

Figure 3.
11-year running mean of annual snow accumulation in ice cores from the AP region between 1750 and 2010.

varying within a range of days up to years [22]. Quantitatively, the SAM index is the difference of the zonal mean sea level pressure between records from six meteorological stations located in the mid-latitudes (around 40°S) and six stations in the Antarctic coast (around 65°S) [47]. A positive phase of SAM occurs when pressures around Antarctica are lower than pressures in the mid-latitudes. Conversely, a negative phase occurs when pressures over Antarctica are higher than pressures in the mid-latitudes.

Since the late 1970s, the SAM has trended into a positive phase, especially in the austral summer and autumn [47–49]. This has led to stronger circumpolar westerly winds over the Southern Ocean. In particular, during this period, the strength of the westerly winds has increased by 15–20% [50, 51] and it has been coupled with a poleward migration of the westerlies by 1–2° of latitude [22]. These two variations have impacted the cyclonic events south of 40°S, decreasing their frequency and increasing their intensity [52]. Furthermore, these new conditions have led to a deepening trend of the Amundsen Sea Low (ASL), a migrating climatological low-pressure center located over the Amundsen-Bellingshausen Seas, which strongly influences the climate in the Southern AP and the coast of West Antarctica [24]. The recent deepening trend of the ASL has produced the increase of meridional (onshore) winds that transport warm and moist air to the coast of Southern AP and West Antarctica, keeping this region mild compared to others at similar latitudes [53]. Overall, these changes caused by SAM, constitute one of the strongest climatic trends in the Southern Hemisphere over the last decades [54–56].

Another source of atmospheric circulation variability in the AP is ENSO, an inter-annual climatic variation over the tropical eastern Pacific Ocean which has impacts atmospheric conditions across the Pacific Basin and beyond [4]. The strength and phase of ENSO are commonly measured using the Southern Oscillation Index (SOI), calculated as the difference in sea level pressure between Tahiti Station and Darwin Station (Australia). Generally, ENSO events peak during September through February [57]. The way in which ENSO impacts the climate from the AP is through a teleconnection that causes a high latitude response, in the South Pacific-Drake Passage region, to tropical changes [57], intensifying climate variations depending on the SOI phase. In the last decades, ENSO teleconnection has shown marked decadal variability, presenting a weak teleconnection during the 1980s, while a strong teleconnection during 1990s [58, 59].

2.4.2 Influence of atmospheric circulation on stable water isotopes and snow accumulation

The recent strengthening in the circumpolar westerlies, associated with a positive phase of the SAM [48], has enhanced the meridional winds, drawing warm moist air to the western AP and influencing inter-annual temperature variability in ice core sites [19]. Indeed, at Gomez, approximately a third of the variability in annual mean surface temperatures (1957–2005) may be attributed to changes in the SAM [31] while it is responsible for a quarter of the snow accumulation increase (1957–2005). However, at all sites the relationship between SAM and both stable water isotopes and snow accumulation is not temporally stable.

Tropical sea surface temperatures (SST) influence atmospheric circulation in the Amundsen Sea region through the generation of a large-scale atmospheric wave train [60, 61]. This relationship is observed during the observational period (post 1979) as strong positive correlations between SMB in the AP and SSTs in the western tropical pacific associated with ENSO [12]. The snow accumulation records from the southern AP (Gomez, Ferrigno, Bryan Coast) reveal a strong negative ENSO-like pattern since 1980, which is not stable when extending the record to the past. Likewise, running decadal correlations of snow accumulation and SOI exhibit a positive correlation since 1980, but periods of insignificant and even negative correlations when extending over the full SOI record (1882–2010).

However, at the southern sites (Gomez, Ferrigno, Bryan Coast) snow accumulation does exhibit a positive correlation between tropical SSTs and surface pressure in the sub-tropical pacific that is not related to ENSO [19, 60]. This pattern appears stable back until at least ~1850s with the trend in snow accumulation, at least for the southern AP cores, consistent with reconstructed SSTs [12].

At Ferrigno, the stable water isotope record is positively correlated with proxy SSTs from coral growing at Rarotonga, in the sub-tropical pacific. The positive correlation remains throughout the past 240 years, with synchronous warm and cold periods observed [19]. This, together with the relationships observed between snow accumulation, suggests that changes in the tropical Pacific, not directly related to ENSO, are also driving high-latitude circulation.

In the northern AP, the Bruce Plateau snow accumulation record is modulated by climate variability in the tropical and subtropical regions, impacting this location through changes in the strength and position of the circumpolar westerlies [7]. The interplay between the phases of SAM, SOI and PDO proposed to explain the multi-decadal behavior between snow accumulation and large-scale atmospheric oscillations during the twentieth century.

An example of this is the relationship between the snow accumulation record and SAM indices. The relationship is positive and statistically significant ($R > 0.5$, $p < 0.001$) from 1971 to 2009, but not temporally stable over the last century, showing a sharp transition from positive to negative between 1950 and 1973 [7]. They explain this longer-term instability by changes in the strength of the tropical Pacific influence over the region. In particular, their results show that there is a stronger tropical Pacific (SOI) influence, over the snow accumulation record, when SAM and PDO are negative, while SOI remains on a positive phase (La Niña-event). Their results support the idea of an ENSO teleconnection modulated by SAM, but also by the phase of the PDO.

It appears that the coupling between modes of variability modulates snow accumulation in the AP [58] and may explain the acceleration in snow accumulation since the 1990s when both ENSO and SAM modes are in-phase.

The direct impact of changes in atmospheric circulation on parameters such as surface temperature and snow accumulation allow ice cores to record these changes over longer time scales. Providing their air-mass source region, or the transport pathway that they follow, is located within the region affected by the circulation changes. Backward trajectories studies have helped to determine the source region and transport pathways of all air masses reaching ice core locations [10, 38]. Even though the trajectories present a seasonal migration, their spatial coverage suggests that ice core records from this region are sensitive to changes in the ASL region [10] and the larger hemispheric scale atmospheric circulation (such as SAM and ENSO), which govern it [53]. Some ice cores from this region are better recording these changes and providing time series to study the atmospheric variability through time [7].

2.5 The role of sea ice on AP climate

Sea ice plays a major role in modulating global and regional climate. It alters the albedo of the Earth's surface and forms a barrier to the relatively warm surface ocean and the atmosphere above it. Changes in sea ice conditions can impact the availability of surface level moisture and the isotopic composition of air masses passing over it.

2.5.1 Observed changes in sea ice

Sea ice conditions are measured remotely, generated from brightness temperature data and passive microwave data collected by satellites. Sea ice conditions are commonly presented as (1) sea ice area, the portion of a grid cell covered by ice, (2) sea ice concentration (SIC), calculated as the percentage of ice cover within a 25 km^2 data cell or (3) sea ice extent (SIE), calculated as the northernmost latitude where sea ice concentration is 15% or greater.

During the observational period (1970 onwards), the total Antarctic sea ice area, calculated as the total area covered by ice, has increased [24, 62]. At a regional scale, however, there are marked differences. In the Weddell Sea and the Ross Sea sectors sea ice has increased, while the Bellingshausen Sea, and adjacent to the AP, there has been a significant decrease in sea ice.

2.5.2 Influence of sea ice on stable water isotopes and snow accumulation

The reduction in sea ice in the Bellingshausen and Amundsen Sea has been linked to the increased surface warming and increased snow accumulation on the western AP [7, 12, 63]. It has also been suggested that variations in sea ice can directly alter the isotopic composition of continental snow, based on the interaction between sea ice and surface exchange [64, 65]. The isotopic signal associated with water evaporated from the sea ice zone is believed to be deposited locally and thus the influence on stable water isotopes is expected to be greatest at coastal locations [65]. Indeed, at the Ferrigno site the relationship between stable water isotopes and sea ice in the Amundsen Ross sea is comparable with the relationship between stable water isotopes and site temperature [19].

Reduced sea ice results in enhanced availability of surface level moisture and increased poleward atmospheric moisture transport [45]. This results in greater snow accumulation, particularly at coastal sites, and this mechanism has been used to explain the longitudinal differences in AP snow accumulation trends during the twentieth century [12], with the greatest changes observed at sites where the adjacent sea ice decline is largest [62].

At Bruce Plateau, strong negative correlations exist between the observed sea ice extent in the Bellingshausen Sea and both stable water isotopes ($r = -0.55$) and snow accumulation ($r = -0.67$) [63]. Over the satellite era, Bellingshausen sea ice extent and snow accumulation exhibit significant decreasing and increasing trends, respectively, with sea ice extent explaining ~25% of the variance in snow accumulation at this site. The combined SMB composite produced from the AP ice cores, reveals a pattern of negative correlations with sea ice in the Bellingshausen Sea and positive correlations in the Amundsen-Ross Sea [42].

The Bruce Plateau snow accumulation record has been suggested as a proxy for past sea ice extent in the Bellingshausen Sea [63]. Porter et al., conclude that the increasing trend in accumulation since the 1970s suggests that the current rate of sea ice loss is unrivaled in the twentieth century. This is supported by other ice core proxy records such as methane sulfonic acid (MSA) record, a commonly used proxy for sea ice extent across Antarctica. The MSA record from the AP ice cores revealed a significant decline in sea ice in the Bellingshausen Sea during the twentieth century [66]. Conversely the MSA record from Ferrigno reflects changes in the Amundsen-Ross Sea, an area that is positively correlated with AP SMB [42, 67] and one that has exhibited a significant positive trend during the twentieth century.

Both the Bruce Plateau sea ice proxy based on snow accumulation and the Ferrigno sea ice proxy based on MSA, confirm the dominant role of ASL [63, 67], and hence large-scale modes of atmospheric variability, in driving changes in sea ice and ultimately AP SMB.

3. Conclusions

The Antarctic Peninsula has experienced considerable climate change during the twentieth century. The short observational period has provided compelling evidence of warming surface temperatures, increased glacial melt and mass loss [68] and reduced sea ice in the neighboring Bellingshausen Sea [62]. However, the observational period is short. A small number of meteorological observations span the past 50 years but the records are sparse and often dominated by local conditions. Here we have demonstrated the important role that ice cores have played in placing these recently observed changes in context.

Ice core stable water isotope records have demonstrated that the reported warming from stations in the northern AP since the 1950s is not just a local phenomenon, but part of a statistically significant 100-year regional warming trend [7, 31]. However, the ice core records also provide evidence that larger, more abrupt warming and cooling trends have occurred in recent centuries [19].

Ice core snow accumulation records represent mass gains to the ice sheet, a vital component of the total Antarctic mass balance. The observed ice melt in the AP since the 1990s [63] represents a mass loss, while the ice core records provide evidence of significant mass gain during the twentieth century [7, 11, 19]. Ice cores have provided evidence that SMB for the whole of Antarctica has increased since 1800, with the largest contribution (~75%) from the AP, where SMB has increased by 123 ± 44 Gt $year^{-1}$ [42].

The increase in surface temperature and SMB has been linked to changes in sea ice and atmospheric circulation. The observational records demonstrate a shift to the positive phase of the SAM since the 1957s that has increased the strength of the Southern Hemisphere westerly winds, deepened sea level pressures in the Amundsen Sea (ASL) and reduced sea ice in the Bellingshausen Sea. These later changes have also been attributed to the increased strength of ENSO, particularly since the 1990, with evidence interplay between these two modes is responsible for the acceleration in surface temperature and SMB in the late twentieth century.

The ice core records capture the influence of large-scale modes of climate variability over centennial time scales. They reveal that changes in SMB are sensitive to changes in the strength and phase of SAM, but that the relationship with ENSO is not temporally stable. However, the observed tropical teleconnection between climate on the AP and surface pressure and sea surface temperatures in the tropical pacific that are not related to ENSO [60], is consistent on centennial time scales [12, 19].

The observational records suggest that the interplay between modes of variability can have a considerable impact on climate of the AP [58]. Indeed, since the 1990s both SAM and ENSO have been in their positive phase, allowing for an amplification of the tropical teleconnection. In the ice core records the late twentieth century is characterized by a period of increased inter-annual variability and exceptionally high values in SMB [42] and sea ice [63–65], both of which are modulated by the variability in ASL (driven by SAM and ENSO). The combination of climate parameters and atmospheric circulation captured by the ice cores from the AP suggest that this recent coupling of SAM and ENSO is unprecedented in the past 300 years [12].

Acknowledgements

This work was funded by the British Antarctic Survey, part of the Natural Environment Research Council (NERC) and UK Research and Innovation (UKRI). D. Tetzner is funded on a CONICYT-Chile Cambridge scholarship.

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