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Research Paper

Advances in Antarctic Sea Ice Studies in India

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Sea ice cover plays a key role in regulating the Earth's climate by influencing the global atmospheric and oceanic circulation through various feedback mechanisms. The only viable source for the continuous monitoring of sea ice cover, its variability and characterization in the vast and remote polr region is the utilization of data acquired by orbiting satellites supported by Ship based observations. India has been contributing significantly in the development of techniques for extraction of sea ice from state-of-art Indian sensors and other international missions. Significant progress has been made towards understanding sea ice variability in the Antarctic region. Based on various studies in polar regions, it has been observed that during last few decades, Arctic is showing the consistent decline of summer sea ice cover, in contrast to Antarctica which is showing regional anomalies with positive and negative trends. Role of sea ice concentration in Indian monsoon has also been examined. Relation of El Nino Southern Oscillation (ENSO) and sea ice extents have been studied. A climatic dataset of Sea Ice Occurrence Probability (SIOP) generated for the Antarctic region was used to compare the climatic sea ice growth and melt patterns in the eastern and the western regions of the Antarctic.This paper reviews the recent contributions mainly by Indian scientists in the studies of sea ice with inclusion of a few international scientific contributions.

Keywords: Antarctic; Sea Ice; Remote Sensing; Microwave Radiometer; Scatterometer; SAR

Introduction

Antarctic and Southern Ocean science is vital to understand natural climate variability, the processes that govern global change and the role of humans in the Earth and climate system (Kennicut II *et al*., 2015). Sea ice is an integral part of polar ocean-climate system. Sea ice dynamics and thermodynamics play an important role in the polar climate, which in turn influences the global oceanic and atmospheric circulation. The extent of global sea ice cover over the polar regions varies between 16.6×10^6 and 27.5×10^6 km^2 at any given time, which corresponds to around 3–6% of the earth's total surface area (Comiso, 2010). For instance, while the Arctic Ocean shows a 2-2.5 times increase in its sea ice cover from summer to winter, the Antarctic shows a five- to six-fold increase (Zwally *et al*. 1983; Gloersen *et al*. 1993, Simmonds, 2015). Monitoring of fluctuations of the Antarctic sea ice indicate an increase of about 2.4 % per decade. (Nayak, 2008). More specifically, Satellite passive-microwave data for the period November 1978-December 2010 reveal an overall positive trend in the ice extents of 17 100$\pm$2300 km^2/year (Parkinson and Cavalieri, 2012). Such changes are primarily driven by the seasonal variation in atmospheric and oceanic conditions. The only viable source for the continuous monitoring of sea ice over the vast and remote polar region is the utilization of satellite remote sensing data.

In the past one decade India has contributed significantly to an increased understanding of the ice variability around Antarctica using space-borne data. Availability of data from Indian sensors like MSMR Multi Scanning Microwave Radiometer (launched on 26 May 1999 onboard OceanSat-1), OSCAT Ku band pencil beam Scaterrometer (launched on 23 September 2009 onboard OceanSat-2) and SCATSAT Ku band pencil beam Scaterrometer (launched on 26 September 2016 onboard SCATSAT-1) have made it possible to contribute in the understanding of Sea Ice extents and variability in the Northern and

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Southern polar regions. This paper presents an overview of the country's contribution specially in Antarctic sea ice studies.

Development of Techniques for Sea Ice Characterization

Teleti and Luis (2013) have extensively discussed the evolution of remote sensing sensors technologies with emphasis on their suitability for observing the polar regions. The study of the extents of sea ice and its variability on a seasonal to longer timescale necessitates global earth observation systems with high temporal coverage. However, such systems compromise on the spatial resolution. Nonetheless, sensors orbiting the earth have been one of the main sources of data collection on the sea ice extent and its spatial and temporal variability. An initial attempt to characterize the sea ice over Antarctica was made by Indian scientists utilising MSMR data onboard Oceansat-1 (Bhandari *et al*., 2005; Bhandari and Khare, 2009; Dash *et al*., 2001; Vyas *et al*., 2003). An atlas of sea ice cover over Antarctica (Fig. 1) is a key outcome of the studies made by Vyas *et al*. (2004).

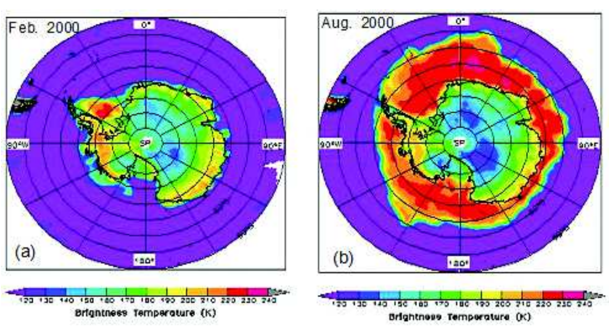

Fig. 1: Antarctic sea ice cover derived from Oceansat-1 MSMR 18 GHz brightness temperature data; (a) summer sea ice cover and (b) winter sea ice cover

Subsequent studies on sea ice detection has come from the use of OSCAT Scaterrometer data onboard Oceansat-2 (Oza *et al*., 2011a). Discrimination between sea-ice and ocean is ambiguous in the Scaterrometer observations under the high wind and/or thin/scattered ice conditions. Oza *et al*. (2011b) developed an algorithm to distinguish ocean winds from the sea ice in both the hemispheres using spatio-temporal coherence techniques, in addition to backscatter coefficient and the Active Polarization Ratio (API). These authors found that the threshold API value of –0.025 was optimum for sea-ice and ocean discrimination. They compared their results with the operational sea-ice products and found that overall sea-ice identification accuracy achieved was of the order of 95 per cent, ranging from 92.5% (during December in the Southern Hemisphere) to 98% (during March in the Northern Hemisphere). This algorithm was used to mask the sea ice area in operational ocean wind product using OSCAT data.

Singh *et al*. (2015) have synergistically utilized the Ka-band SARAL AltiKa data along with Ku-band OSCAT Scaterrometer data to improve the sea ice discrimination from other ice and ocean features.

After discrimination of sea ice from satellite images, further classification of sea ice is required for many purposes which also includes ice routing to serve Ship navigation. Zhu *et al*. (2016) have used Radarsat-2 dual-polarization satellite images to develop an algorithm to classify Antarctic sea ice based on conditional Random Fields (CRF) approach by including multiple features from sea-ice concentration, gray-level co-occurrence matrix textures, polarization ratio, backscatter coefficients and intensity data.

Detection of sea Ice floes in polar region has been demonstrated by use of RISAT-1 SAR data (Srisudha *et al*., 2013). This detection is useful for the analysis of ice floes size distribution which has implications in ice motion dynamics and polar species habitat in the sea ice zone.

Worby and Cosimo (2004) have validated the Passive microwave derived ice edge locations in the Antarctic using in situ observations from ships between 1989 and 2000 (Worby and Cosimo, 2004). They reported the better correlation during growth season compared to that observed during melt season, which could be due to low concentration and saturated nature of ice.

Besides ice cover or extent, ice thickness is much more important parameter which needs to be retrieved from satellite data. Towards the development of a technique for the estimation of sea ice thickness, studies have been carried out by Singh *et al*. (2011) for thin sea ice using 89 GHz AMSRE brightness temperature data and by Maheshwari *et al*. (2015) for the estimation of sea ice freeboard using data from AltiKa altimeter launched by India in SARAL mission.

These techniques have been developed for the Arctic and needs validation for their use in the Southern polar region as well.

Antarctic sea ice thickness has also been retrieved by using Ice Cloud and land Elevation satellite (ICEsat) elevation measurements to retrieve sea-ice (with snow cover) freeboard in the Weddell Sea Antarctica (Kern and Spreen, 2015). They have also discussed the uncertainties involved in measurements.

It is worth mentioning here, that ship-based observations have been used to describe regional and seasonal changes in the thickness distribution and characteristics of sea ice and snow cover thickness around Antarctica (Worby *et al*., 2008). Their data set comprises 23, 373 observations collected over more than two decades of activity and has been compiled as part of the Scientific Committee on Antarctic Research (SCAR) Antarctic Sea Ice Processes and Climate program (ASPeCt). The results show seasonal progression of the ice thickness, surface ridging, snow cover and local variability for each region and season. The long-term mean and standard deviation of the total sea ice thickness (including ridges) is reported as 0.87+0.91m, which is 40% greater than the mean level ice thickness of 0.62m.

One of the important contribution in the understanding of sea ice are the Sea Ice temperature products produced from Earth Observation System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) onboard both the Terra and Aqua satellites (Hall *et al*., 2004). Daily sea ice extent and ice surface temperature (IST) products are available at 1- and 4-km. resolution.

Sea Ice Modelling and Trend Analysis

Sea Ice Modelling

Rana *et al*. (2011) introduced an image processing-based model called active contour model (also known as Snake model) and non-rigid motion estimation techniques to predict sea ice edge in the Antarctic. Recently Deb *et al*. (2016) have used state-of-art Ocean General Circulation Model known as Nucleus for European Modelling of the Ocean (NEMO) coupled with Louvain-la-Neuve Sea Ice Model, version 2 (LIM2) to study the impact of dynamical Southern Annular Mode forcing to a non-annular response in sea ice cover over the Indian Sector of the Southern Ocean.

Long-term Analysis

Trend Analysis: Sreenivasan and Mujumdar (2006) have used SSM/I passive microwave data, to map sea ice around Antarctica during its depletion phase (November 2001 to January 2002).

In another study by Rai and Pandey (2006), Antarctic sea ice edge variability in recent years and its relationship with Indian ocean sea surface temperature based on 23 years of satellite passive microwave observations (1982-2004). Sea ice edge anomaly averaged around Antarctica shows nearly zero trend in the time domain.

Scaterrometer based studies of sea ice variability suggest significant decline of summer (September) sea ice in the Arctic, whereas the Antarctic sea ice shows strong positive trend in the Ross sea sector and statistically significant negative trend in Amundsen and Bellingshausen seas (ABS) sector (Fig. 2). As

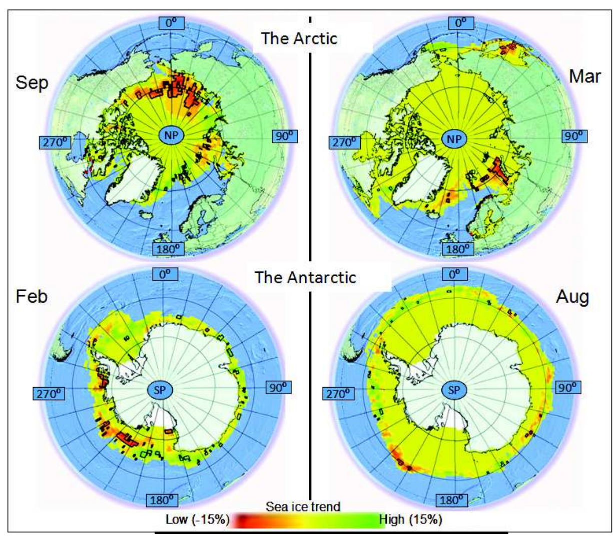

Fig. 2: Summer minimum and winter maximum sea ice trends (1) Chukchi, (2) Okhotsk, (3) East Siberian, (4) Laptev, (5) Barents, (6) East Greenland, (7) Weddell, (8) Indian Ocean sector, (9) Ross (10) Amundsen, (11) Bellingshausen (Oza *et al*., 2012)

observed in Fig. 3, the pattern of scaterrometer-derived observations closely follows the pattern of passive microwave based observations, which is indicative of the validity of the scaterrometer derived estimates.

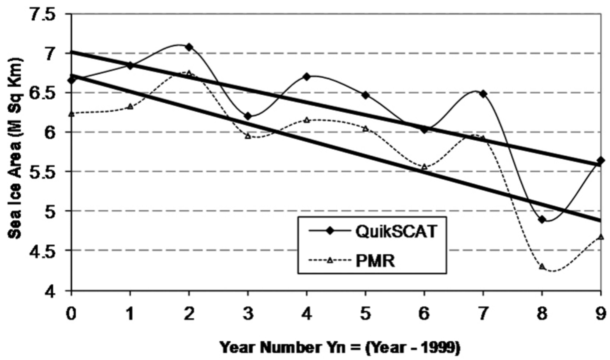

Fig. 3: Comparison of Scaterrometer derived sea ice trend with the passive microwave radiometer (PMR) based estimates obtained from www.nsidc.org

Detailed investigation of these trends and regional anomalies have been discussed in various research publications (Oza *et al*., 2010; 2011a, 2012). Monthly trend analysis data is available on the web portal (vedas.sac.gov.in) of Visualisation of Earth Observation Data and Archival System (VEDAS) of the Space Applications Centre (SAC).

Studies based on observations from passive microwave radiometers by Prabhu *et al*. (2011) showed that the sea ice cover in the ABS (Amundsen and Bellingshausen Seas) sector exhibit a strong decreasing trend. This could possibly be due to the increasing SST trends in this sector and decreasing trends in the Ross Sea sector (Maheshwari *et al*., 2013).

Climatic dataset of Sea Ice Occurrence Probability (SIOP) : A climatic dataset of Sea Ice Occurrence Probability (SIOP) generated for the Antarctic region was used to compare the climatic sea ice growth and melt patterns in the eastern and the western regions of the Antarctic (Rajak *et al*. 2015). The SIOP product developed from a long-term (1978-2012) passive microwave daily-averaged Sea Ice Concentration (SIC) gives the probability of sea ice occurrence for each date from January 1 through December 31. Two of the demonstrated potential applications of this dataset are (i) generation of sea ice majority mask, and (ii) assessment of the climatic intra-seasonal SIOP growth and decay gradients over the eastern and western regions of the Antarctic.

Analysis of the temporal gradients of SIOP growth (indicative of sea ice refreezing rate) and decay (indicative of sea ice melting rate) indicated different rates of sea ice growth and refreezing over the eastern and western parts (Rajak *et al*., 2015). It was also observed that while the sea ice decay gradient is higher compared to growth gradient in the east Antarctic region; the growth gradient is higher than the decay gradient in the western region. It indicates faster melting than refreezing in the east Antarctic while faster refreezing than melting in the west Antarctic. SIOP Data set is available on the mosdac.gov.in and vedas.sac.gov.in web portals; e.g. see Fig. 4.

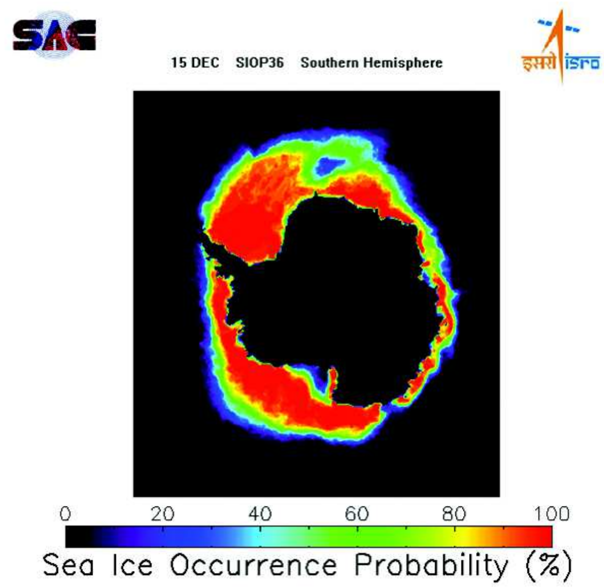

Fig. 4: SIOP data for 15th of December (source: mosdac.gov.in)

Assessment of Sea Ice Melting : Sea ice affects the ocean-atmosphere dynamics through various feedback mechanisms, such as ice-albedo. Srivastava *et al*. (2011) have assessed the impact of the ice albedo feedback mechanism on the Antarctic sea ice melting rates using DMSP SSM/I sea ice monthly concentration data (1988-2006). The melting rate obtained from the SSM/I data was compared with the theoretical melting rate obtained by differentiating a theoretical curve, based on the effect of seasonal cycle of solar irradiance. Further research is required in the assessment of albedo as a consequence of effect of various oceanic features. Albedo is directly connected to heat balance and mass balance of sea ice.

A study by Istomina *et al*. (2015) reveals that melt pond fractions in Arctic affects the energy balance of Arctic ocean in summer. An algorithm to retrieve melt pond fraction and sea ice albedo from Medium Resolution Imaging Spectrometer (MERIS) data is validated against aerial, ship borne and in situ campaign data.

Role of Westerlies and Thermohaline Structure on the Sea Ice Extent : Nuncio and Luis (2011) studied satellite-derived sea ice extent during November 1978 to December 2006 in the Indian Ocean Sector of the Southern Ocean in relation to atmospheric forcing and oceanic thermohaline structure. The study revealed that the sea ice extent increased when the ocean exhibited higher stability.

Sea Ice and Its Global Teleconnection

On the relation of Antarctic sea ice and monsoon variability, Dugam and Kakade (2004), carried out a study to statically evaluate the relation between satellite derived Antarctic sea ice extent and Indian Summer monsoon variability over the various homogeneous regions of India. Analysis was carried out for 22 years (1979-2000). It is observed that deficient monsoon years are preceded by more than normal sea ice extent, and in excess or normal monsoon years the sea ice extent is less than the normal.

Studies by Prabhu *et al*. (2009, 2010, 2011, 2015) indicate the role and impact of Antarctic sea ice on the All-India summer monsoon (AISM). These authors found a coherent propagating pattern between the ASI extent and AISM, as well as the rainfall over most of the homogeneous geographical regions of India. Furthermore, their study reveals that the sea-ice extent (SIE) of the western Pacific Ocean sector in the month of March has a strong association with that of the AISM in the same year. Using SSMR-SSM/I based sea ice products (1979-2009) these authors reported that the SIE over the Bellingshausen and Amundsen Sea Sector (BASS) during the austral summer (October–December) has an inverse relationship with the all AISM of the following year. Furthermore, the sea surface temperature and the upper tropospheric meridional transport of heat over the southeast Pacific, during the period preceding the monsoon season, show contrasting behavior with respect to the extremes of AISM. These authors have also demonstrated that a positive (negative) SAM during February–March is favorable (unfavorable) for the ensuing summer monsoon rainfall over the Indian sub-continent.

Dash *et al*. (2013) studied the teleconnection between ENSO and the sea ice extent (SIE) in the Weddell Sea (South Atlantic) and the Bellingshausen–Amundsen Sea (South-Eastern Pacific) sectors of the Southern Ocean and found that the relationship between the tropical expression of ENSO and the SIE in these two areas has undergone a phase shift around 1992 (Fig. 5). The phase shift is attributed to the contrasting features of the structure and strength

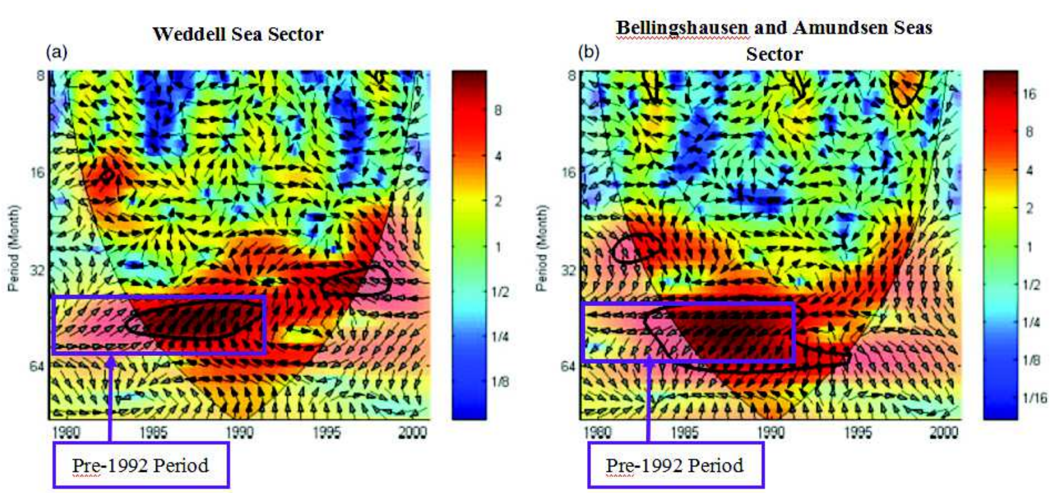

Fig. 5: The wavelet covariance (shaded) and phase difference (vector) between SOI and the sea ice extent anomalies in the cone of influence and 5% significance level contour (thick dark line) is overlaid on the covariance. The vectors indicate the phase difference and the lead/lag relation between the two-time series. (Source : Dash *et al*., 2013)

of the RFC before and after 1992 in both, the South Atlantic and the South-Eastern Pacific.

Deb *et al*. (2014) studied the effect of ENSO on the sea ice behavior in the Indian Sector of the Southern Ocean (ISSO). Their investigation found that sea ice in the eastern part of ISSO (i.e. 50°-80°E) is negatively correlated with ENSO (Fig. 6). Also, they demonstrated that the ENSO induced variabilities in the sea ice area of the ISSO are mainly controlled by (1) the thermodynamics of the region (surface air temperature and sea surface temperature changes due to modulation of the local pressure gradient), (2) dynamics of the sea ice, and (3) the alteration of mean meridional heat flux primarily due to changes in the RFC.

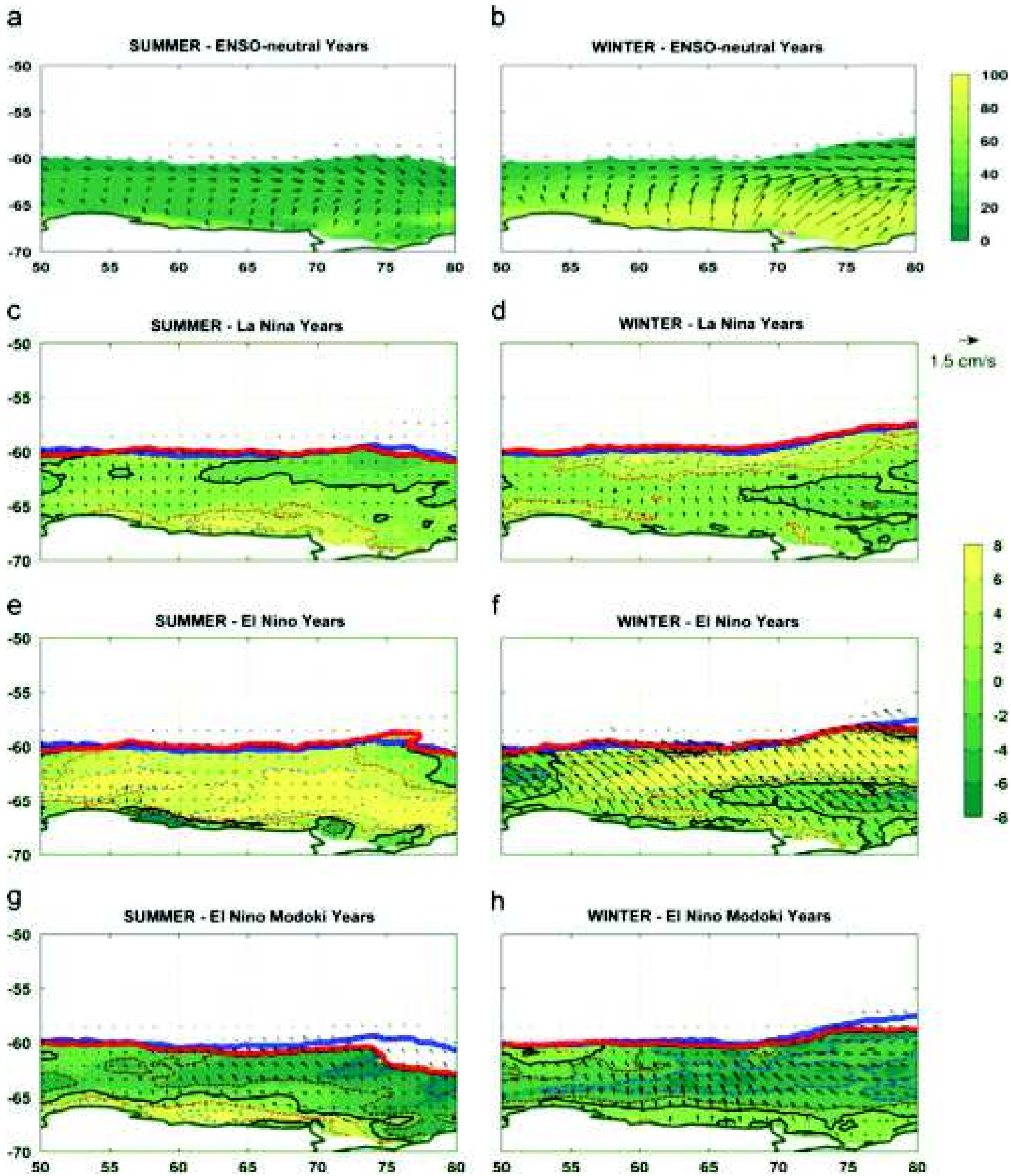

Fig. 6: Distribution of mean sea ice concentration (SIC) during normal/ENSO-neutral years (a) summer and (b) winter. Composite of SIC anomalies for La Niña years (c) summer (d) succeeding winter; for El-Niño years (e) summer (f) succeeding winter and for El-Niño Modoki years (g) summer (h) succeeding winter. Composites of sea ice motion vectors (cm/s) for corresponding seasons are overlaid on them. Red dashed contours and blue dot–dashed contours represent SIC anomalies greater than one and two sigma levels respectively, solid black contours represent zero values. The thick blue contours represent the average sea ice edge for the ENSO-neutral years. The thick red contours represent the composite sea ice edge during corresponding seasons (Deb *et al*., 2014)

Conclusions

During the past one decade, Indian scientists have demonstrated their capability to design and launch of state-of-the-art remote sensing satellites that provide products to study the land- and sea-ice. Advanced techniques have been developed for the sea ice characterization, which have also been utilized for the long-term analysis of sea ice variability. Long-term/ climate-scale studies carried out in the Antarctic region have provided valuable insights into the polar ice processes and the changes. Value added products derived using space-borne data requires further validation in the Antarctic region.Studies carried out so far need to be further expanded with development of more advance instruments onboard satellites and development of algorithms for advance analysis of data. Continuity of missions is required for generation of long term database of sea ice extent, types and thickness. The contrast in the nature of growth and decay of sea ice in Arctic and Antarctic region needs to be thoroughly examined. Modeling is required to understand the effect of sea ice variability in the ocean circulations and sea ice-atmosphere energy balance studies. Monitoring Sea Ice drift is one of the potential area of remote sensing applications in the studies of sea ice using advance image processing techniques.

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