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Palaeoclimatic records from Antarctica and Southern Ocean: A review of Indian contributions

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Polar regions are highly sensitive to climate change and are crucial for regulating the Earth's climate. While the past climatic changes were forced differently than the ongoing and future anthropogenic changes, such periods may provide insights into potential future climate impacts and ecosystem feedbacks, especially over centennial-to-millennial timescales that are often not covered by climate model simulations. As part of the initiatives to better understand the polar climate system and its global linkages, Indian scientists have been undertaking palaeoclimatic studies, mainly from the Antarctica, its margins and the surrounding Southern Ocean. Antarctic palaeoclimate records come primarily from proxy records of ice cores or marine and lake sediment cores. Among ice core records, the Indian contributions have been focussing on a network of annually resolved shallow depth ice cores to reconstruct the Antarctic climate variability and its regional and global climatic teleconnections, especially during the past few centuries. Compared to this, the Antarctic lake sediment records have focussed on long-term climate variability, especially during the late Quaternary. Recently, as part of the collaborative initiatives under the International Ocean Discovery Program, Indian scientists have been studying longer sedimentary records from the Antarctic continental margin that offer opportunity to study the evolution and dynamics of the Antarctic ice sheets since their formation during the Cenozoic.

Introduction

Polar regions form the “cold” end of the global heat engine, connected to the rest of the climate system by fluxes of heat carried by the atmosphere and ocean (King and Turner, 1997). It is also well known that the polar regions are important sources of oceanic bottom

waters, which play a major role in driving global oceanic circulation. The presence of sea ice on the polar oceans introduces important positive feedbacks into the climate system. The sea ice surrounding the Antarctic continent has a maximum winter extent of some 20 million km², the seasonal waxing and waning of which is one of the largest seasonal signal on planet Earth. Sea ice differs between the Arctic and Antarctic, with the Arctic Ocean consisting of multiyear ice, whereas the Antarctic sea ice is typically seasonal ice that doesn't last beyond the winter. The polar region is an important regulator of global climate as its surface is highly reflective and helps this region to remain very cold. The existence of sea ice is another important factor contributing to Antarctic and Arctic's influence on climate.

Climate dynamics in polar regions are controlled by both radiative and non-radiative interactions between the atmosphere, ocean, sea ice, ice sheets and land surfaces (Goosse et al., 2018). Due to the complexity of the underlying processes, we do not fully understand them. Advancing the scientific understanding of climate in polar regions is particularly challenging due to a short and incomplete observational records (Jones et al., 2016), large internal climate variability (Hobbs et al., 2016; Swart et al., 2015) and the large biases of climate models in these regions (Flato et al., 2013). The polar climate system varies on time scales from interannual to the millennial time scale and is closely coupled to other parts of the global climate system (Turner et al., 2013). Although past intervals of warming were forced differently than possible future anthropogenic change, such periods can provide insights into potential future climate impacts and ecosystem feedbacks (Fischer et al., 2018). Therefore, quantitative palaeoclimatic data may help us in better understanding the natural variability, like the thresholds and tipping points in climate system, which could help us in better understanding the future changes.

On millennial times scales, the meridional shifts of the Southern Hemisphere westerly winds have been hypothesized to occur in response to the abrupt North Atlantic climate change events (Dansgaard–Oeschger (DO) events) during the last ice age through an oceanic ‘bipolar seesaw’ mode that lags behind Northern Hemisphere climate by about 200 years (Pedro et al., 2018). However, a latest analysis using synchronized Antarctic ice core records revealed instantaneous linkages between Antarctic and Arctic climate (Buizert et al., 2018). The study found that the abrupt and synchronous ice-age shifts during Dansgaard–Oeschger (DO) events revealed a zonally coherent migration of the Southern Hemisphere westerly winds over all ocean basins in phase with Northern Hemisphere climate. Identification of a rapid atmospheric link between climates at the

poles has huge implications for our understanding of current climate change and how the dramatic changes happening in Arctic could affect the Antarctic climate and stability of its ice sheets.

The Indian research activities in Arctic are very recent and mainly focus on atmospheric, oceanographic and glaciological processes, with limited studies on climatic reconstructions. Therefore, the current review focuses on the palaeoclimatic reconstructions from Antarctica and the surrounding Southern Ocean by Indian scientists (Figure 1). Due to the limited and the short period of observational and instrumental data on Antarctic climatic variables, our knowledge of the functioning of Antarctica within the global system and the spatial and temporal complexity of Antarctic climate is still poor. Fundamental questions remain in this approach are: How typical of Antarctic climatic history is the recent variability? Has Antarctica experienced

a typical spatial climate pattern over the last several centuries to thousands of years, as suggested for other regions of the globe? How heterogeneous is Antarctic climate system and its linkages with other climate modes? To find some answers to the above questions, study of Antarctic climate variability on an array of timescales (millennial, centennial to decadal timescales) is crucial. Towards this, Indian researchers have been undertaking various palaeoclimatic studies in polar region, with a focus on Antarctic and Southern Ocean region.

Results and Discussion

Antarctic long-term climate records come primarily from proxy records of ice cores or marine and lake sediment cores. While ice cores provide one of the most direct and more accurate means to

Figure 1. Schematic map depicting Antarctica and Southern Ocean, with major geographic names, currents and oceanic fronts embedded. The region south of Subantarctic Front (shaded in blue) is generally considered as Southern Ocean for all scientific purposes. The study areas as discussed in the text are shaded in light red. DML – Dronning Maud land; PEL – Princess Elisabeth Land; WL – Wilkes Land

study the Antarctic climate variability, they are limited and may contain a mixture of global, regional and local signals, depending on the site and the proxies used. The lake sediment records are commonly used to identify regional signals such as temperature and relative sea level change, and local changes such as the advance and retreat of catchment glaciers and ice shelves.

Ice core records of Antarctic climate variability and global linkages

Glaciochemical processes and biogeochemistry

To improve the utility of the ice cores as reliable climate archives, it is important to understand the fundamental air-snow transfer processes over Antarctic cryosphere. Indian scientists have put substantial efforts to understand the air-snow processes and the biogeochemical cycling in the Princess Elisabeth Land (PEL) and Dronning Maud Land (DML) regions in East Antarctica (Figure 1). Glacio-chemical analysis of surface snow from the Princess Elisabeth Land provided fundamental data in differentiating multiple sources (sea spray, crustal, cosmic, and biogenic sources) in the snow samples that revealed that significant fractionation of non-sea-salt sulphate happens during summer, with implications on sulphur budget in coastal Antarctica (Thamban et al., 2010). Biogeochemical analysis of Antarctic snow samples also revealed that elevated nutrient concentrations snow may be responsible for the observed enhanced growth of microalgae in snow and subsequent production of bromocarbons, thus explaining the high bromide concentration in snow (Antony et al., 2010).

Study on the distribution and source pathways of environmentally critical trace metals in coastal Antarctic snow revealed that while contributions from natural sources are still dominant in Antarctica, anthropogenic contamination related to the ever increasing logistic activities is locally significant (Thamban and Thakur, 2012). Glaciochemical studies also demonstrated the influence of the degree of slope of the ice sheet surface on the distribution of sea salt ions in Antarctic snow (Mahalinganathan et al., 2012). The association between Ca^{2+} , an important proxy indicator of mineral dust and NO_3^- , the most dominant anion in Antarctic snow along two coastal–inland transects from PEL and central DML in East Antarctica revealed the possible formation of calcium nitrate in Antarctic atmosphere and its deposition in Antarctic snow and ice (Mahalinganathan and Thamban, 2016). The study revealed that the formation of calcium nitrate possibly happens during the long range aerosol transport from South America to Antarctica, which may significantly influence the nitrogen budget in Antarctic snow.

Molecular composition of natural organic matter in Antarctic snow revealed that organic carbon in Antarctic ice sheet is a quantitatively important dissolved carbon source to coastal ecosystems and have two major sources: a). *in situ* microbial processes; b). remotely supplied input from terrestrial vascular plants-derived materials (Antony et al., 2011 & 2014). Biochemical and microbial characteristics of various supraglacial ecosystems such as, snow, melt-water streams, blue ice and cryoconite holes together with their role in biogeochemical cycling on the glacier surface was systematically studied during the past decade. The studies on cryoconite hole and surface snow samples collected from coastal Antarctica has shown that the supraglacial environments contain a substantial reservoir of organic carbon with inputs from microbial, marine and terrestrial

sources (Antony et al., 2014; Samui et al., 2017, 2018). The dissolved organic matter (DOM) transformations by supraglacial microbes revealed that both autochthonous and allochthonous DOM is highly bioavailable and is transformed by resident microbial communities through parallel processes of degradation and synthesis (Antony et al., 2017). The biogeochemistry of DOM is highly complex and intimately connected with microbial and photochemical processes operating individually or in combination (Antony et al., 2018).

Ice core records of late Holocene climate variability

Time-series observations of Antarctic climatic parameters were initiated only since the International Geophysical Year (1957-58) and therefore, the instrumental records of Antarctic climate are very sparse and only some decades old. Study of a network of high-resolution ice core records across the Antarctic continent with annually resolved proxy records ice core records offer one of the most direct and accurate method to study the Antarctic climate variability beyond the instrumental limits (Mayewski et al., 2005; Schneider et al., 2006; Mayewski et al., 2009). This is an area of active research by Indian scientists using shallow to medium depth ice cores from coastal Dronning Maud Land (DML) in East Antarctica (Figure 1). The early results suggested that shallow ice cores are indeed useful for regional climate reconstruction through a careful selection of core sites and a focussed study of proxy parameters (Nijampurkar et al., 2002; Thamban et al., 2006; Laluraj et al., 2009). The annually dated high-resolution (annual) ice core studies revealed the utility of ice records to reconstruct the natural environmental processes as well as the polar and extra-tropical climatic teleconnections during the past hundreds of years (Naik et al., 2010 a,b; Thamban et al., 2011 a,b; Thamban et al., 2013; Antony et al., 2012; Laluraj et al., 2011; Laluraj et al., 2014; PAGES 2k Consortium, 2013; Rahaman et al., 2016). The increased focus on the well-dated ice cores from high accumulation regions of coastal Antarctica have improved our understanding on the recent climate variability in Antarctica and forcing mechanisms.

The ice core proxy based reconstruction revealed significant changes in Southern Hemispheric climate during the past several hundreds of years (Naik et al., 2010 a, b; Thamban et al., 2011 a,b; Thamban et al., 2013). The study revealed utility of shallow ice cores in reconstructing the past changes in major climatic modes like the El Niño Southern Oscillation (ENSO) and Southern Annular mode (SAM) (Naik et al., 2010 a). Naik et al., (2010 b) demonstrated that the $\delta^{18}\text{O}$ based climate records revealed a significant relation to the SAM with a dominant ~4 years variability, except during specific periods (1918-1927; 1938-1947; 1989-2005) when ENSO teleconnection was established through the in-phase relation between SAM and Southern Oscillation Index (SOI). A significant relationship between $\delta^{18}\text{O}$ and SAM was observed on a decadal scale, which overrides the intermittent influence of ENSO. Detailed analysis of the $\delta^{18}\text{O}$ records of IND-25/B5 covering a period of past one century (1905-2005) revealed a significant warming of 1°C during 1905-2005 (Naik et al., 2010 b). The oxygen isotope ($\delta^{18}\text{O}$) records from ice core (IND-22/B4) also supported significant changes in temperature during periods of solar activity as well a warming trend of 2.7°C for the past 470 years, with an enhanced warming during the last several decades (Thamban et al., 2011 a; Thamban et al., 2011 b). Further, nitrate (NO_3^-) records from the IND-22/B4 ice core reveals a close resemblance to the ^{10}Be record (solar proxy) from South Pole and therefore seems to demonstrating the influence of external solar forcing

on the circulation pattern over the Antarctica during last 470 years (Laluraj et al., 2011). Microbiological studies of polar ice at different depths of the above ice core also provided an important comparison, as they preserve records of microbial cells and past climate conditions (Antony et al., 2012). The bacteria identified from the different depth of the ice core might have been transported and deposited into ice along with dust particles and marine aerosols.

By integrating the proxy temperature data using ice cores and various proxy records across seven continental-scale regions, a global study revealed an overall cooling trend across nearly all continents during the last two thousand years (PAGES 2k Consortium, 2013). This cooling trend was reversed by distinct warming, beginning in some regions at the end of the 19th century. The dust record of IND-25/B5 ice core showed that dust deposition in East Antarctica followed the Southern Hemispheric climate change and doubled during the 20th century (Laluraj et al., 2014). Strong positive correlation observed between dust flux and the SAM suggests that the positive values of the SAM index are likely to be responsible for the recent increase in dust deposition over East Antarctica, through strengthening of westerly winds. NCEP/NCAR reanalysis data reveals that the polar easterlies consistently strengthened since 1985 at the study region, leading to the sinking of dust materials brought by the stronger westerlies. Interestingly, the timing and amplitude of the insoluble dust flux matched remarkably well with the trace metal fluxes of Ba, Cr, Cu, and Zn, confirming that dust was the main carrier of airborne geochemical tracers to East Antarctica in the recent past (Laluraj et al., 2014). The observed doubling of dust and associated trace metal deposition in East Antarctica have wide-ranging implications for understanding the factors driving the inter-continental transportation of impurities and their environmental impact on Antarctica. These results have far-reaching implications for understanding the changes in temperature and dust levels and their impact on climate both in the recent past and future.

High resolution study of deuterium excess (d-excess), sea-salt sodium (ss-Na⁺) and methane sulfonic acid (MSA) in the ice core IND-25/B5 from coastal Dronning Maud Land also revealed the history of moisture transport and sea ice condition during the last century (Rahaman et al., 2016). Sea ice extent (SIE) in the Weddell Sea was reconstructed based on Antarctic ice core records of stable oxygen ($\delta^{18}\text{O}$), hydrogen (δD) isotopes and sea-salt-Na⁺. Among them, ss-Na⁺ flux record shows significant positive relationship with winter SIE in the Weddell Sea. Wavelet analysis of SAM index and SOI shows the highest common power in 4–8 year band during 1940–1960 and 1990–2000 overlapping with the period of higher SIE. This shows large variability during the last century (1905–2005 AD) which impacted moisture transport from various oceanic sectors to Antarctica. Cluster of backward wind trajectories shows that air parcels were mainly originated from the Weddell Sea with additional sources from the Ross Sea and the Bellingshausen–Amundsen Sea regions. Dramatic increase in SIE was observed in the Weddell Sea sector during 1940–1980. This study suggests that moisture source and sea ice variability in annual–decadal scale in Antarctica seems to be largely influenced by SAM and its teleconnection to ENSO.

Antarctic surface air temperature (SAT) reconstructed approximately for the past five centuries (~1533 to 1993 CE) based on multiple oxygen isotope ($\delta^{18}\text{O}$) records of ice cores from East and West Antarctica show dominant oscillations in ENSO and Pacific Decadal Oscillation (PDO) frequency (Rahaman et al., 2019). Further, variance of the East Antarctica (EA) temperature record shows

significant increasing trend at ENSO band and decreasing trend at PDO band since the post-industrial era (~1850 CE). This study suggested that the ENSO activity and its influence on Antarctic temperature are increasing in response of continuing greenhouse warming since the industrial era.

Currently, the Indian ice core research is focussing on integrating the various Indian ice core data from central Dronning Maud Land as well as various other ice core based climate records from Antarctica, through statistical processing of data and through modelling initiatives. Additionally, new proxy parameters like triple oxygen isotope ratios are explored as a more reliable proxy of moisture source and humidity as the $\delta^{17}\text{O}$ values of snow/ice are less dependent on temperature variations unlike the $\delta^{18}\text{O}$ and δD records. One of the biggest challenge for obtaining reliable climate records from coastal regions of Antarctica are the possible melting of ice surface during the peak summer season, thus obliterating the stable isotope based climatic reconstruction and age construction. Many ice cores from coastal sites also reveal melt layers which could potentially hold information on the past intervals and extent of warming in Antarctica. In order to establish chronology and extract climatic information, visual stratigraphy techniques are being developed to identify seasonal cycles and melt layers in ice cores and utilize this method for climatic reconstruction in coastal Antarctic sites.

Recent PAGES community based studies have revealed that the climatic records from Antarctica reflect large spatial variability and needs to be explored with an array of annually resolved ice core records across multiple regional domains (Stenni et al., 2017). Since the pattern and amplitude of decadal climate variability in Antarctica 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. Available ice core information clearly suggests that the central Dronning Maud Land is a unique region in East Antarctica and provide a window of opportunity to study the past variability in westerly winds, sea ice and climate over the late Holocene and their possible linkages to the tropical climate. Since the available ice core records from Dronning Maud Land having annual temporal resolution are limited and are restricted to the last few centuries, efforts needs to be undertaken to recover deeper ice core records to determine the range of natural variability and provide realistic boundary conditions for global climate models over timescales of decades to millennia.

Palaeoclimatic reconstruction using Antarctic lake records

Antarctic lakes are sensitive indicators of environmental changes and their sediments integrate information about climatic and biogeochemical changes, enabling to use them as archives of past environmental conditions of its surrounding region (Smeltzer and Swain, 1985; Warriar et al., 2017). The coastal Antarctica is bestowed with several ice-free regions that are characterised by the presence of different types of lakes are also present in these ice-free regions which are classified into epishelf, pro-glacial and land-locked based on their geomorphic characteristics (Ravindra, 2001). Indian scientists have been actively studying the ice free regions within the logistic limitations of the Indian scientific activities around the research stations Maitri (Schirmacher Oasis, in Dronning Maud Land) and Bharati (Larsmann Hills, in Princess Elisabeth Land) in the East Antarctica (Figure 1).

The initial Indian attempts to study the sedimentary records of freshwater lakes in East Antarctica were focussed on the Schirmacher Oasis, mainly to decipher the lacustrine sedimentology, past environmental changes and long-distance transport of palynodebris (Sinha and Chatterjee, 2000; Sinha et al., 2000; Bera, 2004; Sharma et al., 2007). Using quartz grains from lake sediments, the imprint of glacial, glacio-fluvial, and aeolian processes on the sediment deposited in the lakes of Schirmacher Oasis were studied (Asthana et al., 2009; Shrivastava et al., 2009). During the last decade, more systematic studies using improved sediment retrieval techniques and better constrained sedimentary records were undertaken from Schirmacher Oasis, Larsemann Hills and Vestfold Hills to decipher the palaeoclimate and paleoenvironment conditions. A variety of proxy parameters and analytical techniques like environmental magnetism, sedimentology, geochemistry, biogenic silica, and micro-plaeontological parameters were studied.

Several studies have been made on lake sediments from Schirmacher Oasis and Larsemann Hills in Antarctica to better understand the past changes in lacustrine environments (Govil et al., 2011, 2012; Shrivastava et al., 2012; Asthana et al., 2013). Phartiyal et al., (2011) have tried to reconstruct the evolution of the Schirmacher Oasis from 13 ka BP to the present. The results show a drastic reduction in the lake sizes by negative water balance and can possibly be attributed to the combined effect of recession of glaciers feeding them, low melt water, low precipitation and strong winds. Govil et al. (2011, 2012) analyzed a sediment core from Larsemann Hills, East Antarctica to reconstruct the paleoproductivity fluctuations and factors responsible for it, based on Biogenic Silica (BSi), Sand (%) and Total Organic Carbon (TOC). The core show prominent high productivity from ~8.3 to ~6 cal ka BP in comparison to less productivity in mid-late Holocene (~6 cal ka BP to recent). Moreover, the glacio-fluvial deposition condition prevailed from ~8.3 to ~5 cal ka BP. The increased productivity in the upper part of the core possibly indicates presence of algal mat due to exposure of the lake to the ice free (glacier free) conditions. Presence/absence of diatom along with variation of sand percentage suggests the alternate glacial-interglacial phase prevailed in this region. Further, few studies have focussed on sediment records of the Vestfold Hills (Mazumder et al., 2013a; Mazumder et al., 2013b; Mazumder and Govil, 2013). Mazumder et al. (2013a) suggested that the constant seawater influence in the lake (which was predominated in early Holocene) got weakened after ~5000 yrs BP till date, based on diatom population and the abundance of salt crystal present in sediments. Mazumder et al. (2013b), Mazumder and Govil (2013) reported the relatively warmer climatic condition in late Holocene based on the abundance of icier condition indicator species *Fragilariopsis curta* along with other diatom assemblages.

Studies by the Geological Survey of India revealed that the overall characteristics and composition of the sediments in the epi-shelf lakes of the Schirmacher Oasis are a function of source rock compositions, sediment transportation, depositional processes and weathering. The lake sediments indicates changing conditions in the transporting medium and/or the contribution of sediments from multiple provenances (Shrivastava et al., 2012). Field observations, granulometric analyses of sediment and morphological studies of selected quartz grains in Schirmacher Oasis and Larsemann Hills showed similar results, except for the extent and strength of glacial and glaciofluvial processes. Change in energy conditions is evident from the distribution pattern of sediments in both places (Asthana et

al., 2013). Sedimentological properties of surface sediments from lakes of Schirmacher Oasis and Larsemann Hills helped to understand the sedimentary and glacial erosional processes taking place in the two regions. The sediments from Fisher Island showed a lithic arenite to arkosic composition, indicating slightly to moderately weathered source rocks. Sediments on Fisher Island show intense mechanical textures characteristic of glacial transport (Asthana et al., 2013). The periglacial environment of Schirmacher Oasis and Larsemann Hills is characterized by a wide range of sedimentary and glacial processes, resulting in different combinations of erosional and depositional features.

Proxy records of magnetic susceptibility (MS) and loss-on-ignition (LOI) data for seven sediment profiles from five paleo-lake deposits were used to reconstruct the climatic changes (Phartiyal et al., 2011). The LOI data suggested a very low organic content, whereas MS data helped in the reconstruction of changing detrital input. The presence of longer sediment profile (> 1 m thick) indicated the presence of five large lakes in the Schirmacher Oasis during the Holocene, which shrunk over a period of time leading to the occurrence of smaller lakes. The authors inferred that from 13 to 12.5 cal ka B.P., the whole of Schirmacher Oasis was dominated by glaciers with the present day land-locked lakes being the glacial lakes. The onset of Holocene warming at 11.5 cal ka B.P. led to the retreating of glaciers giving rise to five large proglacial lakes which occupied the low-lying valleys of Schirmacher Oasis. The drying of the landlocked lakes was attributed to several factors such as lack of water supply during summer months due to the recession of glaciers, reduced precipitation or snow accumulation, less melt-water streams, strong winds and sublimation of the lake due to prolonged ice-cover. On the other hand, the proglacial and the epishelf lakes continue to have a regular source of melt water from the continental ice sheet and the ice shelf, respectively. Another study using environmental magnetic and geochemical properties of sedimentary deposits of Schirmacher Oasis described six phases of climatic fluctuations between 13 and 3 ka using mineral magnetic parameters (Phartiyal, 2014). According to the study, Schirmacher Oasis experienced a short phase of relatively warmer climatic conditions during 12.5 cal ka B.P., 11-8.7 cal ka B.P. and 4.4-3 cal ka B.P. (Mid-Holocene Hypsithermal).

Based on the environmental magnetic properties of sediments deposited in the Sandy Lake in the Schirmacher Oasis, glacial-interglacial climatic variation was reconstructed for the past 42.5 cal. ka B.P. (Warrier et al., 2014). This study provided environmental magnetic evidence for the Schirmacher Oasis escaping full glaciation during the past 40,000 years. The magnetic mineralogy was dominated by the presence of titanomagnetite. Glacial periods were characterized by high magnetic mineral concentrations and coarse SSD titanomagnetite. The LGM has documented the highest concentration of magnetic minerals, indicating widespread glaciation in the Schirmacher Oasis. The Holocene period was characterized by alternating phases of relatively warm (12.55–9.88 cal. ka B.P. and 4.21–~2 cal. ka B.P.) and cold (9.21–4.21 cal. ka B.P. and from ~2 cal. ka B.P. onwards) events. Many of the relatively warm and cold events discerned in this study were correlatable with other lake sediment and ice-core records from the Schirmacher Oasis and other ice-free areas in East Antarctica. The organic geochemical and sedimentological data from sediments deposited in Long Lake (L-27), Schirmacher Oasis, provide a history of glacial-interglacial climatic variations during the last 48,000 cal. years B.P. (Mahesh et al., 2015). The last glacial and major part of Holocene records the

lowest organic carbon indicating that the productivity was generally lower suggesting longer ice-cover period due to extreme cold conditions. The sustained Holocene warm conditions would have resulted in the lake experiencing longer ice-free conditions beginning at 6 cal ka B.P. as evident in the grain size variation. The results showed that Long Lake's response to Antarctic climate is reflected in its response to the ice-cover conditions which regulates the productivity and sedimentation in the lake system. These multi-proxy records from the sediment cores will help to reconstruct high-resolution past climatic variations in Antarctica.

The sediment particle size and quartz grains deposited in the sediments of Sandy Lake were used to understand their provenance and also the strength of the transporting medium during the past 42.5 cal ka B.P. (Warrier et al., 2016). The sediments are poorly sorted and finely skewed and show different modes of grain size distribution throughout the last 43 cal ka B.P. The statistical parameters of grain size data indicate that the sediments are primarily transported by melt-water streams and glaciers. During the last glacial period, wind activity was strong as evident by the good correlation between rounded quartz data and dust flux data from EPICA ice-core data. SEM studies of selected quartz grains and analyses of various surface textures indicate that glaciogenic conditions must have prevailed at the time of their transport. Semi-quantitative analyses of mineral (quartz, feldspar, mica, garnet and rock fragments & other minerals) counts suggest a mixed population of minerals with quartz being the dominant mineral. The study reveals the different types of physical weathering, erosive signatures, and chemical precipitation most of them characteristic of glacial environment which affected these quartz grains before final deposition as lake sediments.

Recently, multi-proxy sedimentological data, generated from the sediment cores from land-locked lakes and grab sample from a proglacial lake, lying in the same drainage line in the central part of Schirmacher region has provided better insight into the paleoclimatic evolution of the region (Srivastava et al., 2018). The study revealed that different phases of warmer and cooler intervals are highlighted by the patterns of fluctuations in different sedimentological and statistical parameters. The dominance of glacial signatures is very clear on the lake sediments as revealed by the surface textures of quartz grains. Physical weathering has mainly controlled the overall sediments and the composition of clay fraction. The clay minerals indicate a gradual shift in the weathering regime and therewith in climate from strongly glacial to fluvio-glacial specially around 42 ka. This indicates beginning of warming of the area much before the LGM. But the warm period is not strong enough to alter the overall clay chemistry. Proxy records indicate short-period climatic oscillations during late Quaternary.

Considering the local influences on Antarctic lacustrine records, it is imperative that an array of palaeoclimatic records using multiple environmental proxies is required for a better understanding the past environmental conditions in coastal Antarctic lakes. Another issue that needs to be addressed is the separation of climatic signals from neotectonic influence on lake records due to the postglacial isostatic upliftments (Mahesh et al., 2018). The Indian efforts need to be focussed to obtain more reliable and quantitative palaeoclimatic records.

Palaeoceanography of the Southern Ocean

The Southern Ocean surrounding the Antarctic continent is a vital

link in the global oceanic heat engine, in part because of its unique geography: the Southern Ocean occupies the only band of latitudes on Earth where ocean waters circle the globe (Figure 1). This simple fact turns out to have profound implications for the global ocean circulation and the Earth's climate system. The Antarctic Circumpolar Current (ACC), which flows from west to east between the Antarctic continent and Antarctic Convergence is the earth's major ocean current, leading to a colder and isolated seawater in the Southern Ocean that supports a unique marine ecosystem. Because the ocean basins are almost surrounded by land except at their southern boundaries, the ACC is the primary means by which water, heat, and other properties are exchanged between the ocean basins. The ACC connects the Atlantic, Pacific and Indian Oceans to form a global network of ocean currents that redistributes heat around the Earth and so influences climate. The circumpolar connection in the Southern Ocean also permits global thermohaline circulation to exist. The water masses thus formed in the Southern Ocean spread throughout the world ocean. When these new water masses sink from the sea surface, they carry oxygen and carbon dioxide into the deep sea, to 'ventilate' the sub-surface ocean (Toggweiler, 1999). In the absence of this dense, oxygen-rich water sinking near Antarctica, the deep ocean would have very low oxygen levels. The water sinking in the Southern Ocean also carries carbon dioxide into the ocean. About one third of the carbon dioxide produced by human activities is accumulating in the ocean, slowing the rate of climate change due to the enhanced greenhouse effect. Of this, 40% is being sequestered in the Southern Ocean by water masses sinking from the sea surface as part of the overturning circulation.

The Southern Ocean sink is centred near 50°S (between 35° and 60°S) and is more pronounced in the Atlantic and in the Indian sectors of the Southern Ocean. The recent changes in Antarctic climate are found to impact on its effectiveness as a CO₂ sink (Le Quere et al., 2007). Proxy data and models demonstrate that a combination of biological and physical processes contributed to lowering the atmospheric CO₂ during glacial times, whereby the Antarctic zone was more strongly stratified (Francois et al., 1997; Sigman et al., 2010) and productivity was higher in the Subantarctic during ice ages (Kumar et al., 1995; Martinez-Garcia et al., 2011). Accordingly, the Southern Ocean during different time period could have acted either as a source or a sink of atmospheric CO₂ by changes in the productivity regime or oceanic circulation, or both (Jaccard et al., 2013).

Late Quaternary oceanic changes in the Indian sector of the Southern Ocean

Southern Ocean sediment records provide versatile archives on major oceanographic changes such as changes in currents or distribution of water masses, regional changes in parameters such as sea-ice extent and surface water productivity, and local changes such as the extent of ice shelves and its stability. Indian scientific activities that focus in the Indian sector of Southern Ocean (SO) were initiated since 2004. Since then, several studies have been undertaken for better understanding the past climate variability in the Indian sector of the Southern Ocean at millennial and glacial-interglacial timescales. Based on the samples collected during various expeditions, several studies were undertaken by Indian researchers within the Indian sector of Southern Ocean to understand the modern and past changes in oceanographic processes using sedimentological, micro-palaeontological, stable isotope and geochemical proxies (Thamban

et al., 2005; Mohan et al., 2006, 2008, 2011 and 2015; Saraswat and Khare, 2010; Tiwari et al., 2011; Sruthi et al., 2012; Manoj et al., 2012, 2013 and 2015; Khare and Chaturvedi, 2012; Shukla et al., 2013; Patil et al., 2014, 2015 a,b, 2017; Nair et al., 2015; Prasanna et al., 2016).

The first Indian attempt to understand the changes in the terrigenous sediment source and transport mechanisms during the late Quaternary in Indian sector of SO were undertaken using four sediment cores, through the magnetic susceptibility and sedimentological records (Thamban et al., 2005). Sediments deposited during the Holocene and other interglacial periods were characterized by low magnetic susceptibility (MS), low sand content, reduced ice-rafted detritus (IRD) input and increased illite possibly transported via hydrographic advection from south. Significant reduction in clay fraction and illite content during glacials suggest that the erosive and transporting capabilities of the deep and bottom waters could have reduced compared to the interglacial times. The changes in terrigenous influx were significantly influenced by the rhythmic glacial-interglacial fluctuations in bottom circulation and the position of the Polar Front (PF) in this region (Thamban et al., 2005).

A comparison of the rock magnetic records with the planktic $\delta^{18}\text{O}$, IRD and calcium carbonate records from a marine sediment core from Indian sector of SO reveals that the terrigenous influx, ice rafting, sea-surface temperature and carbonate productivity at the core site are apparently interrelated (Manoj et al., 2012). The records of ice rafted detritus (IRD) in the Southern Ocean sediments offer potential as proxy indicators to investigate the dynamic behaviour of Antarctic ice sheets and Antarctic climate (Thamban et al., 2005). The concentration of IRD in the sediment core SK200/27 retrieved from Indian sector of SO (south of PF) was nearly twice that in the SK200/22a (north of PF). Moreover, IRD was more abundant at the LGM in SK200/27 with its peak abundance preceding by nearly two millennia than the abundance in the core SK200/22a (Manoj et al., 2013). It seems that an intensification of Antarctic glaciation combined with a northward migration of the Polar Front during LGM promoted high IRD flux at SK200/27 and subsequent deglacial warming could have influenced the IRD supply at SK200/22a (Manoj et al., 2013). A high resolution multi-proxy (calcium carbonate, opal, total organic carbon, biogenic barium and planktonic isotope records) palaeoproductivity on a core from the Indian sector of SO reveal an inverse relationship between the calcium carbonate concentration and opal productivity, indicating the influence of shifting nutrient regimes in the Southern Ocean. (Sruthi et al., 2012; Manoj and Thamban, 2015). To the north of PF, reduced calcite productivity during glacial period suggests an equatorial migration of the frontal regimes. In contrast to the south of AF, increased opal productivity during the interglacial period indicates a southward migration of AF (Manoj and Thamban, 2015). North of PF (Indian sector) was characterised by reduced carbonate productivity as compared to Holocene and the last deglaciation, as indicated by barium concentrations (Sruthi et al., 2012).

Micropalaeontological studies in tandem with sedimentological and geochemical studies offer excellent opportunities to reconstruct paleo sea-ice and hydrographic changes in the Southern Ocean and its impact on biological productivity. Mohan et al., (2006) analysed the latitudinal variation of diatom in surface sediments of Southern Ocean (Indian sector) to understand its relationship with the changing nutrient conditions, and its utility in palaeoceanographic reconstruction. The study revealed that the spatial distribution of diatoms in surface sediments shifts in tandem with the frontal changes

(SST and salinity) and related nutrient availability in the water column. Study of diatoms from surface sediments of Enderby Basin of Indian Sector of Southern Ocean revealed that the diatom abundance correlates well with the variation in Antarctic summer and winter sea-ice extent (Mohan et al., 2011). An interesting application of the morphology of diatom as a proxy is to analyze if and how it varied over glacial to interglacial transitions at the Polar Front, as this may reflect millennial-scale shifts in the position of this front, and the associated high export of biogenic silica (Shukla et al., 2013; Nair et al., 2015; Nair et al., 2017). Shukla et al. (2013) suggested that variations in circum-polar upwelling were the main controlling factor in opal production during the last ~20,000 years. It was also hypothesized that high nutrient input from the Antarctic Peninsula during the last deglaciation may have exerted a strong control on *F. kerguelensis* valve size and opal export in the Atlantic sector of the Southern Ocean (Shukla et al., 2013).

A diatom based palaeoceanographic reconstruction from the Indian sector of SO deciphered that the Polar Front shifted significantly towards north (Nair et al., 2015). This study also reported that glacial periods north of the Polar Front were characterised by high diatom productivity and larger *Fragilariopsis kerguelensis* (pennate diatom) and *Thalassiosira lentiginosa* (centric diatom) sizes. The larger and heavily silicified diatoms such as *F. kerguelensis* and *T. lentiginosa* may have effectively contributed to transporting biogenic silica and organic carbon to the sea bed during the last 42 ka BP (Nair et al., 2015). Both the geochemical and palaeontological records of paleoproductivity revealed the significant association with shifting nutrient regimes as a consequence of varying frontal zones (Manoj and Thamban, 2015; Nair et al., 2015).

Oceanic records of Cenozoic climatic variability in Antarctica

Antarctica has occupied polar latitudes since the Early Cretaceous (145 – 100 Ma before present), but has not been extensively glaciated for most of its history. A number of tectonic events during the Cenozoic era (beginning at 65 Ma) contributed to persistent and significant planetary cooling (Kvasov and Verbitsky, 1981; Lurcock and Florindo, 2017). At 40 Ma, ongoing plate motion widened the narrow gap between South America and Antarctica, resulting in the opening of the Drake Passage. The timing of events leading to the earliest connection between the Pacific and Atlantic oceans at Drake Passage had a profound effect on global circulation and climate. A rigorous analysis demonstrated that a major change in the motion of the South American and Antarctic plates at about 50 Ma was accompanied by crustal extension and thinning during the middle Eocene around 30–34 Ma, which was the trigger for abrupt Eocene–Oligocene climate deterioration and the growth of extensive Antarctic ice sheets (Livermore et al., 2005).

In order to study of evolution and dynamics of the Antarctic cryosphere during the Eocene–Oligocene transition (~34 Ma) through the significant subsequent periods of likely coupled climate and atmospheric CO_2 changes, Indian scientists have joined the Integrated Ocean Drilling Program (IODP) that drilled through the Antarctic Wilkes Land margin (Fig. 1). The major aim was to provide a long-term record of the sedimentary archives along an inshore to offshore transect of Cenozoic Antarctic glaciations and its intimate relationships with global climatic and oceanographic change. Since paleoceanographic reconstructions from Wilkes Land margin drill

cores critically depend on a robust stratigraphic framework, efforts have made for a robust chronological framework. A stratigraphic framework was developed that allows the placement of future proxy-based paleo-records into a context of global climate and ocean circulation models during a critical period of time. The record from the Wilkes Land Margin will contribute significantly to our understanding of Antarctic climate and ice sheet evolution and their feedbacks to the global climate system (Tauxe et al., 2012).

Provenance study of Pleistocene sediments from Site U1359 of the Wilkes Land IODP Leg 318 revealed evidences for multiple sourcing from the East Antarctic Craton and Ross Orogen (Pant et al., 2013). The nature of rock fragments in Pleistocene sediments from Wilkes margin of East Antarctica and the composition of minerals is suggestive of a polymetamorphosed provenance, with peak metamorphism at least in the amphibolite–granulite transition. A subordinate low to medium grade metamorphic component is also reflected. The composition of basalt fragments suggest sediment sourcing from the Transantarctic Mountains. This implies a change of ocean currents, which is possible in the case of warmer climate and recession of the East Antarctic Ice Sheet. Increased kaolinite content in the clay mineral fraction supports this inference. Chemical geochronology of euhedral accessory minerals, indicating Ordovician–Silurian provenance ages, corroborates sediment sourcing from the Ross Orogen (Pant et al., 2013).

A global “colder” late Miocene (prior to 5.33 million years) and a ‘warmer’ Pliocene is commonly inferred mainly from the benthic foraminiferal records mainly from the low-latitude proxy data, but ice-sheet proximal records are limited. The clay mineralogy records of Core U1359 (IODP Hole 318) collected from the continental rise off Wilkes Land (East Antarctica) indicate that the beginning of ‘warming event’ occurred in late Miocene rather than early Pliocene in the eastern sector of Wilkes Land (Verma et al., 2014). In their study the ice retreat condition deciphered during 6.8–6.2 Ma shows that in the eastern sector of Wilkes Land margin ‘warming’ had started in latest Miocene, much earlier than the other part of East Antarctica and was preceded by a high concentration of IRD during 9–7 Ma period indicating a prolonged cooling period. This study also revealed that during times of ice growth, the East Antarctic craton provided biotite-rich sediments to the depositional site. On the other hand, the presence of smectite, only in the clay size fraction, suggests the effective role of sorting probably due to the deposition from distal source in ice retreat condition. During times of ice retreat, smectite-rich sediment derived from Ross Orogen is transported to the core site through surface or bottom water currents.

Conclusions

Analysing the past changes in Antarctic climate can provide insights into the potential future climate impacts and ecosystem feedbacks, especially over the millennial-to-centennial timescales. Recent initiatives made by the Indian researchers in Antarctica and the surrounding ocean have contributed to the understanding of past dynamics and variability of Antarctic climate, ice sheet processes, oceanic changes and the biogeochemical processes. Among the different types of palaeoclimate archives used, the ice core studies have generated excellent knowledge base on the past few centuries of Antarctic climate and its global linkages. Studies using high resolution climate records from Antarctica have revealed the climatic response to solar forcing as well as the decadal to inter-decadal

behaviour of the major climate modes like the Southern Annular Mode (SAM), El-Nino-Southern Oscillation (ENSO), Pacific-South American mode (PSA), and the Pacific Decadal Oscillation (PDO). Compared to the ice core records, the Antarctic lake sedimentary records have provided information on the millennial scale regional climatic variability during the late Quaternary. Recent developments in the study of undisturbed and high quality sedimentary records from lakes of Schirmacher Oasis and Larsemann Hills have provided improved understanding of the Holocene variability with better temporal resolution and stratigraphic constraints. The deeper sedimentary records from the Antarctic continental margin under the initiatives of IODP offer us an important opportunity to study of evolution and dynamics of the Antarctic cryosphere from its inception. However, it is imperative that multiple types of palaeoclimate records having complex stratigraphic constraints and sampling resolution needs to be integrated with suitable error estimations to have a better understanding of the Antarctic climate system on different time scales.

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