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Recent Indian Contributions from the Polar Realm

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Polar science in India has gained enough impetus post the 1980's with the launching of the Indian Scientific Expedition to Antarctica on 6th December 1981 and the establishment of the Department of Ocean Development (now the Ministry of Earth Sciences). Indian scientific endeavors in the polar realm are tripolar with emphasis on the Arctic, Antarctica (including the Southern Ocean) and the recent addition of Himalayas to the mandate (not covered in this article). The scientific endeavors of the Indian Scientific Expedition to Antarctica (ISEA) have increasingly covered a wide spectrum of fields since 1981. These include, geological investigations of exposed outcrops in the vicinity of the Indian Antarctic research bases, paleolimnological studies, satellite remote sensing related work, polar biological science, and the snow, ice and ice core studies. Indian researchers have put footprints in the Arctic (since 2007) at the Ny-Ålesund scientific village, Svalbard. India therefore has now its presence in both Arctic and Antarctica with active research bases (Arctic: Himadri; Antarctica: Maitri and Bharati; managed by the National Centre for Polar and Ocean Research based in Goa). In addition, India launches dedicated expeditions to the Southern Ocean to decipher its hydrodynamics and biogeochemistry. A brief overview of scientific achievements of Indian researchers in the various fields of research is provided in this compilation.

Keywords: Polar Science; Southern Ocean; Arctic and Antarctica

Geological Studies

In the view of twin limitation of scanty outcrops and logistic constraints in reaching rock exposures, most of the Antarctic geology has evolved either (a) near vicinity of the permanent research stations owing to better accessibility of resources; or (b) in expedition cum camping mode to cover relatively remote areas. The Indian Antarctic Expeditions started in the year 1981 with building a permanent research base (Dakshin Gangotri) firstly on Ice shelf of the Lazarev sea and then second research base (Maitri) on stable rocky outcrops of the Schirmacher Oasis. The initial thrust was preparation of baseline geological maps of the region, what started as a much localized geological mapping and interpretations of the Schirmacher Oasis later expanded into geological mapping and crustal evolution studies of a sizeable 19,000sq. km of the central Dronning Maud Land (cDML) region. From the year 2011, with the building of India's third research station – 'Bharati' in the Prydz bay, Indian contributions to Antarctica started with the initiation of mapping and understanding the geological complexities of this region.

Contributions towards possible extension of the East African Orogeny (EAO); Late Quaternary climatic conditions; Polar ice-sheet dynamics and to an extent sub-ice geology sums up the present pursuit of country's geoscientists. In this section, recent salient contributions to Antarctic geology are described for the three domains, namely, the central Dronning Maud Land (cDML), the Larsemann Hills, and the Wilkes Land sector.

The Central Dronning Maud Land Sector (from East to West)

Geological Survey of India (GSI) has completed

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systematic regional mapping between 3°E to 15°E, covering an area approximately 19,000 sq. km on 1:50,000 scale. The area covered include, the mountain ranges of Wohlthat, Orvin and part of Muhlig Hoffmannfjella in the cDML of the East Antarctica. The small hillocks (nunataks) in these areas as well as in the Schirmacher Oasis on which the Indian station is located, have also been covered. Wohlthat Mountains (German: Wohlthat massiv) is a large group of associated mountain features consisting of the Gruber, the Petermann Ranges and the Humboldt Mountains, which is located immediately east of the Orvin Mountains in Fimbulheimen in the central Queen Maud Land.

Area between the Schirmacher Oasis and Humboldt Mountains is covered by a thick polar ice-sheet. However, there are eight nunataks of approximately 4-10 km^2 in the area that stand out projected above the ice sheet. These nunataks are strategically placed to infer the sub-ice geology. These nunataks are namely Tallaksenvarden, Stenersenknatten, Baalsrudfjellet, Hauglandtoppen, Sonstebynuten, Starheimtind, Pevikhornet etc. and others such as Austree and Midtre lying north of the Petermann ranges. These nunataks have been investigated by Kaul *et al*. (1988), Roy *et al*. (2017) and others, who have described the geology and petrography of the gneisses, basic granulites and quartz-syenite rocks exposed therein.

The studies indicated that, the cDML occupied a prominent position in the processes involving formation of the mega continents like Rodinia and Gondwanaland. Geological observations made in Antarctica are being extended to conceptualizing models and processes of crust formation during two major tectonic events - Grenvillian and Pan-African those were associated with the formation of these super continents. Apparently, these important geological events in the cDML have larger intercontinental implications and can be correlated with important geological terrain in Mozambique, South Africa and Madagascar. The sustained efforts with a systematic approach in the fieldwork and resultant database will eventually help to evolve a model of best fit of landmasses in Gondwanaland. The outcome of continued regional geological mapping has enabled GSI to publish geological maps most parts of the region. These maps have been circulated to the Scientific Committee on Antarctic Research (SCAR). Geological Survey of India has also been conducting thematic studies to evaluate metamorphism and tectonic events in Humboldt Mountains and in the area to the south of the Schirmacher Oasis.

Based on the similarities of granulites representing 660Ma-600Ma (Stern1994) to those of Schirmacher Oasis (Ravikant *et al*., 2004, 2007; Baba *et al*., 2006), the EAO has been extended to the cDML, Antarctica through Schirmacher Oasis. Rocks of the Schirmacher Oasis have shown to be late Neoproterozoic. Structurally, the NE-SW trending shear zones and mylonites in the Schirmacher Oasis show flow planes parallel to regional foliation of EAO are believed to have evolved during the late phase of D_2/M_2 to early D_3/M_3 tectonothermal event. Based on the regional settings, nature and timing of this shear zones and its association with the retrogressive amphibolite facies metamorphism, these shear zones are opined to be a part of exhumation (D'Souza *et al*., 2011; Pant *et al*., 2017).

The cDML regions expose Mesoproterozoic polydefomed, magmato-metamorphic terrain of high-grade rocks that have undergone granulite grade of metamorphism. The southern extension of EAO is believed to have acted as a suture between the East and West Gondwana blocks during Neoproterozoic (Pant *et al*., 2013, Pant 1991; Pant *et al*., 2009, 2013). Pant *et al*. (2013) opined that metamorphic neocrystallization began in Neoproterozoic at ~640-650Ma time and continued up to 580Ma. The 500-600Ma magmatic activity is wide spread in the cDML.

The protracted metamorphism was overprinted by a strong thermal imprint at ~540Ma and it is correlatable with large scale charnockite and A-type granite emplacements. Extensive pan-African thermal imprint in the Whol that Mountains is represented by anorthosite (~600Ma), charnockite and anorogenic granite. The zone of ~640Ma granulite grademetamorphism is inferred as the remnant of suture between East and West Gondwana (Pant *et al*., 2013).

Dharwadkar and Shrivastava (2017) have recorded the presence of orthopyroxene within the amphibolitic enclaves in Gjelsvkfjella in the western margin of the cDML suggesting an earlier granulite grade event. Geochronological studies assign an age of 1170Ma to 970Ma for the migmatites/gneisses and an emplacement age of 501Ma for the Stabben gabbro and syenite.

Recent Contributions from the Larsemann Hills

Larsemann Hills in the Prydz Bay region of the East Antarctica offers a key setting for correlation between the East Antarctica and the Eastern Ghat Belt of eastern India. The study of Grenvallian (~1000Ma) Pan-African (~500Ma) high grade tectono-metamorphic evolutionary history in the Prydz Bay, including Larsemann Hills and its adjoining areas, like Sostrene Islands, Bolingen Islands, Brattstr and Bluffs, Rauer Islands, Vastfold Hills etc. is significant in the present-day reconstruction and correlation with India and East Antarctica.

The major rock types exposed in the Larsemann Hills area are: garnetiferous granite granodiorite gneiss; orthopyroxene bearing granite representing the metamorphosed acid igneous suite; pyroxene granulite representing the metamorphosed basic igneous suite and the metapelite representing the metamorphosed sedimentary suite. Small scale quartzo-feldspathic melts (migmatite) are also preserved at a few locations. The post tectonic igneous suite is represented by small patches of granitoids. Mapping of few Islands by GSI have been completed in this sector.

Ghosh *et al*. (2017), presented new U-Pb Zircon ages using Multicollector LA-ICP-MS which supports presence of a Late Neoproterozoic basin in the Larsemann Hills. They sampled and dated zircons from Bradstr and Paragneiss that were devoid of any visible metamorphic melt segregations. Zircons from all three sedimentary rocks dated show prominent concordant cluster around 550Ma. In fact, in the bedded meta-arkosic rock of McLeod Island 550Ma is the dominant concordant cluster. This rock is interpreted to be a tuffite and signifies the age of deposition of basin. The interpretation of Grew *et al*. (2012) shows that, younger concordant clusters of 800Ma and 550Ma in the Tasse Tarn metaquartzite signifies new zircon growth during metamorphism is not supported by this data.

The Princess Elizabeth Land (PEL) and Contiguous Areas

The first campaign of an international collaborative project, ICECAP (International Collaborative Exploration of Central East Antarctica through Airborne geophysical Profiling), funded partially by United Kingdom Global Innovation Award was undertaken in 2015-16. This season operations were hosted by the Polar Research Institute of China (PRIC) and conducted from the Zhongshan Station with participation from USA, UK, China and India using airborne geophysical surveys for 44,000 line km of ice sounding radar, laser altimetry, gravity andmagnetic data collection. Following are some of the preliminary findings of this campaign (Sun Bo *et al*., 2016).

- PEL hosts an assortment of previously unidentified subglacial lakes and complex geomorphology.
- Confirms the presence and extent of a 1,100 km-long system of canyons connecting the Lambert Rift to the Leopold and Astrid Coast.
- A subglacial lake situated within the southern section of the canyon system, likely one of thelargest known lakes in the Antarctica.

Corroborative geological field investigations are in progress.

The Wilkes Land Sector

Examination of heavy mineral fraction of the marine sediments of Integrated Ocean Drilling Program (IODP) Expedition 318 off the coast of the Wilkes Land in the East Antarctica (drill site U1359) brought out the sourcing of sediments from the Precambrian hinter land constituting the East Antarctic shield as well as from the Palaeozoic Trans Antarctic Mountains and Ross Orogen (Pant *et al*., 2013). The shield area is indicated to be a polymetamorphic terrain with a low-grade orogeny indicated by ~800Ma monazite within biotite schist (Pant *et al*., 2016). This is the first report of signatures of a Neoproterozoic orogeny in this area and has significant bearing on the Australo-Antarctica reconstruction. Clay mineral record was employed to reconstruct the fluctuations of the East Antarctic Ice Sheet (EAIS) during Mio-Pliocene and increased concentration of smectite suggested retreat of EAIS during 6.8Ma-6.2Ma, 5.8Ma-5.5Ma, and ~4.5Ma-~2.5Ma possibly coincident with the formation of the Antarctic Bottom Water in the Ross sea (Verma *et al*., 2014). The period between 7Ma-9Ma at this depocenter marks the maximum concentration of Ice Rafted Debris (IRD) which includes basaltic rock fragments sourced from the Ferrar Large Igneous Province towards east. This is also in conformity with the ice-retreat phases inferred using clay minerals at 7.4Ma-7.3Ma and ~8.5 Ma (Verma *et al*., 2014). Unusual mafic rock fragments in Plio-Pleistocene marine sediments were recorded from the East Antarctica (suspected meterotite fragments) at IODP Site U1359, deposited between *c.* 3Ma and 1.2Ma (Pant *et al*., 2018).

Paleolimnological Studies

Antarctica plays a vital role in controlling Earth's climate. Recent records indicate that there has been unprecedented change in the Antarctica. Therefore, collecting past climatic information from ice-cores, marine sediments, and lake sediments are extremely important as the data can be utilized in the available models to plausibly model the future climate for the region. There are very few researchers who have focused on Antarctic paleolimnology which is reconstructed from ice-free regions of the East Antarctic viz. Schirmacher Oasis, Larsemann Hills and Vestfold Hills. The paleolimnologists have employed multi-proxy approach through environmental magnetism, sedimentology, sedimentary geochemistry, biogenic silica, diatoms, and major and minor trace elements to reconstruct past Antarctic climate history (see Table 1). Majority of the earlier work from Indian researchers was able to resolve historical climate up to Holocene. In the past one decade, paleolimnologists were able to retrieve longer sediment cores and resolve climate data beyond the Last Glacial Maximimum (up to 43 kyr). Also, high resolution records have been published from Larasemann Hills, as compared to the low-resolution records of Schirmacher Oasis. Warrier *et al*. (2017), in a review paper published in PINSA has discussed in detail the initial works on lake biogeochemistry by the Indian researchers along with the works on lake surface sediments. Early historical records from the Schirmacher Oasis (Phartiyal *et al*., 2011; Phartiyal, 2014) are limited to the Holocene. The paleolimnological group of National Centre for Polar and Ocean Research has made significant contributions to the past-climate reconstruction from the Antarctic coastal regions where marine sediments and ice-core data is limited due to coastal dynamics. Hence, the lake records form one of the most important and crucial archives along the Antarctic continental margin which respond rapidly to changes in climate and integrating the information about climatic changes in the sediments.

The first long-term record spanning glacial-interglacial stage was published based on environmental magnetism (Warrier *et al*., 2014) for Sandy Lake located in the Schirmacher Oasis for past 42kyr. Further studies were carried out in the Schirmacher Oasis utilizing other proxies such as, size and surface textural observations of quartz grains (Mahesh *et al*., 2015; Warrier *et al*., 2015; Choudhary *et al*., 2018) to understand the sediment transport processes and their depositional environment. A recent study from the Schirmacher Oasis (Choudhary *et al*., 2018) discuss about the type of weathering, hydraulic sorting occur during transport to the lake basin, topographic setting and climatic conditions which regulate trace elements abundance and distribution in sediments. Another study based on long-term trends (up to 22kyr) in the grain size distribution and biogenic silica variation suggest that, the possible fluctuation of the Antarctic ice-sheet superimposed on global climatic fluctuations due to solar activity in the Schirmacher Oasis. A solitary record from the Vestfold Hills lake documented the presence of inverted sequences with older sediments rich in marine microfossils and increased abundance of broken diatoms, which was inferred as a result of paleostorm (Raza *et al*., 2018). Previous research has revealed the importance of sedimentary organic matter to understand the productivity pattern, depositional environment and source of organic matter in the lake. The sedimentary organic matter based stable isotope geochemistry has revealed crucial information about the past lake environment and its response to the Antarctic climate (Mahesh *et al*., 2015; 2017; 2018; 2019).

ICE Core Studies

Study of ice core proxy records provide one of the most direct and accurate method to study the Antarctic climate change beyond the instrumental limits. The Indian ice core initiatives focusing on the high-resolution proxy based studies during the past few centuries have enhanced the understanding of the Antarctic climate variability and the various factors involved. The proxy environmental parameters used include temporal variability of stable isotopes, trace metal chemistry, ionic composition, dust particulates, and microbial components that are indicators of environmental change in the coastal Antarctica. The shallow (up to 100 m depth) ice core proxy based reconstruction by the Indian scientists revealed significant changes in the Southern Hemispheric climate during the past several hundreds of years (Laluraj *et al*., 2014; Thamban *et al*., 2013, 2016; PAGES 2k Consortium, 2013; Rahaman *et al*., 2016 and 2019). Salient findings of the ice cores studies during the past five years are discussed below.

The nitrate (NO_3^-) profile in an ice core revealed a close relationship with the Antarctic ^{10}Be record (solar proxy) and supported significant changes in the 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*., 2013). The ice core based temperature reconstructions during the past five centuries also revealed substantial warming by 0.6°C-1°C per century, with greatly enhanced warming during the last few decades (~0.4°C per decade) (Thamban *et al*., 2013). The dust record of IND-25/B5 ice core showed that dust deposition in the East Antarctica followed the Southern Hemispheric climate change and doubled during the 20th century (Laluraj *et al*., 2014). Strong positive correlation observed between ice core dust flux and the Southern Annular Mode (SAM) revealed 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. 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 the East Antarctica have wide-ranging implications for understanding the factors driving the inter-continental transportation of impurities and their environmental impact on the Antarctica.

Proxy records of sea ice [sea-salt sodium (ss-Na^+) and methane sulfonic acid (MSA)] and moisture [deuterium excess (d-excess)] variability of IND-25/B5 ice core also revealed the history of moisture transport and sea ice condition during the last century (Rahaman *et al*., 2016). This study suggested 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. The Antarctic surface air temperature (SAT) reconstructed approximately for the past five centuries (~1533 to 1993 CE) based on multiple oxygen isotope ($\delta^{18}O$) 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 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.

The Indian ice core studies have also contributed to the PAGES 2k synthesis of past 2000 years of truly global temperature reconstruction across the globe (PAGES 2k Consortium, 2013). Integrating the proxy temperature data using various proxy records across seven continental-scale regions, this global study revealed an overall cooling trend across nearly all continents during the last two thousand years. This cooling trend was reversed by distinct warming, beginning in some regions at the end of the 19th century.

Satellite Remote Sensing Based Studies

To understand the mechanism of sea-ice expansion in the Indian Ocean sector of Antarctica (IOA), satellite derived analysis of sea-ice extent, during 1979 to 2015, in the IOA revealed expansion of 2.4±1.2% decade^{-1}. The study resulted in strengthening of westerly wind during the austral summer facilitated northward advection of a cool and fresh layer (Jena *et al*., 2018). NCPOR initiated a series of geospatial activities to an accurate DEMs and land cover maps of the cryospheric regions such as, satellite-based DEM for monitoring Antarctic topography with a special focus on glaciers (Jawak and Luis, 2016); synergistic use of imaging SAR, GLAS/ICESat and ground survey (GPS) data to produce an accurate DEM of the Schirmarcher Oasis and the Larsemann Hills (Jawak and Luis, 2012). During the 35th Indian

Scientific Expedition to Antarctica, inter-annual variations in the backscatter response of fast ice using ground penetrating radar (GPR) and backscattering coefficient from scatterometer in the Larsemann Hills, East Antarctica, studies show volumetric contribution from sheet ice and domination of snow metamorphism towards increase in backscatter over fast ice (Bothale *et al*., 2018). Jayaprasad *et al*. (2016) studied two of the Indian Satellites namely Radar Imaging Satellite-1 (RISAT-1) and Resource SAT-2 (RS-2) for monitoring and mapping of the Antarctic terrain. It is extended for other applications such as change detection studies, safer ship navigation and extreme events of the Antarctica.

Polar Biological Research

The Polar Regions always received a significant attention for biological research due to their pristine nature, where it is comparatively easy to predict, measure and to develop model systems for understanding the origin microbial life forms and their role in the functioning of marine as well as terrestrial ecosystems (Venkatachalam *et al*., 2019). The geographical surface area of polar region is about 10.9 million sq. mi. of the earth biosphere, with about 46 countries actively undertaking polar biology based research activities every year. Based on the scientific findings and applications from the Antarctic research activities, Indian Arctic programme was initiated in the year 2008 and scientific experiments were conducted. Significant contributions were accomplished in the field of natural sciences within the areas of microbiology and molecular biology by researchers across Indian institutes and universities. Here, in this subsection, we are summarizing significant research activities undertaken by Indian researchers in the polar regions within the domain of biological research for past ten years.

Microbial Diversity Based Research for Bioprospecting Applications from Polar Environments

Microorganisms are the primary drivers of any ecosystem, which play a critical role in keeping the ecosystem in a healthy state through nutrient recycling. It needs to be emphasized that microbes living in the harsh climatic conditions, also known as psychrophiles (grow from subzero to 30°C) are found to have distinct applications on healthcare sectors, metabolites and enzyme industries (Cavicchioli 2015). Till now, various microbial diversity-based studies have been led by Indian researchers on different habitats of the polar regions, including soil, cyanobacterial mats, water, sub-glacial outflows, fjord systems, oceanographic frontal systems, freshwater lakes, sediments and ice cores during past ten years. Researchers from the Centre for Cellular and Molecular Biology (CCMB), extensively worked in the various habitats of polar environments and have isolated more than 30 novel microbial species belonging to the members of genera *Thalassospira, Iodobacter, Arcticibacter, Winogradskyella, Cyclobacterium, Oceanisphaera, Arthrobacter, Leifsonia, Exiguobacterium, Marinomonas* sp., with few draft genomes by using next generation sequencing based technology from the various habitats of polar region (Shivaji, 2017). Significant key findings have also been published on marine environments in the past few years especially in the polar frontal regions. It was shown that, distinct microbial communities are known to assist in enhanced primary productivity of the surrounding regions of sub Antarctic islands (Sivasankar *et al*., 2018; Venkatachalam *et al*., 2019). Biological diversity of the marine ecosystems in the Arctic regions, especially, fjord ecosystems are extensively studied by researchers from the National Centre for Polar and Ocean Research, which is known for its complexity due to heavy discharge of glacial meltwater into the fjord system. It has also been demonstrated that increasing incidence of warm water associated microbial communities were observed in the fjord systems, due to the intrusion of Atlantic water bodies (Sinha *et al*., 2017). Bacterial communities were further explored for their role in biogeochemical processes (Carbon, Nitrogen and Phosphorus cycling). Further, significant number of culture based studies were also being done in the past, with an aim to isolate industrially important microbial strains for potential enzyme producers including amylases, cellulases, pectinases, proteases, lipases and β-galactosidases (Hatha *et al*., 2013; Neethu *et al*., 2012; Salam *et al*., 2017; Srinivas *et al*., 2009).

Anthropogenic Activity Associated Biological Research in Svalbard, Arctic

Thawing permafrost, rapid melting of glaciers, accelerated heavy discharge of glacier freshwater, which also carries significant amount of sediments from coal mining areas into different fjord systems, has significant impact on the native microbial flora. Recent studies have shown the presence of high mercury content and associated mercury tolerant bacteria (Bineesh *et al*., 2018) in the fjord sediments. Furthermore, fjords and associated adjacent tundra ecosystems are also being investigated for the presence of health indicator bacteria, whereas, it is being hypothesized that migratory birds such as Arctic terns, Barnacle goose are assisting in the widespread distribution of the mesophilic, antibiotic resistance microbes in the Arctic environments (Hatha *et al*., 2015). Further microcosm studies on how these mesophilic and other pathogenic bacteria are adapting to the cold climatic conditions will be of great importance in this area of research.

Future Perspectives

Laboratory culture based microbiological investigations have been a gold standard in the polar research with respect to the isolation of novel bacteria species and further exploitation of these strains for bioprospecting potentials. In the era of drastic climate variability, indigenous microorganisms in the polar ecosystems are constantly under selection pressure, where many such ecosystems are slowly shifting towards more temperate conditions and species within these systems are changing in time and space. To understand these complex processes, the current advancement in genome based high-throughput sequencing technologies will be of great help to understand and monitor the changes in the polar ecosystems in order to harmonize and negate the impact of anthropogenic activities. During the last few decades, significant progresses were achieved by the studies carried out by Indian researchers in the polar regions. Further, exploring the unexplored regions in the polar environments will provide more unique opportunity to study about structure and functioning of different ecosystems, with an aim to get leads for novel therapeutic agents and health supplements. With this aspect in the forefront, the National Centre for Polar and Ocean Research is spearheading many new expeditions to the coastal areas of the Northern Svalbard and associated Arctic open ocean to venture into the unexplored territory of the Arctic regions.

Arctic Palaeoceanographic Studies

Studies of marine sediment cores provide the sedimentary, geochemical and biological evidence of past changes in the Earth system. The sediment cores provide robust reconstructions of large oceanographic regions and provide insights to climatic change beyond the instrumental data available. The palaeoceanographic data from the sediment cores derived from many proxies found in deep sea sediments including microfossil composition, isotopic composition of microfossils and lithology etc. The Indian palaeoceanographic research ventures in the Arctic, has improved our understanding of its climate variability for the past few centuries and scaling back up to 14,500 years BP, covering the entire Holocene and before. The research projects include both Ministry of Earth Science (MoES) funded in-house projects and international collaborative projects. The important findings and publications within the last few years are discussed below.

The diatom microfossil-based quantitative SST reconstructions from Iceland basin showed that the cold interval at 4-2ka BP may have resulted from a strengthened East Greenland Current and/or melting of Greenland ice sheet in response to a negative North Atlantic Oscillation. It highlights the influence of atmospheric circulation changes that likely cause pronounced variations in the latitudinal heat exchange which may have consequences for deep water formation and global ocean circulation (Orme *et al*., 2018). The biogeographic distributional studies of polycystic radiolarians from the North Atlantic revealed the distribution and interaction of water masses from Polar to North Atlantic was clearly reflected in assemblages retrieved from deep sea sediments; three from the North Atlantic and two from the Nordic seas (Matul and Mohan, 2017). The diatom and coccolithophore microfossil-based temperature reconstructions from the eastern Fram Strait reveal that in the last 2000 years, the Roman Warm Period (upto 456 CE) and Recent Warm period (1850 CE-present) to be the warmest intervals throughout this time period (Matul *et al*., 2018). The multi proxy (sedimentary organic matter, ^{13}C and ^{15}N isotope ratios and microfossil abundance) study from Kongsfjorden, Svalbard revealed warming driven melt-dynamics history of the fjord for the past 200 years. The proxy data shows decreasing trends in productivity, which was controlled by the melt dynamics throughout the last two centuries (Kumar *et al*., 2018). The microfossil (Foraminifera) and isotope proxy-based study along with paleotemperature estimates from Reykjanes Ridge, document that after the warm Bølling-Allerød (BA), the middle Younger Dryas (YD) ca. 12.5ka-12.2ka was the next significant step towards the Holocene warming. Also, warming in the region during Termination I occurred on subsurface regions earlier than the sea surface; also proposes further studies into the question (Matul *et al*., 2018).

The MoES funded in-house projects along with the collaborations by Norwegian research council (OCTEL) and Russian Science Federation reveals the climatic variability across the Arctic from 14.2ka BP till the present day. The multi-proxy studies, from marine sediment cores obtained from 40°N to 79°N reveals various climatic oscillations and oceanographic changes within the time period studied but with significant warming in the Arctic post 19th century, opposed to the cooling trend which was observed during the late Holocene.

Southern Ocean Processes and Ecosystem Responses

The Southern Ocean (SO) is a unique region which tends to have a global scientific relevance in terms of its role in climate change, its distinct physical, chemical properties and related biological processes. In the light of above perspective, the SO in general and the Indian sector of the SO (ISSO) in particular, is still an understudied region. In ISSO, the Subtropical and Polar Fronts confluence and split again, but the exploration to understand the mechanisms of this variability in these regions are very sparse (Belkin and Gordon, 1996). The seasonality and extent of sea-ice formation are shown to influence the oceanographic as well as the biogeochemical processes across various fronts in the SO. It was reported that Antarctic ice sheet mass loss has been linked to an increase in oceanic heat supply that enhances the basal melt and thinning of the Antarctic ice shelves (Herraiz-Borreguero *et al*., 2015). Also, accelerated glacier discharge into the SO due to the collapse of ice shelves could be one of the major sources contributing to sea level rise (Scambos *et al*., 2004; Shepherd *et al*., 2010). Although warm water near the coast is thought to be the main factor causing the ice to melt, the process by which this water ends up near the cold continent is not well understood. In order to understand the processes those are involved in modulating the climate variability in a regional as well as global scale and its implications on the living resources, biogeochemical cycles and sea level rise, Indian SO research program was initiated by MoES in 2004 with the National Centre for Polar and Ocean Research as a national nodal agency. Till date, 10 expeditions have been carried out in the region between 40ºS and 69ºS and 40ºE and 80ºE (Fig. 1). More than 20 National/International organizations/ Universities participated in these multidisciplinary and multi-institutional expeditions. However, the information gathered from these expeditions are not sufficient to establish the influence of the SO on global climate and also at what extent the SO processes respond to or drive the tropical climate variability. This underscores the need for sustained observations from the SO to understand the physical and biogeochemical processes responsible for climate variability. Therefore, in future, detailed investigations will be carried out in the Tropical Indian Ocean (TIO) as well as ISSO to understand the teleconnection between high and low latitude biogeochemistry and climatic changes.

Scientific Outcomes

Due to the influence of Southwest Indian ridge and Weddell gyre, the eastward flowing Antarctic Circumpolar Current (ACC) is meandering towards south in the ISSO, which perhaps brings warm water to the coastal Antarctica and causes glacier/sea-ice melting and further the freshening of bottom watermasses (Anilkumar *et al*., 2014, 2015). The Subtropical Front (STF) is the most dynamic region in the SO, where eddies are more predominant when Agulhas retroflection confluence with the STF. Eddies present in the STF transported Subtropical Surface Water (STSW) southward by means of the enhanced meridional velocities along the peripheries of eddies (Chacko *et al*., 2014), and the presence of cyclonic eddy significantly transported cold and fresh Antarctic Intermediate water (AAIW) from deeper depths (>1000 m) to near surface. Anti-cyclonic eddies are transporting high saline subtropical surface waters to south from their source region (Sabu *et al*., 2015). The subtropical front being a highly mesoscale

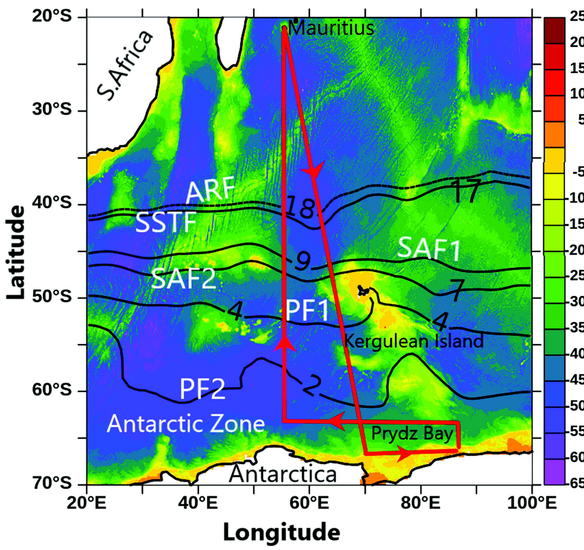

Fig. 1: ISSO study region. Position of the fronts is marked using WOA climatology data. Background color represents the bathymetry of the study region from ETOPO data

turbulent region, the primary supply of nutrients is attributed to advection (vertical or zonal) rather than vertical mixing (George *et al*., 2018). The ocean sectors north and south of 16°S are dominated by continental aerosol and maritime aerosol with the sea salt and non sea salt components, respectively (Menon *et al*., 2015). High degree of freshening of Antarctic Bottom Water (AABW) was observed from 2006 to 2010 in the ISSO, which is attributed to both the Weddell Sea and Cape Darnley Polynya origin (Anilkumar *et al*., 2015). Freshwater layer thickness relative to the winter water in 2011 was more compared to that during 2010. This was due to the increased amount of sea ice present in the 2010 winter, its subsequent melting and advection of melt water from south and west of the study region. The increase in Chlorophyll *a* (Chl*a*) concentration (~0.38 mg m^{-3}) observed south of the Polar Front1 in 2011 both in *in-situ* observation and satellite data is attributed to the influence of this melt water (Anilkumar *et al*., 2015). Furthermore, the low saline waters formed by melting of glacial ice and snow could be the predominant factor for the high Chl*a* (>3 mg m^{-3}) resulting in high meso-zooplankton biomass and abundance along the coastal region (65°40°S; 57°30'E) (Anilkumar *et al*., 2014).The enhanced Chl*a* observed in the study region (60°S; 47°E), was attributed to the phytoplankton bloom, likely resulted from the influx of nutrient-laden freshwater derived from melting sea ice (Sabu *et al*., 2014). A strong relationship between wind speed and concentration of atmospheric CO_2 has been encountered, and at south of 50°S the mixing of ventilated CO_2 was observed (Prasanna *et al*., 2015). Variations of $\delta^{13}C$ and $\delta^{15}N$ in Particulate Organic Matter (POM) in the surface waters exhibited depletion in $\delta^{13}C$ and a wide range of $\delta^{15}N$ of POM in the TIO compared to ISSO and it was largely controlled by biological community and biological activity (Soares *et al*., 2015). Increase in the $\delta^{13}C$ (DIC) value of the surface water with latitude is observed between 35°S and ~60°S, with a peak at ~42°S. This can be caused by increased organic matter production and associated removal (Prasanna *et al*., 2016). Stable isotope ratios of water vapor, rainwater and seawater samples from the TIO and the ISSO showed features characteristic of evaporation and precipitation zones (Rahul *et al*., 2018). Variation in phytoplankton community structure was observed at six hours intervals and that was actively governed by top-down control at juncture of the Agulhas Retroflection Front (ARF) and the STF (Naik *et al*., 2015). Tripathy *et al*. (2014) reported that Chl*a* concentration was very high in the coastal waters of Antarctica; however, the corresponding primary productivity (PP) values were not very high compared to the offshore stations. High Chl*a* and primary productivity observed at the PF was attributed to the dominance of diatoms. Owing to their higher sinking rate, the diatoms with sequestered CO_2, would generate substantial export production/flux, thereby making the PF region as a sink for atmospheric CO_2 (Tripathy *et al*., 2015). The changes in environmental settings can influence biological community succession by providing windows for opportunistic groups of phytoplankton, thereby influencing the carbon sequestration efficiency of this ecosystem (Naik *et al*., 2015; Mishra *et al*., 2015, 2017). Discrepancy in the ecological efficiency and the plankton community structure suggest a multivorous food web and a conventional food web at the subtropical and polar fronts respectively (Pillai *et al*., 2018). A strong contrast in terms of zooplankton population structure and biovolume was observed between the Subtropical and Polar Fronts (Venkataremana *et al*., 2019).

Southern Ocean Paleoceanography Contribution

The SO is considered as a crucial region for global climate and ocean biogeochemical cycling. Indeed, the SO forms a link between the Atlantic, Pacific and the Indian Oceans and modulates the global circulation which holds a key to the future climate. Considering the importance of ocean, it is important to fully understand it and the microfossil forms this gateway for revealing the past of oceans. These are the remnants of microscopic flora and fauna which thrive in different conditions of the ocean. This includes siliceous organisms like diatoms, radiolarians, silicoflagellates or the calcium bearing organisms like foraminifera and coccoliths. The Indian researchers have contributed in all the fields of microfossils through surface sediments, water samples and sediment cores in understanding the SO paleoceanography.

A significant step towards understanding the role of coccolithophore as a proxy for environmental variation has been taken up. In view of this, a study by Patil *et al*., 2017 focused on understanding the biogeographic distribution of extant coccolithophores, which provided a vital knowledge on vertical and latitudinal distribution and community composition quantitatively along N-S transect in the Indian sector of the SO. Their study also reported the morphological variation of *Emiliania huxleyi* in the SO using scanning electron micrographs depending upon different hydrographic conditions (Patil *et al*., 2014a). Occurrence of silicifying haptophytes in marine waters was largely neglected and their role in marine biogeochemical cycle was not taken into consideration. Two silicifying haptophytes (*Petasaria heterolepis* and *Prymnesium neolepis* documented from Southern Indian Ocean and ecology, biogeography and mineral composition was studied. The Energy Dispersive Spectrometric studies showed presence of calcium in the silicifying test (Patil *et al*., 2014b, 2015). In addition, mechanisms behind formation of xenospheres (combination spheres) were suggested as a controlled strategy to hydomechanical/ biochemical cues to sense coccoliths and incorporate into coccosphere (Patil *et al*., 2016).

Using isotopic compositions ($\delta^{13}C$ and $\delta^{18}O$) of planktonic foraminifera Prasanna *et al*., 2016 established a linkage between geographical position and depth range of planktonic species *Globigerina bulloides*. The major finding of this study was the calcification depth of *G. bulloides* which according to the researchers is restricted to a depth of ~75m-200m till 40°S latitude. They demonstrated the validation of the isotopic composition of *G. bulloides* as a paleoclimate proxy.

A study based on silicoflagellate records over the last 48kyr have been used to examine past changes in the polar frontal variability in the SO (Shetye *et al*., 2014). They observed a strong northward and southward shift of the Polar Front during the LGM and 43kyr-45kyr respectively. The Indian research is trying best to match up with the recent progresses in science has now moved one step forward and been successful in reconstructing and quantifying the northward migration of the SO fronts through past Sea Surface Temperature (SST) and Sea Ice variability. The paleoclimatic records going back till last 95kyr have been reconstructed using diatoms. A study by Nair *et al*. (2019) documented the interaction of the SO with Agulhas leakage and Asian summer monsoon. The diatom size and the abundances are being used to comment on the paleoproductivity. Their study reports the response of diatom size (*F. kerguelensis* and *T. lentiginosa*) to the glacial interglacial variation, wherein the diatoms shows larger valve size during the Last Glacial Period. According to them the reason is possibly related to greater iron availability through wider sea-ice coverage and higher aeolian dust input. Similar studies have also been reported by Nair *et al*. (2015), Shukla *et al*. (2016), Shukla and Crosta, (2017), and Shukla and Romero (2018).

Although many studies are being carried to understand the SO paleoceanography but it still remains understudied from the perspective of longer time scale and quantitative reconstructions using microfossils. Hence, there is a need to fill this knowledge gaps as microorganisms are the first one to respond to the changes in environmental conditions.

Some Salient Achievements for Past 15 Years from the Indian Expedition to ISSO

So far, 10 expeditions were launched from 2004 to 2018 with National-International collaborations and multi-disciplinary data were generated; Nearly 90 papers were published in the International and National journals; Nearly 85 papers were presented in International /National conferences; Eight Ph.D degrees were awarded based on the data collected from the SO expeditions. Special issues: Current

Science Nov, 2010 and Deep Sea Research II Aug, 2015 were published and special issue of Deep Sea Research II-2019 is in progress.

The SO accounts for half of the uptake of anthropogenic CO_2, nutrient supply fertilize 3/4 biological production north of 30°S and the excess heat transferred from atmosphere. Further, the Indian Ocean is land-locked in the north and behaves differently in circulation which leads to a much faster climate change.

Considering this, the imperative queries to be addressed are.

a. How does the atmospheric and oceanic dynamics in the SO affect the tropical weather and climate?

b. How the physical processes and atmospheric aerosols and other trace gases are modulated by Biological pump/Biogeochemistry and vice versa?

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