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Review Article

Sea Ice Studies: An Indian Perspective on Polar Research

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Sea ice acts as a vital part of the Earth's climate system. This entity affects the planet's ocean circulation, weather patterns, and global ecosystems as a whole. While most research on sea ice has historically been led by countries with territorial interests in the polar regions, India's involvement in this domain has grown significantly over the decades since the early 1980s. Despite its tropical location, India is deeply invested in polar research due to the impacts on its climate, especially the monsoon. This review gives a detailed analysis of India's contributions to sea ice research. Main focus here is on the country's scientific advancements in the field of cryospheric studies, with discussions on the interrelationship between sea ice dynamics and regional climate patterns, and the strategic importance of such studies. Various established national institutions perform research efforts, contributing to international collaborations and advancements in remote sensing technology. Also, this review identifies the challenges faced by Indian researchers and suggests potential future directions for the country's polar research efforts.

[**Keywords**: Climate change, Indian monsoon, Polar research, Remote sensing, Sea ice dynamics]

Introduction

Sea ice is the super cooled layer of seawater in Polar Regions. It plays an essential role in sustaining the Earth's climatic equilibrium. It serves as a reflective layer, controlling exchange of heat energy between the ocean and the atmosphere. Therefore, it impacts weather and climate patterns across the globe[1], thereby influencing oceanic circulation, weather patterns, and global temperatures. Sea ice helps regulating the Earth's temperature by reflecting sunlight. This helps in preventing excessive warming of the earth. Additionally, it acts as an insulating layer, reducing transfer of heat between the ocean and the atmosphere. This insulation effect helps stabilise polar climates. Moreover, sea ice is the natural habitat for a variety of polar species, including polar bears, seals, and penguins.

Historically, studies on sea ice have been carried out dominantly by countries with immediate access to the Arctic and the Antarctic regions, such as the United States of America, Russia, and Norway. These countries have invested significantly in polar research infrastructure, empowering them to carry out a wide-range of field studies and deploy cutting-edge technologies. Nonetheless, the importance of these studies surpasses geographic boundaries, as any changes in sea ice will have global ramifications. It is true that melting of sea ice per se will have no significant contribution to sea level rise, but it can show impacts on the stability of the ice-shelf fronts. In the absence of nearby sea ice (fast ice),, significant pressure is exerted on ice shelves by oceanic waves. Also, warmer ocean water can melt the bottom of the shelf, possibly leading to ice shelf disintegration[2], *e.g.*, the Larsen Ice Shelf calving[3]. Moreover, the loss of sea ice can change weather patterns, bringing in more extreme weather events across the world. Consequently, sea ice research is vital for improving global climate models and informing international climate policies[4].

Research on sea ice requires understanding of various scientific principles, such as thermodynamics, fluid dynamics, and cryospheric sciences. Thermodynamics provides an understanding of the energy exchanges that take place when sea ice freezes and melts of. Fluid dynamics is helpful in tracking the motion of sea ice and how it interacts with ocean currents. Cryospheric sciences deal with the overall study of all frozen forms of water on the Earth, such as sea ice, glaciers, and permafrost. Researchers employ a mixture of satellite imagery, in-situ measurements, and climate models to investigate the extent, thickness, and seasonal variations of sea ice. Satellite imagery provides a broad perspective of sea ice cover, allowing scientists to monitor changes over large areas. In-situ measurements, such as ice cores and buoys, offer precise information on the physical properties of sea ice. Climate models simulate the interactions between sea ice and various elements of the climate system, aiding scientists forecast future changes. These studies are essential for comprehending the processes of sea ice formation and melting, the interactions between sea ice and the atmosphere, and the overall impact of sea ice changes on the global climate system[5].

Since the late 20th century, India's venture into this field of study has grown in leaps and bounds. India's curiosity in polar research, motivated by both scientific curiosity and strategic interests, has led to important contributions in understanding sea ice dynamics. For India, a country heavily influenced by climate change, sea ice research holds significant importance. Changes in Sea Ice Extent (SIE) and Thickness (SIT) can significantly impact climate system of Earth, which in turn impact India's weather patterns, particularly the monsoon. The Indian monsoon plays a vital role in the country's agriculture, water resources, and overall economy. Gaining insights into the dynamics of sea ice will help in prediction and mitigation of the effects of climate change on India.

This article examines sea ice research from an Indian perspective, focusing on India's contributions to this field, current research initiatives, and the broader ramifications for the nation. By exploring the work of Indian researchers and institutions, insights can be gained on how India is supporting the global sea ice research and how this research is helping to tackle the difficulties posed by climate change. Another comprehensive review on this regard can be found in Oza *et al*.[6], who outlined the progress in sea ice research in India, highlighting key initiatives and future directions.

Historical background of Indian polar research

India's polar research initiatives began with its first Antarctic expedition in 1981, leading to the establishment of the Dakshin Gangotri station (70.09° S, 12.00° E) in 1983[ref. 7]. This was followed by the laying down of the Maitri station (70.76° S, 11.72° E) in 1989 and the more recent Bharati station (69.40° S, 76.19° E) in 2012. These stations (Fig. 1) have served as key platforms for Indian scientists to conduct a wide range of research, including studies on sea ice.

In 2007, India launched its first scientific mission to the Arctic and set up its research station "Himadri" at Ny-Alesund in 2008 (Fig. 1). This demonstrated its sincere desire to conduct studies in the Arctic region following its substantial experience in Antarctic science and logistics[7,8]. Since then, the scientific community in India has progressively expanded its focus to include the Arctic, recognising the interconnectedness of the Polar Regions and their influence on the global climate system.

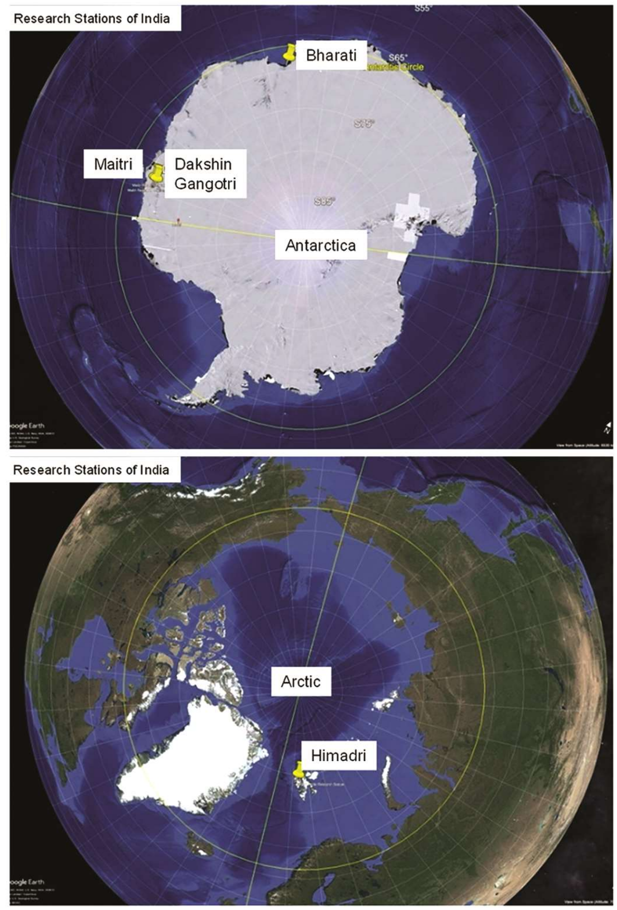

Fig. 1 — Indian research stations (indicated by yellow pins) in Antarctica (left), and in the Arctic (right)

In India, the Ministry of Earth Sciences (MoES), Government of India through its nodal centre- The National Centre for Polar and Ocean Research-NCPOR (formerly, National Centre for Antarctic and Ocean Research), under the aegis of, is actively involved in managing these efforts, assisting a growing body of research on both Antarctic and Arctic sea ice. In addition to this, other national research agencies, such as the Indian Space Research Organisation (ISRO), Defence Research & Development Organisation (DRDO), as well as many academic and research institutions across the country also contributes significantly to this field. These institutions focus on various elements of sea ice studies, spanning from remote sensing and satellite monitoring to climate modelling and field measurements.

Indian researchers have been actively involved in international collaborations, contributing to significant findings related to sea ice dynamics. Through participation in international programs such as the Scientific Committee on Antarctic Research (SCAR) and the International Arctic Science Committee (IASC), India has established itself as a key player in polar research. These collaborations have enabled Indian scientists to work with their counterparts from other countries, sharing knowledge, expertise, and resources.

Indian contributions to sea ice research

As mentioned above, India has a bi-hemispheric approach towards polar science[7]. Therefore, this article will highlight some noteworthy contributions from the Indian pool of polar researchers in the Antarctic as well as the Arctic fronts.

Antarctic sea ice studies

India's research in the Antarctic has focused on various areas, including atmospheric science, geoscience, biology, environmental science, human physiology, medical science, cold region engineering and communications[7]. However, various researchers have also studied the physical properties and seasonal variations of sea ice. This paper will focus solely on sea ice studies.

Vyas *et al.*[9] and Dash *et al.*[10] used the passive microwave-based multi-channel scanning radiometer (MSMR) onboard the Oceansat-1 to discriminate sea ice regions from open water. They also found that sea ice concentration information could be obtained from different brightness temperature values. Vyas *et al.*[11] inferred SIE over the Antarctic region by analysing the from the brightness temperatures data from MSMR during its initial phase between 1999 and 2001, showing seasonal variability in SIEs across different sectors of the southern polar ocean. A slight positive trend was observed in the Antarctic SIE during their study period. An atlas of Antarctic sea ice, based on MSMR data, was prepared by Vyas *et al.*[12]. This atlas has become a valuable reference for researchers worldwide, offering insights into the monthly variations in sea ice cover in the southern polar region. Further, Bhandari *et al.*[13] discussed the use of MSMR onboard OCEANSAT-1 to monitor polar sea ice regularly and attempted an inter-comparison of MSMR with SSM/I measurements and derived sea-ice parameters.

Further, Sharma *et al.*[14] used MSMR data from 1999–2001 and showed that every sector in the Antarctic responded differently to sea ice melting and formation. During the 1999–2000 melt season, an increase in SIE was found in the Indian Ocean sector, while a decrease (15–20 %) was observed in the Western Pacific Ocean during the growth in 2000. They also observed a short melting spell within the during ice growth in the Bellingshausen & Amundsen Seas sector in the year 2000.

The growth and decay of Antarctic sea ice was also studied by Oza *et al.*[15] using scatterometer (an active microwave sensor) data from QuikSCAT and OSCAT onboard the Oceansat-2 for the period 1999-2009. They found that the deviation in interannual maximum SIE was very high and that there was no permanent shrinkage of SIE. However, regionally, statistically significant trends were observed (*e.g.*, positive in the Ross sector and negative in ABS sectors). Similar such regional trends were also observed in Oza *et al.*[16].

Another study by Srivastava *et al.*[17] calculated the rates of Antarctic sea-ice melting using the seasonal cycle of solar irradiance and SSM/I data for the period 1988–2006. The observed melting rate pattern suggests that in addition to the seasonal cycle of solar irradiance, it is also influenced by factors such as sea ice feedback, the amount of sea ice present, age, thickness, etc. More recently, research on the onset of snowmelt over the Antarctic sea ice has also begun[18].

Moreover, to properly differentiate sea ice from other ice and ocean features, Singh *et al.*[19] have combined Ka-band/AltiKa data with the Ku-band OSCAT Scaterrometer data in a synergistic manner. The sea ice extent from this method was found to be satisfactory in comparison with well-established, passive microwave derived sea ice boundary.

In addition to the above-mentioned studies on Antarctic sea ice mapping and its growth and melt cycles, Antarctic-wide SIT has also been estimated by Joshi *et al.*[20] using SARAL/AltiKa altimetry data and waveform retracking methods. It was found that the thickness was larger near the Antarctic ice shelves than the far-off regions, suggesting the role of shelves in sea ice growth. Sea ice freeboard, which is defined as the height of floating ice above the sea surface, has also be derived from the Ka-band Altimeter (SARAL-AltiKa) over the Arctic for spring and autumn 2013 by Maheswhari *et al.*[21]. They used a waveform template matching technique to classify leads and floe. With freeboards ranging between 8 cm and 15 cm.

Also, SARAL/AltiKa satellite data from 2013 to 2020 were used to determine Sea Ice Concentration (SIC) in the Arctic[22]. The study adapted the NASA bootstrap algorithm[23] to estimate daily and monthly SIC. It is crucial for determining climate variables and fluxes between air and sea. The SIC estimates were compared with NSIDC CDR, OSISAF, and ASI products, showing RMSEs of 11–13 % overall, with better accuracy in winter. A bias-correction method reduced the RMSE by 6 %. The algorithm was validated across 14 Arctic regions, confirming its reliability as a dataset for SIC records.

SIC data can also be used to derive Sea Ice Occurrence Probability (SIOP) as shown by Rajak *et al.*[24]. This dataset was employed to examine the difference between sea ice growths and melt patterns in the eastern and western Antarctic regions. Other important applications such as generating a sea ice majority mask and assessing intra-seasonal growth and decay gradients can also be performed using this dataset. The analysis revealed differing rates of sea ice refreezing and melting between the two regions. This dataset is expected to be valuable for global sea ice research.

Besides, there are studies on the variability of Antarctic sea ice. Deb *et al.*[25] examined how wind-driven sea ice drift impacted sea ice cover in the Indian Ocean sector of the Southern Ocean during different phases of the Southern Annular Mode (SAM) in summer and winter. Positive SAM events caused stronger zonal westerlies in the west and northerly winds in the east, linked to asymmetric sea level pressure. The wind patterns resulted in increased sea ice drift eastward in the west, leading to thicker and more concentrated sea ice, while in the east, south-eastward drift caused ice to accumulate near the coast and diverge near the edge, reducing ice concentration and thickness. Overall, SAM influences sea ice cover non-uniformly across the region.

Jena *et al.*[26] found that there was an overall expansion of the Antarctic sea ice with regional variations in growth as well as decline. They used satellite data from 1979 to 2015, which indicated a 2.4±1.2 % per decade expansion in the Indian Ocean sector of Antarctica. It was found that strengthened westerly winds during austral summer had driven cool, fresh water northward, contributing to sea ice expansion north of 62° S. They also found that sea ice near the Kerguelen Plateau had retreated on account of upper ocean warming, leading to a non-uniform pattern of SIE in the Indian Ocean sector.

An ice core study from coastal Dronning Maud Land by Rahaman *et al.*[27] revealed the moisture transport and SIE history over the last century. Dramatic shifts in deuterium-excess values were linked to the SAM changes. Positive excursions in sea salt sodium flux indicated a higher SIE during 1940–1980. Moreover, correlation with satellite data suggested a ~10 % increase in SIE relative to the last century's average SAM, while El Niño Southern Oscillation (ENSO) has an impact on controlling sea ice and moisture at annual to decadal scales in coastal Antarctica.

Another interesting study by Ejaz *et al.*[28] reconstructed Antarctic SIC from coastal ice core oxygen isotopes. Remarkably, they could provide SIC record for two centuries from 1809 through 1993 for the Western Indian Ocean Sector (WIOS) of Antarctica. From this study, they found that there was a significant sea ice decline in the period between 1830 and 1884. A moderate increase was observed in the period 1927–1993. When they added satellite data from 1994–2019 to the ice core data, they found the highest increasing trend during 1994–2014, but in 2015–2016, they observed a sharp decrease which was due to an extreme El Niño event. There is a strong periodicity from annual to decadal scales in the WIOS sea ice variability. The sea ice variability was found to be largely influenced by wind-driven dynamics associated with the Southern Annular Mode (SAM) and teleconnections with Pacific oscillations.

Although sea ice fluctuations affect only a small portion of the Earth's surface, they can significantly impact atmospheric circulation in the Polar Regions. If the large-scale flow is favourable, these effects may also extend to middle and subtropical latitudes[29].

Dugam & Kakade[30] studied the relationship between Antarctic SIE and Indian summer monsoon variability. From the 22-year (1979–2000) long analysis, they found that the Antarctic sea ice anomaly in winter has a statistically significant inverse relationship with subsequent Indian monsoon in terms of its deficiency, excess or normal behaviour.

Rai & Pandey[31] and Rai & Pandey[32] discussed the relationship between the Antarctic sea ice variability and the Indian Ocean Sea Surface Temperature (SST) for the region 72–122° E and 4–26° S, which is considered to be a unique precursor to the Indian monsoon, besides others. They found a positive correlation (statistically significant at 95 %) between the SST and the variability of sea ice in the Ross and Bellingshausen-Amundsen Seas (BAS).

Further studies by Prabhu *et al*.[33] found that Antarctic sea-ice extent (AnSIE) influences global climate and is connected to the Indian Summer Monsoon Rainfall (ISMR). Cross-correlations between AnSIE and ISMR from 1988 to 2005 showed a coherent propagating pattern, indicating a potential link. The sea-ice extent in the Western Pacific Ocean (WPO) sector in March strongly correlates with ISMR of the same year. AnSIE variations provided an early signal that the severe drought in 2002 would result in a deficit monsoon, which models failed to predict.

In another study by Prabhu *et al*.[34], during 1983–2015, they identified a strong relationship between ISMR and sea ice cover in two Antarctic sectors, namely, the WPO and the BAS. ISMR shows a direct relationship with sea ice cover in the WPO sector and an inverse relationship in the BAS sector. The study linked these relationships to El Niño Modoki, where sea ice cover in the BAS (WPO) sector corresponds with warm SST anomalies in the central (western) Pacific. These SST anomalies and associated meridional circulations affected ISMR through large-scale zonal circulation, suggesting a connection between Antarctic sea ice and the Indian monsoon. Bajish *et al*.[35] has also found a linkage between ISMR and sea ice cover in the BAS during austral autumn. They found an excess (deficit) rainfall corresponding to negative (positive) anomalous BAS SIC. They opined that there may be a link to ENSO-related SST variability.

The importance of southern oceans SST was studied by Maheswhari *et al*.[36] using 30 years of the U.S. National Oceanic and Atmospheric Administration's (NOAA) SST data from 1982–2011. They found that summer SSTs had more variability than winter. Also, the influence of El Niño/La Niña on SST was analysed. The Western Southern Ocean experienced greater anomalies in the period between 1992 and 1994; while the eastern part saw positive anomalies in the years between 1997 and 1998, and also in the period 2002–2003. Different regions showed significant positive/negative trends in interannual average SST. However, there was an overall trend of weak interannual cooling in the Southern Ocean.

Some other interesting studies by the Indian researchers on Antarctic sea ice worth mentioning are as follows. Studies by Rajak *et al*.[37] and Mishra *et al*.[38] deal with the optimisation of ship voyage route (Fig. 2) using remotely sensed data of different sea ice

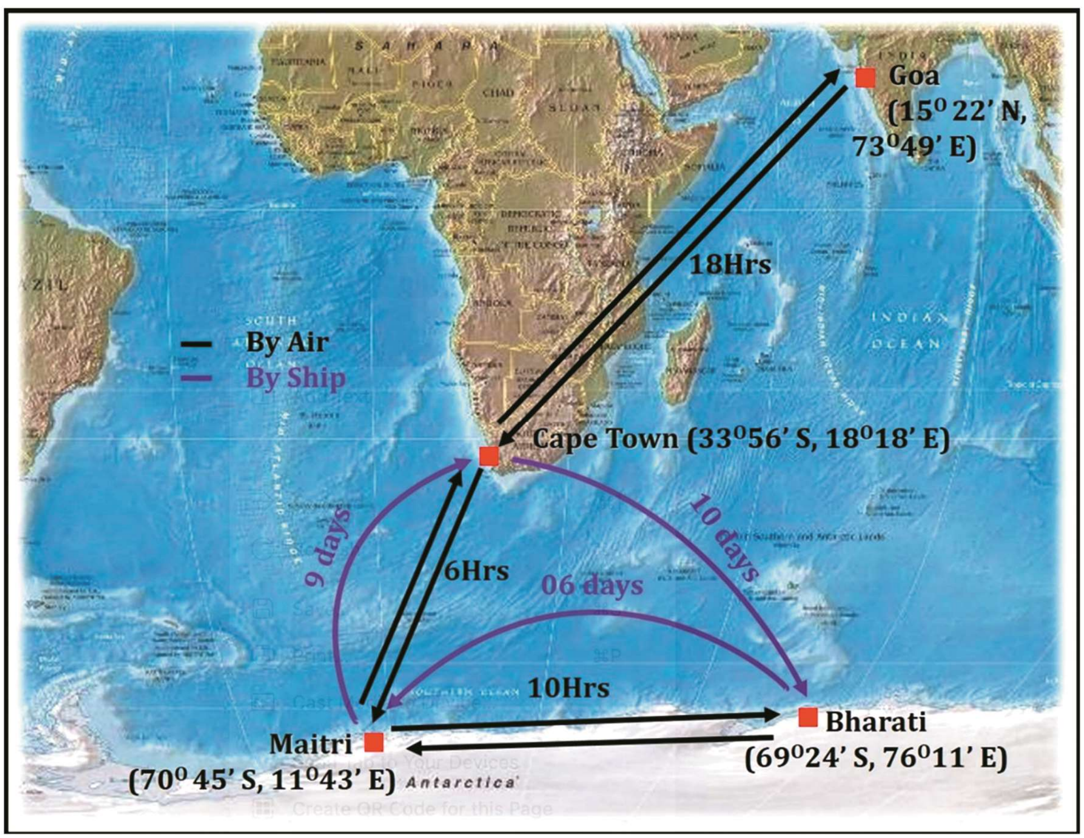

Fig. 2 — Indian Antarctic expedition voyage route (Source: Fig. 4.3 of SAC, 2020[ref. 58])

parameter and features, and wind information from satellite sensors during Indian Antarctic expeditions. In this regard, another study by Joshi *et al.*[39] employed near real-time Synthetic Aperture Radar (SAR) data from Sentinel-1 to identify safer, more efficient routes through sea ice during the 40th Indian Scientific Expedition to Antarctica (ISEA) in 2021. By analysing SAR backscatter and intensity images, the researchers developed a standardised procedure to distinguish different ice types, including navigable thin ice from hazardous thick ice and icebergs.

Studies have also been carried out on the impact of the Southern Ocean SIC on the northern Indian Ocean wave fields[40]. They used a wave model for numerical simulations and found that the impact of SIC was reflected as a change in swell heights by a few centimetres. They opined that simulations with sea ice concentration could accurately forecast the timing of high swell events in the NIO coastal regions.

Arctic sea ice studies

Murthy & Haykin[41] investigated the application of Bayes classification to differentiate between various sea ice types using surface-based marine radar imagery. The radar data acquired using dual-polarised Ku-band (16 GHz) and like-polarised S-band (3 GHz) systems near Baffin Island, Canada, underwent range compensation before being subjected to statistical analysis. The ice types were characterised by histograms approximated as continuous density functions. Classification was accomplished by maximising the probability in accordance with Bayes's rule. The results demonstrated that radar reflectivity contains sufficient information for reliable ice classification, illustrating the potential of decision-theoretic methods for accurate sea ice type discrimination.

The identification of near-real-time sea ice versus open ocean was further refined by Oza *et al.*[42], utilising dual-polarised Ku-band backscattering data from the QuikSCAT scatterometer. Despite the inherent challenges posed by high wind speeds and thin or scattered ice conditions, this approach yielded a high degree of accuracy. The authors highlighted the critical importance of such discrimination in preventing erroneous wind vector retrievals from satellite sensors in ice-covered oceanic regions. Their findings underscore the value of accurate sea ice detection for improving satellite-based observations and ensuring more reliable meteorological data.

Further, Oza *et al.*[16] used the QuikSCAT data gridded to 1° × 1° in latitude-longitude, to determine the Arctic sea ice trend from 2000 to 2007. Strong negative trends during September-October season were found in Beaufort, Chukchi, East Siberian and Laptev Seas with declines of around 13–18 % per year. The overall decline rate was almost five times faster than the decline observed from 1979 to 1998.

Sea ice thickness, which contributes to the volume of pack ice, is an important parameter that is being retrieved from satellite data by various researchers worldwide. In this regard, Singh *et al.*[43] initiated an experiment for determining thin ice thickness for coastal polynyas in the Chukchi and Beaufort Seas using AMSR-E 89-GHz brightness temperature data. The algorithm is validated with an independent thermal ice thickness derived from MODIS- . It was found to be useful for detecting thickness between 1 and 10 cm. This method finds usefulness regions where ground observations are scanty such as in high latitudes. This aids in better understanding and monitoring of thin ice regions.

In another study by Panicker *et al.*[44], the energy balance of the Barents Sea was studied using data on atmospheric conditions and sea ice. They found potential energy to be much higher than kinetic energy, leading to colder temperatures in the region. Peak radiation was observed in June, and the lowest in December, with the highest surface heat flow occurring in December. A new method for estimating Thermodynamic Equilibrium Thickness (TET) using total thermal radiation was introduced in this study, which would help in understanding energy exchanges between the ocean and atmosphere. The Barents Sea's sea ice thickness was capped at 3.5 meters, compared to 4.5 meters in the Arctic. The study underscored the effects of Atlantification on the Barents Sea.

The onset of the summer melt season is vital in the Arctic sea ice cycle and serves as a marker of climate change[45]. In this regard, using 34 years of passive microwave radiometry data, Singh *et al.*[46] analysed the variability in Arctic Snowmelt Onset Dates (SMOD). This was done for the sea ice regions north of 40° N, which are divided into thirteen sectors. Out of these sectors, ten sectors showed negative trends meaning earlier snowmelt onsets. They were statistically significant in the East Siberian Sea, Kara Sea, Laptev Sea, and others. However, a statistically significant positive trend was observed in the Greenland Sea , indicating a later melt onset. Strong positive correlations were observed among sectors (*e.g.*, Canadian Archipelago and Central Arctic), whereas the Arctic Oscillation (January–March) showed negative correlations with SMOD.

Another study by Oza *et al*.[47] investigated how changes in the earliest and latest melting onset dates of Arctic sea ice derived from space-borne passive microwave radiometer data, between 1979 and 1998, might give an indication of climate change. By applying a cluster classification technique to satellite data, the study identified regions with similar melting tendencies, revealing patterns of early or delayed melting onset. Crucially, areas showing a large difference between the earliest and latest melt dates corresponded to areas that became ice-free in September 2007, suggesting this analysis could help predict vulnerable zones in the future.

Kumar *et al*.[48], used satellite observations and reanalysis data to analyse the Arctic SIE and its correlation with SST, air temperature, and outgoing long-wave radiation. They highlighted a significant reduction in Arctic sea ice over the 40 year period (1979–2018), with the Barents-Kara Sea (BKS) region experiencing the highest decline rates. The authors suggested that the decline was driven by ocean warming and transport of heat from the Atlantic waters, especially affecting the Barents Sea in summer. Of particular interest is that the BKS plays a major role in stabilising sea ice in the rest of the Arctic. This change in sea ice cover in BKS affects the Indian summer monsoon rainfall[49]. It was discovered that during significant sea ice coverage in the Central Arctic, unique pressure patterns emerged extending from Western Europe to the western Pacific Ocean, producing extensive rainfall in the north-western and peninsular India. However, when sea ice cover in the Barents-Kara Sea is reduced, it triggers the North Atlantic-Eurasia teleconnection wave train, leading to ridge formation over north-western Europe. This atmospheric pattern influences the onset of the Indian monsoon.

Kumar *et al*.[50] documented a significant decline in Arctic SIE and concentration for the past forty years, largely driven by ocean-atmosphere interactions, which are central to global climate dynamics. By working with satellite data and model reanalysis, the researchers analysed sea ice variability across nine regions of the Arctic. The findings show a consistent reduction in sea ice throughout the seasons, with the most pronounced reduction during summer and the least during winter and spring. Four regions *viz*. the Arctic Ocean, Kara and Barents Seas, Greenland Sea, and Baffin Bay are identified as the primary contributors to the overall decline in Arctic sea ice. The study also highlights the complex interannual and seasonal fluctuations in sea ice, as well as the interactions between the atmosphere, ocean, and ice, which are crucial in understanding the observed trends.

Ravindran *et al*.[51] studied the spatio-temporal variability of sea ice and ocean parameters in the Arctic Ocean due to climate change. They used simulations from the Community Earth System Model for the period from 1850 to 2100 and observed significant changes in SST (increase), sea ice thickness (decrease) and sea salinity (decrease) in the future relative to the present climate. The result highlights regional variations in the sea ice parameters; particularly the East Siberian Sea and the Central Arctic showed the most significant changes. This study provided future projections indicating an ice-free region in September by the year 2050.

Moreover, Panicker *et al*.[52] discussed the retrieval, cross-validation, and analysis of Arctic SIE using daily datasets from the EOS-06 satellite's scatterometer (SCAT-3). The study, alike Kumar *et al*.[48], examined SIE variations in relation to air temperature and SST across six marginal seas of the Arctic in 2023. They found that the East Siberian Sea had the highest SIE, while the Barents Sea had the least. SIE was found to be negatively correlated with SST across all seas, with the strongest negative correlation in the Barents Sea. They also observed that the summer sea ice melt duration ranged from 30 to 60 days, with the shortest in the Barents Sea and the longest in the East Siberian Sea. The study highlighted the importance of understanding Arctic environmental dynamics and suggested incorporating additional factors, such as wind and ocean currents, in future research.

In another interesting study by Joshi *et al*.[53] using Sentinel-1 Synthetic Aperture Radar (SAR) data and a Python-based module, Arctic Sea Ice Drift (SID) was determined. SID helps create safer navigation routes in polar regions by forming openings. Their module integrates various algorithms and performs better with HH polarisation. Validation against the International Arctic Buoy Program data shows high accuracy, with only ~1 % deviation in drift measurements. The algorithm performs optimally with a maximum temporal resolution of ~1–2 days for SAR image pairs.

The importance of studying Arctic SST was demonstrated by Singh *et al*.[54], who analysed 30 years of Arctic SST data from the U.S. National Oceanic and Atmospheric Administration (NOAA) Optimally Interpolated SST Version 2 dataset (1981–2011). Key Increase in SSTs for the regions north of 60° N were observed, that were statistically significant . Most parts of the Arctic showed warming, including the Beaufort Sea, Chukchi Sea, Hudson Bay, Labrador Sea, Iceland Sea, Norwegian Sea, and Bering Strait. While evidence of cooling trends was seen in the Central Arctic, parts of Baffin Bay, Kara Sea, Laptev Sea, Siberian Sea, and Fram Strait. They have also found that the Central Arctic has experienced cooling from 1992–2001, with warming trends during 1982–1991 and 2002–2010.

Although geographically distant, the Arctic region holds significant implications for India's climate, particularly the Indian monsoon system. Indian researchers have increasingly focused on understanding the linkages between Arctic sea ice decline and changes in monsoon patterns. The work of Krishnamurti *et al*.[55] shows that there is a link between the South Asian monsoon and the Arctic sea ice melt. The study identified a connection between the South Asian summer monsoon and the rapid Arctic ice melt, highlighting the role of monsoonal outflows in transporting heat to the Arctic. It defined a pathway for heat flux from the monsoon belt to the Canadian Arctic, showing that these pathways carried significantly larger heat fluxes than poleward atmospheric fluxes. Heavy rain events in northern India and Pakistan were linked to the formation of wave trains that transport heat to the Arctic, contributing to ice melt.

Chatterjee *et al*.[56] suggested that there is a phase difference between the Arctic summer (June-August) SIE in the Kara Sea and the occurrence of extreme ISMR events. This is consistent with the rapidly declining sea ice since 1980s. Heavy rainfall events in central India towards the end of the ISMR season is influenced by a combination of upper atmospheric circulation anomalies, driven by decreased SIE in the Kara Sea region, and low-level circulation anomalies over west-central India. These are both bolstered by warm SST anomalies in the north-western Arabian Sea.

In the study by Sundaram & Holland[57], they found that the Indian Summer Monsoon (ISM) influences Arctic sea ice, with strong ISM years leading to increased sea ice in the Chukchi and Beaufort Seas, and weak ISM years leading to decreased sea ice. Further, the ISM was found to affect the North Atlantic Oscillation (NAO), which in turn influences the Beaufort Sea High (BSH) and Arctic atmospheric circulation, thereby impacting sea ice formation. The study highlights an atmospheric teleconnection between the tropics and the Arctic, linking ISM variability to changes in Arctic sea ice.

Technological advancements

India's progress in space technology has significantly facilitated the country's ability to study sea ice. The Indian Space Research Organisation (ISRO) has developed and launched several remote sensing satellites, such as OSCAT, SARAL/AltiKa, etc., fitted with sensors that are capable of taking detailed information on sea ice extent and concentration, as mentioned earlier. Other Indian satellites, such as RISAT and RESOURCESAT series, provide high-resolution imagery that is invaluable for monitoring changes in sea ice over time[58]. By combining these satellite data with ground-based observations, Indian researchers have provided significant insights into the dynamics of polar sea ice and its interactions with the global climate system.

Strategic relevance of sea ice research for India

India's involvement in sea ice research is not solely motivated by scientific interest only but also by its strategic significance. As a permanent observer to the Arctic Council since 2013, India, is keen on shaping the international governance framework surrounding the Arctic region. Through sea ice research, India has become an indispensable partner in global forum on polar resource management, shipping regulations, and environmental protection.

This strengthens India’s diplomatic relationships with various Arctic nations, including Russia, Norway, Canada, and the United States, which have keenly interests on developments in this field.

Moreover, in the Arctic, sea ice melt has freed up sea routes, such as the Northern Sea Route, which may have substantial economic implications on international trade[59,60]. For India, understanding the evolving sea ice dynamics is crucial for evaluating the possible perils and opportunities linked with these new routes. Furthermore, India's participation in international polar research programs enhances its standing in global discussions on Arctic governance and environmental protection.

Challenges and future directions

Although significant advancements have been made so far, Indian research on sea ice faces several critical challenges. The scope of field studies in the polar regions is limited by the fact that there are logistic complications of conducting research in such remote, harsh polar environments as the polar regions. The situation is also complicated by high expenses associated with polar expeditions. Additionally, there is a need for greater collaboration between Indian institutions and international research networks to share data and resources. In this regard, joint collaborative research projects with Arctic countries enhance India's influence in strategic decision-making related to resource extraction, maritime safety, and environmental conservation in the Arctic.

In spite of the above challenges, since sea ice is the part and parcel of the Earth's climate system, it is our bounden duty to safeguard it. Accordingly, the priority for future research should be on the development of more accurate predictive models for sea ice behaviour, enhanced by advancements in computational technology and machine learning. Expanding India's satellite capabilities and fostering stronger international partnerships will be essential for addressing these challenges and advancing the country's role in global sea ice research.

Conclusion

India has made good advance in the field of sea ice research, contributing to understanding of polar dynamics and their wider effects on global and regional climate systems. Through its dedicated polar research initiatives, technological progress, and strategic efforts, India has positioned itself a prominent position in this domain. However, continued investment in research infrastructure, international collaboration, and technological advancements will be crucial for overcoming existing challenges and ensuring that India remains at the forefront of polar research in the coming decades.

In this article, significance of sea ice in the Earth's climate system and India's increasing involvement in this research since the beginning of 1980 were emphasized. Sea ice has been highlighted as a critical component of the Earth's climate system, influencing ocean circulation, weather patterns, and global ecosystems.

A detailed analysis of India's scientific contributions to sea ice research, including its scientific advancements, the interplay between sea ice dynamics and regional climate patterns, and the strategic importance of such studies were thoroughly examined. Leading national agencies driving these research efforts, fostering international collaborations and promoting advancements in remote sensing technology were identified.

In summary, the significance of sea ice in the Earth's climate system, India's ever-expanding association in sea ice research, and the strategic significance of this research for the nation were comprehensively addressed in this review. In-depth perspectives on India's contributions to both Antarctic and Arctic sea ice studies, highlighting the key challenges and future directions in this field were also provided. Overall, India's engagement in sea ice research is depicted as a vital and evolving aspect of the country's scientific and strategic endeavours.

Conflict of Interest

There is no conflict of interest.

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