Millennial to quasi-decadal variability in Antarctic climate system as evidenced from high-resolution ice core records

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The Antarctic climate system fluctuated through glacial–interglacial and millennial–centennial–decadal timescales in the past, closely coupled with other components of the global climate system. Analysis of ice core records offers critical insights on the millennial, centennial and decadal scale climate processes in Antarctica and its tropical linkages. Recent studies have demonstrated that annually-resolved high-resolution ice core records offer the best possible means to understand the quasi-decadal climate variability during the last millennia, when both natural and anthropogenic forcing influenced the climate system. This study discusses the quasi-decadal Antarctic climate variability in response to the solar forcing as well as the decadal to multidecadal climate modes like the Southern Annular Mode, El Niño-Southern Oscillation and the Pacific Decadal Oscillation, with special emphasis on the Indian ice core studies.

Keywords: Antarctica, decadal climate variability, El Niño-Southern Oscillation, ice core, Pacific Decadal Oscillation, Southern Annular Mode.

Introduction

THE surface air temperatures across Antarctica are more spatially heterogeneous compared with other continental regions, with statistically significant warming trends since the early 1950s along the western flank of the Antarctic Peninsula that were five times higher than the global average warming[1]. However, the instrumental records from Antarctica are only some decades old, as the time-series observations of climatic parameters across Antarctica are limited. Antarctica seems to have undergone complex and significant temperature changes in recent decades[1,2]. While the largest annual warming trends are found on the western and northern parts of the Antarctic Peninsula (about +0.56°C per decade at Faraday/Vernadsky station), the Amundsen-Scott Station at the South Pole has shown a minor cooling (–0.05°C per decade) in the annual mean temperature[3]. Temperatures on the eastern side of the Antarctic Peninsula have increased most (+0.39°C per decade during 1946–2011 at Esperanza) during the summer and autumn[4]. Significant warming of nearly 0.1°C per decade since the late 1950s has also been reported across West Antarctica, essentially based on satellite and limited instrumental data[5,6]. Consistent with these warming trends, there are also changes in the surrounding sea ice conditions, with significant decreases in length of the sea ice season in the Bellingshausen and Amundsen Seas[7]. However, neither the temperature nor the sea ice trends is uniform across the interior and around the coast of Antarctica[5]. A possible explanation for the asymmetry in observed temperature and sea ice trends across and around Antarctica are changes in the regional atmospheric circulation[8].

An important influence on large-scale climate variability in Antarctica is the southern annular mode (SAM), which is the principal mode of variability in the atmospheric circulation of the southern extra-tropics and high latitudes (Figure 1). SAM is a circumpolar pattern of atmospheric mass displacement in which the intensity and location of the gradient of air pressure between mid-latitudes (higher pressure) and the Antarctic coast (lower pressure) changes in a non-periodic way over a wide range of time scales from days to years[1,9–11]. The SAM has both positive and negative phases. During the negative phases of SAM, the strength of the meridional pressure gradient is weaker than normal, whereas in positive phases of the SAM a stronger than normal pressure gradient is observed. The sign and magnitude of the SAM strongly influences the strength and position of the polar front jet that flows from west to east around the Antarctic continent, and therefore is associated with temperature variability across the coastal and interior Antarctica[9,12]. During the last 50 years, the SAM became more positive (stronger circumpolar westerly winds) in the austral summer, as pressure dropped around the coast of the Antarctic and increased at mid-latitudes[1,13]. Such a systematic positive shift in SAM was attributed primarily to the enhancement of the Antarctic ozone hole[4]. Recent studies have highlighted the importance of tropical Pacific forcing for the Antarctic climate variability, altering the atmospheric circulation mainly in the Amundsen and Bellingshausen Seas region, which could also be linked to the observed warming across West Antarctica and the

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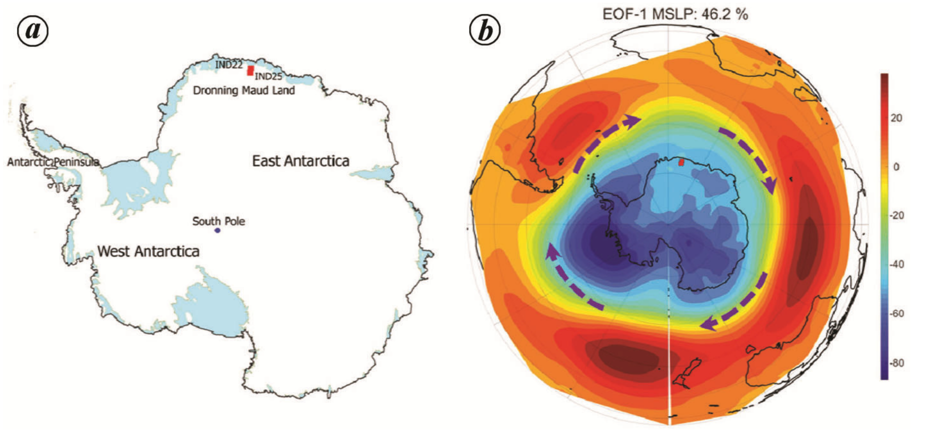

Figure 1. ***a***, Antarctic map depicting the major geographic regions discussed in the study; ***b***, Composite mean sea level pressure (MSLP) anomalies around Antarctica showing southern annular mode (SAM) in its extreme positive conditions. The arrows represent a schematic of Westerly winds belt around Antarctic that transport dust to Antarctica from the Southern Hemisphere continents. The red dots on (***a***) and (***b***) represent the ice core locations.

Antarctic Peninsula[14,15]. The El Niño Southern Oscillation (ENSO) is the farthest reaching climatic system on Earth on decadal and sub-decadal time scales, with profound effect on the weather and oceanic conditions across the tropical Pacific as well as in remote regions like the southern high latitudes[15–17]. The ENSO signals can be identified in the physical and biological environment of the Antarctic, although some of the links are not very robust and there can be large differences in the extra-tropical response to near-identical events in the tropics[17]. Studies have proposed two major mechanisms whereby tropical Pacific ENSO signals reach the Antarctic. They include: (i) the Pacific–South America (PSA) pattern, interpreted as a Rossby wave train driven by anomalous tropical deep convection during ENSO events[15,17]; and (ii) the mechanism involving the interactions of the SAM and ENSO activity, through a combination of thermally driven zonal wind anomalies in the tropics and subtropics and eddy-driven zonal wind anomalies in the mid- and high latitudes[15]. The influence of these and their tropical linkages is evident in regressions of seasonally stratified Antarctic station temperature data and annually resolved ice core records on global fields of sea surface temperature, sea level pressure and precipitation.

Since the instrumental records extend only for some decades, ice core-based proxy records offer a reliable method to study the past Antarctic climate variability. Antarctic ice cores offer key archives for studying polar climate variability using the isotopic composition of water stored in the ice serves over a wide range of timescales ranging from subannual to glacial–interglacial variations. Nevertheless, the relationship between isotopic composition and surface temperature is not constant through time and space, mainly due to the processes within the local boundary layer[18]. Studies have shown that interpretation of isotope records in terms of local atmospheric temperatures is thus complicated by a multitude of processes that distort the original relationship present in precipitation[19,20]. The impact of post-depositional processes on ice core records is significant in dry low-accumulation sites[19]. Contrasting studies using ice core records from remote Antarctic interiors and the marine-influenced West Antarctic sites have revealed that the isotopic signal-to-noise ratio have significant differences in the spatial and temporal scales[20]. This study demonstrated that while the signal-to-noise ratio for remote Antarctic interior sites is very low in interannual timescale, it steadily increases on multidecadal and centennial time scales. Compared to this, marine-influenced West Antarctic ice core records provided excellent signal-to-noise ratio on interannual to decadal timescales and found increasing variability towards longer timescales[20]. Therefore, the potentially more homogeneous atmospheric conditions on the Antarctic Plateau are ideal for multidecadal to centennial regional palaeoclimate reconstruction, whereas the ice core records from coastal regions could be more useful for interannual to decadal climatic reconstructions. Although individual ice cores from such regions would represent more localized climate, synchronous signals in multiple ice cores would be useful to extract the dominant regional patterns of atmospheric circulation variability.

As part of the Indian initiatives to obtain reliable climatic records beyond the instrumental period, several ice cores have been retrieved from the coastal Dronning Maud Land in East Antarctica. For the present review, two well-dated ice cores (IND-22/B4 and IND-25/B5) from the coastal Dronning Maud Land in East Antarctica were studied for stable isotope based temperature records (Figure 1). Of these, IND-25/B5 core represents the past 100 years (1905–2005) with seasonal resolution and the IND-22/B4 core represents the past 470 years (1530–2002), with quasi-annual resolution. The proxy temperature record of IND-25/B5 revealed an average warming of 1°C for the period 1905–2005 (0.1°C/decade), with greatly enhanced warming trend (0.4°C/decade) during the recent decades[21,22]. Compared to this, the temperature record of IND-22/B4 revealed an estimated warming of 3°C (0.06°C/decade) for the past 470 years (1530–2002) (ref. 22). The estimated warming of 0.6–1°C per century is comparable to other climate records from coastal Dronning Maud Land using the ice core proxy data[23] and station records[1], considering the different time periods involved. Together with the long-term proxy records and limited instrumental records, it is evident that the coastal Dronning Maud Land is experiencing significant warming in the recent decades and even longer period.

Millennial to centennial climate variability in Antarctica and its global linkages

The Antarctic climate system fluctuated through multiple timescales in the past, closely coupled with other components of the global climate system. Analysing and understanding the past changes in climate and forcing factors can provide insights into the potential future climate impacts and ecosystem feedbacks, especially over the millennial-to-centennial timescales that are often not covered by climate model simulations[24]. On the longest time scales, it fluctuates on Milankovitch frequencies in response to slow changes in the Earth's orbit around the Sun that cause regular variations in the Earth's climate on these recurrent time scales[25]. These changes in incoming solar energy initiated feedback loops whereby small changes in temperature brought about larger changes in global atmospheric CO_2 and CH_4, which enhanced the temperature rises by positive feedback[13]. Supported by the large number of marine, ice and terrestrial proxy records as well as modelling efforts, the past variations in climate attributed to the natural causes are now far better understood than they used to be, and provide crucial context against which changes caused by human interference in the system are assessed.

Ice cores drilled deep into the Antarctic ice sheets have yielded highly resolved information on large numbers of climate variables over the past 800,000 years[26]. Analysis of such deep ice cores using a variety of proxy parameters like stable isotopes in water, greenhouse gas concentrations, atmospheric aerosols and glaciochemical concentrations enable us not only to understand the Antarctic climate on a long term basis, but also provides an opportunity to explore the interhemispheric climate linkages. Antarctic ice core records could potentially be extended as far back as 1.5 million years, beyond which the layers are seemingly not preserved and climatic information may not be preserved due to various complexities[27]. The 'oldest ice' project proposed by the International Partnerships in Ice Core Sciences (IPICS) aims to better understand the Mid Pleistocene Transition of climatic cycles from the 41 ka to 100 ka and the role of greenhouse gas cycles in this progression. The continuous improvement in the ice core proxy records and chronology has also helped to synchronize the Antarctic and Arctic ice core records that revealed interhemispheric linkages through the slower oceanic link and a rapid atmospheric link between the north and south[28]. However, there are complexities in the ice core proxy data because of the reliance on annual data, uncertainties in dating, seasonality of deposition, and other uncertainties that need to be addressed[29]. One of the most important findings from the Antarctic ice core study is that throughout the last 800,000 years, the atmospheric carbon dioxide (CO_2) and mean temperature values remained around 180 ppm and 10°C respectively during glacials and around 280 ppm and 15°C during the interglacial periods[26,30]. Antarctic ice core records confirmed that both the magnitude and rate of current increase in CO_2 concentration are unprecedented over the last 800,000 years, when it started increasing dramatically during the late 19th century and its concentration is now nearly 40% higher than it was before the industrial revolution. While the ice core stable isotope records from Antarctica do not exhibit the large climate variability attributed to the so called Dansgaard–Oeschger (DO) events during the last glacial period seen in Greenland records, they clearly exhibit the systematic millennial-scale variability with a one-to-one correspondence between all these Antarctic Isotope Maxima (AIM) and DO events[26,31]. The millennial-scale variability in temperature and its interhemispheric linkages have been attributed to oceanic teleconnection called the thermal bipolar seesaw mechanism[32]. According to this model, the Greenland temperature jumps abruptly into its warm phase when the overturning circulation in the North Atlantic Ocean speeds up. This adjustment in ocean circulation concentrates heat in the Northern Hemisphere and causes Antarctica to gradually cool[33]. However, the oceanic mode of heat exchange between the hemispheres can explain only the delayed and/or gradual changes in Antarctic temperature that accompanied the past abrupt shifts in the Arctic temperature. Through a precise synchronization of ages among five ice cores across the Antarctic continent using characteristic sequences of volcanic eruptions, Buizert *et al.*[34] found that throughout the last glacial cycle, there were two modes of variability explaining the temperature records. The first and dominant one is attributed to the spatially homogenous classical oceanic bipolar seesaw mode, which lags by nearly 200 years behind the Arctic warming. The second one is the spatially heterogeneous mode attributed to atmospheric teleconnection, which is nearly instantaneous. The temperature anomalies of the atmospheric mode are similar to those associated with the present-day SAM variability, rather than the PSA pattern[34]. This atmospheric mechanism forces an almost instantaneous northward shift in the westerly winds encircling Antarctica when Northern Hemisphere moved into its warm phase (and vice versa), modulating the moisture source belt in the Southern Ocean[28,34]. Such synchronous and zonally coherent meridional shifts in the past have implications for our understanding of ongoing changes in the Arctic and its possible influence on the Antarctic climate.

Multi-decadal and quasi-decadal variability in Antarctic climate

The study of decadal climate variability (DCV), which has regional characteristics and modulates the long-term global warming trends, is critical to understand the recent climate variability and its societal implications. However, the attribution of DCV offers unique challenges to climate scientists due to the combination of factors involved[35]. Further, the pattern and amplitude of decadal variability can be significantly influenced by the presence of natural, low frequency climate variability when the record is not sufficiently long[36,37]. Such decadal to interdecadal variations of regional and global mean surface temperature have often been attributed to changes in ocean heat uptake and heat redistribution. The oceans play a central role in DCV because of its thermal and dynamical inertia, even in cases of external forcing due to natural (solar and volcanic) or anthropogenic factors and even during internal climate system interactions[36]. The decadal to interdecadal climate variations in Antarctica climate records have been identified in a suite of instrumental, reanalysis, proxy data and models[13,21,38–44]. Studies have also demonstrated a decadal variability of the ENSO teleconnections to the Antarctic[39] as well as the possible influence of Atlantic Ocean on decadal–interdecadal climate variations in Antarctica[41].

An array of annually resolved high-resolution ice core records spanning the last few centuries across the Antarctic continent offer the only possible means to study the decadal climate variability[21,40,45–48]. The international effort in this regard was pioneered by the International Trans Antarctic Scientific Expedition (ITASE) projects that established calibration tools as well as reconstructed climate indices based on shallow ice cores covering the past nearly 200 years[45]. The ice core based high resolution climate records from Antarctica have revealed the climatic response to solar forcing as well as the decadal to interdecadal behaviour of the major climate modes like the SAM, ENSO, PSA and the Pacific Decadal Oscillation (PDO). These quasi-decadal and multi-decadal variabilities in longer term records of Antarctic climate and its implications on Antarctic climate variability are discussed in the following sections.

Solar forcing and the Antarctic climate variability

Quasi-decadal variability in solar irradiance is evident in several climatic records around the globe, including the Antarctica. A possible mechanism for the solar modulation of the southern hemisphere climate system is attributed to the dynamical coupling between the troposphere and stratosphere during the late spring/winter[49]. According to this, enhanced solar activity would enhance the ultraviolet and ozone production that could lead to stronger troposphere–stratosphere coupling through a strong interaction between the planetary waves and radiation. Kuroda and Yamazaki[50] demonstrated that the 11-year solar cycle and the stratospheric equatorial Quasi-Biennial Oscillation (QBO) significantly influence the modulation of SAM in late winter/spring. When both the solar cycle and the QBO are considered, the effects from the solar cycle dominate and those from the QBO work as linearly superimposed factors[50].

Ice core based annually resolved proxy records across the Antarctica have also revealed the decadal-scale associations between the solar activity (irradiance) and atmospheric circulation and/or chemistry[22,42,51–53]. Chemical proxy records of an ice core from Victoria Lower Glacier revealed a direct influence of solar activity variations on the McMurdo Dry Valleys climate system during the last 50 years through controls on air-mass input from two competing environments, the East Antarctic ice sheet and the Ross Sea[51]. Analysis of several ITASE ice cores for atmospheric circulation proxy records (Ca^{2+}, Na^+ and NO_3^-) from different sites of Antarctica and their comparison with proxy record of solar variability (cosmogenic ^{10}Be record from the South Pole) over the last 600 years have revealed quasi-decadal associations between the two[52]. Since magnetic fields of the solar wind deflect primary flux of charged cosmic particles, increased solar activity leads to a reduction of cosmogenic nuclide (like ^{10}Be) production in the earth's atmosphere and vice versa[54]. The temporal records of ^{10}Be would be similar in Antarctica and could be utilized as a reliable indicator for solar activity as well as production of odd nitrogen. Mayewski *et al.*[52] have shown that an increased (decreased) solar irradiance is associated with increased (decreased) zonal wind strength near the edge of the Antarctic polar vortex. The association between solar activity and zonal wind strength appears to be particularly strong in the Indian and Pacific Oceans[52]. The identification of solar forcing of the Antarctic atmosphere and its impact on lower latitudes offers a mechanism for better understanding modern climate variability and potentially the initiation of abrupt climate-change events that operate on decadal and faster scales.

Records of nitrate (NO_3^-), oxygen isotopes ($\delta^{18}O$) and non-sea salt sulphate ($nssSO_4^{2-}$) for the past five centuries in the IND-22/B4 ice core from Dronning Maud Land (East Antarctica) have revealed a close relationship of these proxies to the ^{10}Be record (solar proxy) from South Pole[42]. The rate of accumulation of new odd nitrogen (the sum of all oxidized forms of nitrogen) in ice may mainly depend on the production rate of nitrogen oxide molecules in the atmosphere through the reactions of O_2 and

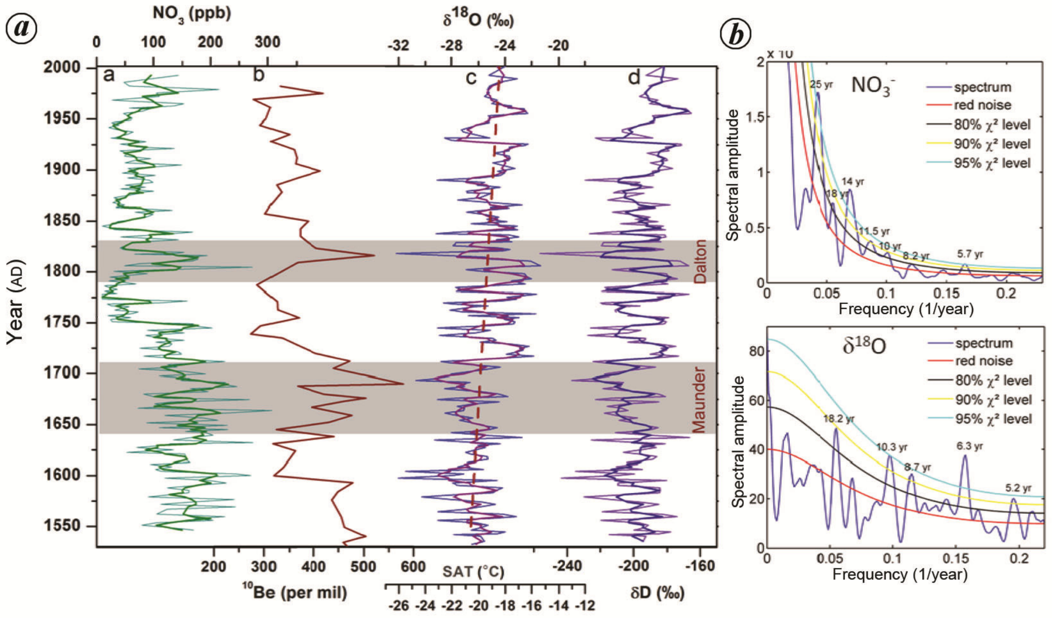

Figure 2. Influence of solar variability on Antarctic climate variability. ***a***, Relationship between the nitrate (NO_3^-) and stable oxygen isotope ($\delta^{18}O$) records of IND-22/B4 core from coastal Dronning Maud Land (East Antarctica) and the South Pole ^{10}Be proxy data of solar variability (after Thamban *et al.*[22]). ***b***, Periodicities in NO_3^- and $\delta^{18}O$ records of the IND-22/B4 ice core. The spectral analysis was undertaken using the MATLAB based Redfit program[78].

N_2 by solar and geomagnetic charged particles that are modulated by the solar activity[55]. Among the various environmental factors, temperature has significant influence on the preservation of NO_3^-, with an increased NO_3^- preservation occurring at low temperatures in snow[56]. The NO_3^- record of the IND-22/B4 ice core revealed synchronous changes with the solar activity records, showing relatively enhanced NO_3^- values during periods of reduced solar activity like the Dalton Minimum (~1790–1830 AD) and Maunder Minimum (~1640–1710 AD) (Figure 2*a*). Comparison of NO_3^- and $\delta^{18}O$ profiles of the IND-22/B4 core revealed that the shifts towards more negative values of $\delta^{18}O$ were synchronous with the NO_3^- peaks, supporting an enhanced preservation of NO_3^- during periods of reduced air temperatures. The prominent shifts detected in nitrate record of the IND-22/B4 core and South Pole ^{10}Be (solar proxy) record suggest that solar activity influenced the nitrate record at the site through the enhanced production of odd nitrogen species during periods of reduced solar activity[42]. Power spectrum analysis carried out on NO_3^- and $\delta^{18}O$ records of the IND-22/B4 core revealed significant (90% χ^2) common periodicities at 5–6 years and 10–11 years (Figure 2*b*). The 10–11 years in both NO_3^- and $\delta^{18}O$ records seem to be related to the solar cycles that have an average periodicity of about 11 years. Such cycles are commonly found in the Antarctic climate data and ice core records and studies have suggested that increased (decreased) solar irradiance is associated with increased (decreased) zonal wind strength near the edge of the Antarctic polar vortex[45]. The present study thus supports the influence of solar forcing on the Antarctic climate change during the past few centuries. While the shorter periodicities of 5–6 years can be attributed to the ENSO band (2–8 years), the longer periodicities of 18–25 years found in our ice core record could be attributed to the PDO bands.

Southern Annular Mode influence on southern hemispheric temperature variability

The SAM is the primary mode of climate variability in the atmospheric circulation of the southern high latitudes and significantly influences the Antarctic climate system on spatial and temporal scales. The SAM controls the strength and position of the circumpolar southern westerly winds and contributes to a significant proportion of Southern Hemisphere climate variability from high-frequency to low-frequency time scales[10,57]. Since the Antarctic climate records are sparse and short, the nature and causes of SAM variability beyond interannual scales are poorly known. The temporal variability of SAM over the past few centuries has been assessed in a number of studies through integration of station observations, modelling and palaeoclimatic proxy records[10,21,58–60]. Studies have also demonstrated the crucial role of SAM on the recent climate changes across the Antarctic continent. During the last 50 years, the SAM has shifted more into its positive phase with decreases of surface pressure over the Antarctic and corresponding increases at mid-latitudes[10]. The positive trend in the SAM seems to have resulted in a strengthening of the circumpolar westerlies and contributed to the spatial variability in Antarctic temperature change[57,61].

A study using the instrumental data from Halley station as well as the IND-25/B5 ice core record from coastal

Dronning Maud Land revealed that the key factor affecting the regional SAM-temperature relationship is the relative magnitude of two climatological low pressure centres to the west and east of the area, which determines the source region of air masses advected into the locality[62]. Such a reversal is also found in the sign of the correlation between the SAM and oxygen-isotope values from the IND-25/B5 ice core from Dronning Maud land[21]. This relationship demonstrated significant relationship between the ice core δ^{18}O records (temperature proxy) and SAM was observed on a decadal scale throughout the 20th century, which overrides the intermittent influence from ENSO. It was suggested that the switches in the SAM-temperature relationship are more likely to reflect natural variability in the long-wave patterns over the Southern Ocean rather than the influence of an anthropogenic forcing[62]. A running decadal correlation between the annual δ^{18}O records and SAM indices also indicated an overall negative relationship, with certain periods (1918–1927; 1938–1947; and 1989–2005) showing absence of correlations or even weak positive relationships[21]. The δ^{18}O record also revealed a significant 4-year periodicity, broadly in agreement with the apparent 4–5 year variability of the SAM[9]. Naik *et al.*[21] showed that while SAM is the dominant mode of climate variability on a decadal scale, the SAM also interacts with the ENSO intermittently to produce a combined effect on temperature variability. It is therefore, complicated to completely differentiate the SAM and ENSO influence on Antarctic climate records.

Since SAM influences the Southern Hemisphere westerly winds, it is also a potential driver of the dust transport to Antarctica from the surrounding continents. High-resolution records of dust fluxes in a firn core from the coastal Dronning Maud Land, revealed a doubling of dust flux since the 1980s (ref. 63). The observed increase in wind speed is synchronous with shift in the SAM index towards more positive values since 1980s and suggests its dominant role in transporting dust flux to East Antarctica, through its influence on the westerlies. Strong positive correlation observed between dust flux and the SAM index suggests that the shifting of SAM state to more positive values was responsible for the strengthening of westerly winds and resultant dust transport from the Southern South America[64]. The increased dust flux is occurring dominantly during winter periods, possibly due to the reduced moisture content and increased wind intensity[63]. Similar increases in dust fluxes during the 20th century were also observed in an ice core from Antarctica Peninsula[65]. These findings from geographically and climatologically different regions in Antarctica support the preposition that SAM variability significantly controlled the dust transport to Antarctica.

The SAM has undergone a progressive shift towards its positive phase since the 15th century, causing cooling of the main Antarctic continent and warming of the Antarctic Peninsula[58]. This study also revealed that the SAM index is now at its most positive level over the past 1000 years. The simulations using the CMIP5 climate models display large internal multi-decadal variability in the high southern latitudes[59]. With the exception of SAM, which shows a clear positive trend, most observed trends are not unusual when compared with Antarctic palaeoclimate records of the past two centuries, supporting that the natural variability overwhelms the forced response. Multidecadal to centennial-scale variability of the SAM evaluated through palaeoclimatic reconstructions revealed similar patterns of quasi-decadal variability in SAM during the last two centuries in all proxy records, but earlier centuries are less coherent[60]. This study also revealed similar trends towards more positive SAM values since the onset of anthropogenic forcing from increasing greenhouse gas concentrations and ozone depletion, which is unprecedented over at least the last 500 years. Since the future greenhouse-driven increases in the SAM are also likely to have implications for limiting the warming over continental Antarctica[66], it is critical to understand the interactions of SAM with other climate forcings like the ENSO.

El Niño Southern Oscillation and its interactions with Southern Annular Mode

The ENSO, arising from air–sea interactions in the tropical Pacific, is the dominant source of global climate variability on interannual to decadal time scales[15,67]. The ENSO-influenced shifts in tropical precipitation and resultant latent heat release may force an atmospheric barotropic Rossby wave into the extratropics, where it modifies the circulation patterns through interactions with transient eddies along the storm tracks[68,69]. Over the South Pacific sector, such Rossby wave trains may extend poleward and eastward to South America during ENSO events, named as the PSA pattern[70]. The PSA mode is now widely recognized as the primary mechanism by which ENSO influences the Antarctic climate. Within the high southern latitudes, the South Pacific off the coast of Antarctica and near the Drake Passage has strong ENSO teleconnection[17].

Studies have also revealed a strong decadal variability of the ENSO signal in the South Pacific[38,39,71]. Such decadal variability is found in many fields including the annual mean sea level pressure (MSLP) and the 500 hPa geopotential height[39]. The ENSO is also known to affect the SAM in a highly nonlinear way and the two forcings can combine, partially offset or even enhance their influence on each other and the Southern Hemisphere as a whole[39,72]. The significant positive correlation between ENSO and SAM only during times of strong teleconnection suggests that both the tropics and the high latitudes need to work in tandem for ENSO to strongly influence Antarctic climate[39]. While it is evident that the tropical ENSO activity plays an important role in the Antarctic climate, it is not possible to differentiate the control from natural internal climate variability or climate change in the coupling observed between the high-latitude southern hemispheric circulation and ENSO due to the limitations on the available instrumental and reanalysis data. It is therefore, necessary to have long-term climate data from proxy records to have a better understanding of the interactions between the ENSO and SAM on the regional climate variability in Antarctica.

The interactions and relationships between the surface air temperature and the southern hemispheric climatic modes SAM and ENSO in the central Dronning Maud Land (DML) in East Antarctica was studied using high-resolution proxy records and the reconstructed SOI (Southern Oscillation Index) as well as the SAM indices[21]. This study revealed that for periods when the δ^{18}O and SAM relationship was more positive, the relationship between the SOI and SAM also tend to be in-phase. A similar ice core based study from the coastal DML suggested that ENSO teleconnections to this region occurred only during certain periods and were caused due to bi-decadal variability in SAM, forced by the tropical Pacific[23]. Naik *et al.*[21] demonstrated that when the years of El Niño and La Niña events are omitted from the records, the relationship between the filtered δ^{18}O records and SAM data are statistically significant, suggesting that ENSO events weaken the SAM-temperature relationships. The study thus revealed that during the past century, the combined influence of ENSO–SAM modes has controlled the temporal changes in δ^{18}O records at the central DML region. As revealed by the NCEP reanalysis data for the period 1989–2005, the SAM and SOI indices showed a significant negative relationship with surface air temperatures, during the austral summer[21]. This relationship between SOI and surface air temperature suggests that during the El Niño years within the period of 1989–2005, warmer air temperatures prevailed over the central DML. These evidences further support the finding that both the SAM and ENSO cause a combined influence on surface temperatures during austral summer in the central DML region. Further, a significant relationship between δ^{18}O and SAM was observed on a decadal scale, which overrides the intermittent influence of ENSO.

The SAM–ENSO teleconnection is considered as an integrated mechanism influencing sea ice conditions in Antarctica[7]. High resolution proxy records of sea-salt sodium (ss-Na^+) and methane sulphonic acid (MSA) are useful for reconstructing the sea ice extent (SIE) beyond the satellite era. In order to investigate the link between the SIE variability and the climate modes (SAM and ENSO) in the central Dronning Maud Land, annually averaged profiles of SAM index and SOI were compared with the sea ice (ss-Na^+ and MSA) and moisture (δ^{18}O and *d*-excess) proxy records[43]. This study showed a dramatic shift in d-excess values from 8‰ during 1905–1920 to –1‰ around 1940 and thereafter positive excursion during 1940–1980 (Figure 3). Such a large shift during 1920–1940 has been attributed to the reduced moisture supply from low/mid latitude to Antarctica associated with shifting of SAM from positive to negative mode. The ss-Na^+ flux profile shows systematic positive excursion during 1940–1980, overlapped with positive excursions of *d*-excess values and a negative excursion in the MSA flux profile, suggesting increased SIE (Figure 3). To further understand the SAM–ENSO teleconnection and their phase relation influencing SIE and moisture source variability, the authors performed wavelet analysis of SAM and SOI time series data for the period 1905–2005. Based on the cross wavelet analysis, significant highest common power is observed in 4–8 year band during 1945–1965 and 1990–2000. These periods overlap with the periods of higher SIE, as reflected in the ss-Na flux and *d*-excess profiles. Further, the wavelet coherency plot shows ENSO overriding SAM in 4–8 year band during same periods. The periods of highest common power in SAM–ENSO at 4–8 years band and the time when SOI overrides SAM (phase lag ~90°) coincide with the higher periods of SIE during 1940–1965 and 1990–2000 (ref. 43). This study also revealed that the SAM–SOI shows

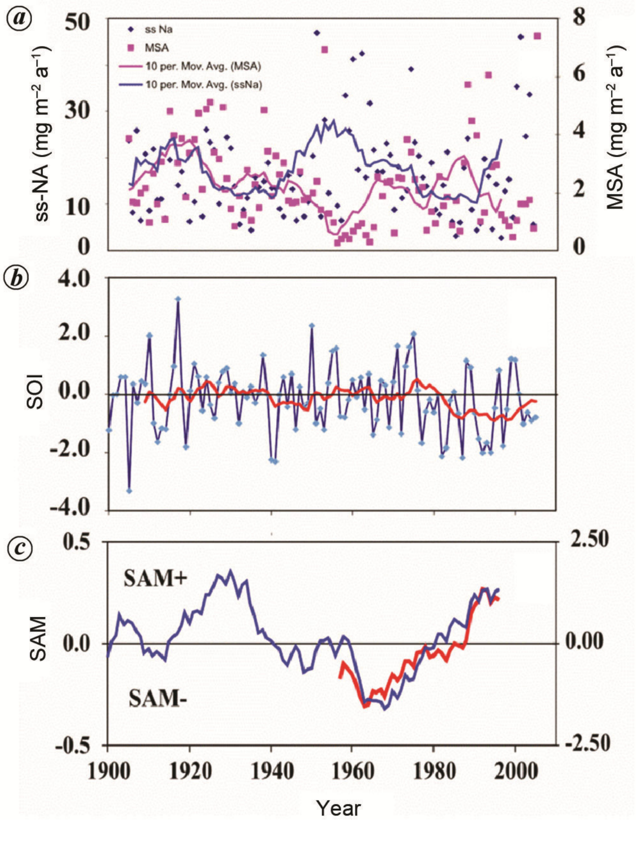

Figure 3. Annually averaged ice core proxy data from IND-25/B5 ice core from coastal Dronning Maud Land (East Antarctica) depicting the relationship between the sea ice extent variability and ENSO and SAM indices during the past 100 years. ***a***, Sea ice proxy records (ss-Na^+ and MSA fluxes). ***b***, Southern Oscillation Index profile. ***c***, SAM profiles. Red line is the principal SAM index by Marshall[10] and the blue line is the modelled longer term SAM index by Jones *et al.*[79] (after Rahaman *et al.*[43]).

opposite phase in 10–16 years band during 1905–1930 and 1990–2005, coinciding with the periods of higher *d*-excess supporting a strong SAM–ENSO teleconnection that allowed more meridional transport of warm and moist air from remote sources in the lower latitudes.

The relationships between Antarctic climate variability, ENSO and SAM are complex. For example, the positive phase of the ENSO is expected to increase the global mean temperature, and lead to a negative phase of the SAM. However, such a relationship of a high global mean temperature associated with a negative SAM, is opposite to the relationship found between their trends under greenhouse warming. Wang and Cai[73] suggest that the relationship between the global mean temperature and the SAM underwent significant multidecadal fluctuations over the 20th century through their common forcing by ENSO variability. Regional characteristics of Antarctic climate variability also need to be considered while understanding the impact of ongoing climate change in Antarctica. The rapid warming on the Antarctic Peninsula since the 1950s and subsequent cooling since the late-1990s have been attributed to the internal decadal scale climate variability of the regional atmospheric circulation in the region[74]. This study emphasizes that the decadal temperature changes in the Antarctic Peninsula are not primarily associated with the drivers of global temperature change, but may reflect the extreme natural variability of the regional atmospheric circulation.

In addition to the SAM and ENSO, the PDO also influences the climate of Antarctica, especially the West Antarctica[75,76]. The PDO, a recurring pattern of ocean–atmosphere climate variability centred over the mid-latitude Pacific basin, is often described as a long-lived El Niño-like pattern of Pacific climate variability. Over the past century, the amplitude of this climate pattern has varied irregularly at interannual to multidecadal time scales. Analysis of a network of seventeen annually resolved ice core records continent in conjunction with global instrumental datasets and tropical proxy records revealed that while ice core records in central West Antarctica are positively correlated with Pacific interdecadal variability, the records from the Antarctic Peninsula and eastern West Antarctica are negatively correlated with Atlantic interdecadal variability[77]. Using an objective filtering method to characterize the observed versus modelled decadal variability, it was demonstrated that the surface temperature anomalies associated with the multidecadal variability originate in the North Atlantic and spread out to the Pacific and Southern oceans and Antarctica, with the Arctic following suit in about 25–35 years[37]. How much tropical Pacific decadal variability is due to coupled processes operating on fundamentally decadal time scales and how much is the residual of weather noise-driven ENSO dynamics remains to be understood.

Recent studies have suggested that global climate extremes could be amplified by the combined influence of ENSO and PDO[76]. The Antarctic surface air temperature (SAT) reconstructed approximately for the past five centuries based on multiple oxygen isotope ($\delta^{18}O$) records of ice cores from East and West Antarctica show dominant oscillations in ENSO and PDO frequency bands[44]. The variance of the East Antarctica (EA) temperature record shows significant increasing trend at ENSO band and decreasing trend at PDO band since the industrial era (~1850 CE). Analysis of greenhouse gas forced model simulation revealed that the ENSO activity and its influence on Antarctic temperature are increasing in response to continuing greenhouse warming since the industrial era[44]. Such findings indicate that increasing ENSO activity since the industrial era presumably intensified its influence on Antarctic surface temperature through stronger responses of southern hemisphere atmospheric circulation to ENSO under the increasing greenhouse forcing.

Perspectives

Since the pattern and amplitude of decadal climate variability can be significantly influenced by the presence of internal low frequency variability, it is critical to have long-term climate records obtained from annually resolved ice core proxy records spanning the last few centuries across the Antarctic continent. Our study examined the decadal and multidecadal modes of Antarctic climate variability through the analysis and review of several high-resolution climate records, with special emphasis on Indian findings. Several ice core records have indicated decadal-scale associations between the solar activity and atmospheric circulation. While SAM is the dominant mode of climate variability on a decadal scale, it also interacts with the ENSO intermittently to produce a combined effect on Antarctic temperature in the past. Proxy records from different regions in Antarctica also demonstrated that past shifts in SAM state also controlled the dust transport to Antarctica. The SAM–ENSO teleconnection also acts as an integrated mechanism influencing sea ice conditions in Antarctica. However, the relationships between SAM and ENSO are complex, and over longer time scales, the PDO also influences the Antarctic climate variability. Considering the knowledge gap and limited number of long term climate records, it is proposed to generate long-term high-resolution ice core records from the East Antarctica that could provide better insights on the decadal and multidecadal variability during the past few millennia.

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ACKNOWLEDGEMENTS. The Ministry of Earth Sciences (Government of India) and National Centre for Polar and Ocean Research are acknowledged for sustained support through the ‘Cryosphere and Climate’ project. Tariq Ejaz is acknowledged for Figure 1 and spectral analysis shown in Figure 2. This is the NCPOR contribution no. J15/2020-21.

doi: 10.18520/cs/v119/i2/255-264