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Trends in the polar sea ice coverage under climate change scenario

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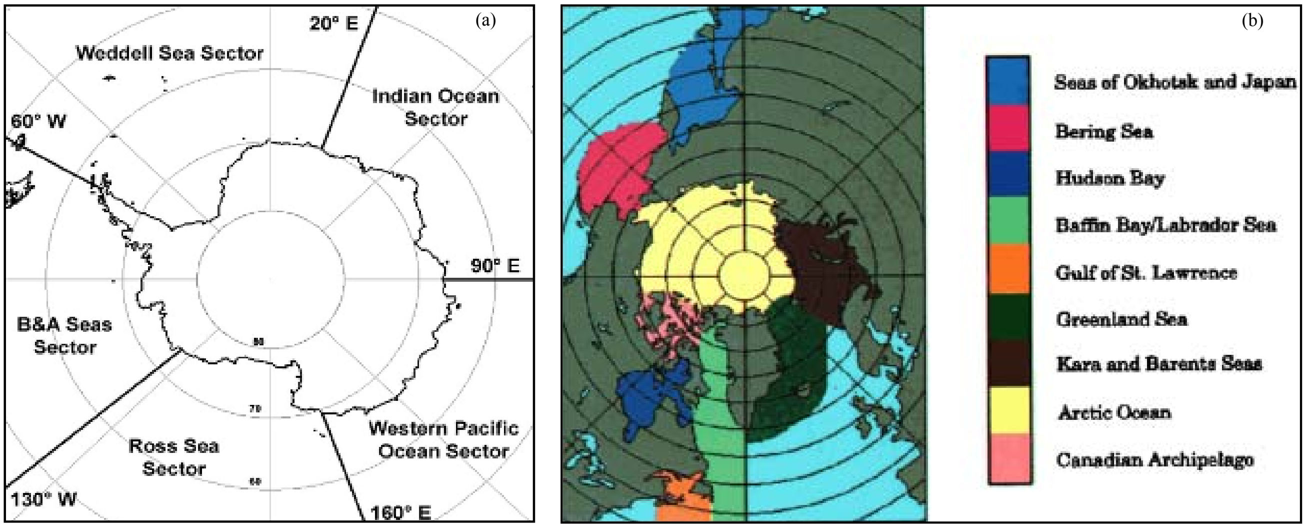
सार – गत तीन दशकों में उपग्रह सूक्ष्म तरंग प्रौद्योगिकी के विकास ने ध्रुवीय क्षेत्रों में समुद्र हिम आँकड़ों को प्राप्त करने के लिए वैज्ञानिक समुदाय को अवसर दिया है जिसे अन्यथा किसी अन्य उपायों से निरंतर मॉनिटरन द्वारा प्राप्त नहीं किया जा सकता है। यह अध्ययन आर्कटिक और एंटार्कटिक क्षेत्रों के विभिन्न भागों में समुद्र हिम सीमा (एस. आई. ई.) की प्रवृत्तियों तथा इनकी चरम सीमाओं में अन्तः वार्षिक विविधताओं पर केन्द्रित हैं। सामान्यतः 1979–2007 की अवधि के आँकड़ों से एंटार्कटिक और आर्कटिक क्षेत्रों में क्रमशः वृद्धि और कमी की प्रवत्ति सहित समुद्र हिम परत में अन्तः वार्षिक विविधता का पता चला है। दक्षिणी गोलार्द्ध में मात्र बेलिंगशाउसेन और अमंडसेन समुद्री भागों में अत्यधिक कमी की प्रवृत्ति देखी गई है। तथापि उत्तरी गोलार्द्ध के सभी भागों में कमी की प्रवृत्ति देखी गई है जिनमें से कारा और बारेंटस समुद्री भाग सबसे अधिक प्रमुख हैं। यद्यपि आर्कटिक में समुद्री हिम सीमा की कमी की प्रवृत्ति भूमंडलीय उष्णता में योगदान देती है इस समय एक कुतूहलपूर्ण प्रश्न बना रहता है कि अन्य ध्रुवीय क्षेत्रों की प्रवृत्ति इससे अलग क्यों है।

ABSTRACT. The development in the satellite microwave technology during the past three decades has offered an opportunity to the scientific community to access the sea ice data over the polar regions, which was otherwise inaccessible for continuous monitoring by any other means. The present study focuses on the trends in the Sea Ice Extent (SIE) over different sectors of the Arctic and the Antarctic regions and the interannual variability in their extremes. In general, the data over the period (1979-2007) reveal marked interannual variability in the sea ice cover with an increasing and the decreasing trend over the Antarctic and the Arctic region respectively. Over the southern hemisphere, only the Bellingshausen and Amundsen Seas sector shows an exceptional decreasing trend. However, in the northern hemisphere, all the sectors show a decreasing trend, with the Kara and Barents Seas sector being the most prominent one. Although, the decreasing trend of the SIE over the Arctic could be attributed to the global warming, an intriguing question still remains as to why the other polar region shows a different behaviour.

Key words – Sea Ice Extent, Climate change, Global change, Global warming, Cryosphere.

1. Introduction

It is realized that the long-term variation of sea ice is an indicator of climate change. Long-term changes in Sea Ice Extent (SIE), covering tens of millions of square kilometers of the ocean, can easily influence the climate. In reverse, the climate change influences the SIE and this can serve as a sensitive indicator to the changing climate. Thus, monitoring the SIE with satellite observations provides a useful quantitative measure towards our understanding of the role of cryosphere in influencing the global climate. Over the past three decades, satellite derived sea ice products have been made available, but they are not yet enough to provide a conclusive evidence of the change on climatic time scales. Nevertheless, the existing satellite record has been examined for the short-term and long-term changes in SIE in both the Antarctic (Budd, 1975; Kukla and Gavin, 1981; Zwally *et al*., 1983) and the Arctic (Campbell *et al*., 1984; Parkinson *et al*., 1987; Gloersen and Campbell, 1988, Parkinson and Cavalieri, 1989). In our study, as per the definition of the polar sectors by Gloersen *et al*., (1992), the Antarctic region is divided into five sectors [Fig. 1(a)] namely: Weddell Sea (WS), Indian Ocean (IO), Western Pacific Ocean (WPO), Ross Sea (RS) and Bellingshausen and Amundsen Seas (BAS). Likewise, the Arctic region is also divided into nine sectors [Fig. 1(b)] namely: Seas of Okhotsk and Japan (SOJ), Bering Sea (BS), Hudson Bay (HB), Baffin Bay/Labrador Sea (BBLS), Gulf of St. Lawrence (GSL), Greenland Sea (GS), Kara and Barents Seas (KBS), Arctic Ocean (AO) and Canadian Archipelago (CA). Our main objective is to understand the interannual variations of SIE along with its trends for the five sectors of the Antarctic and the nine sectors of Arctic as mentioned above and thereby identify if there is any prominent signal with respect to the current global



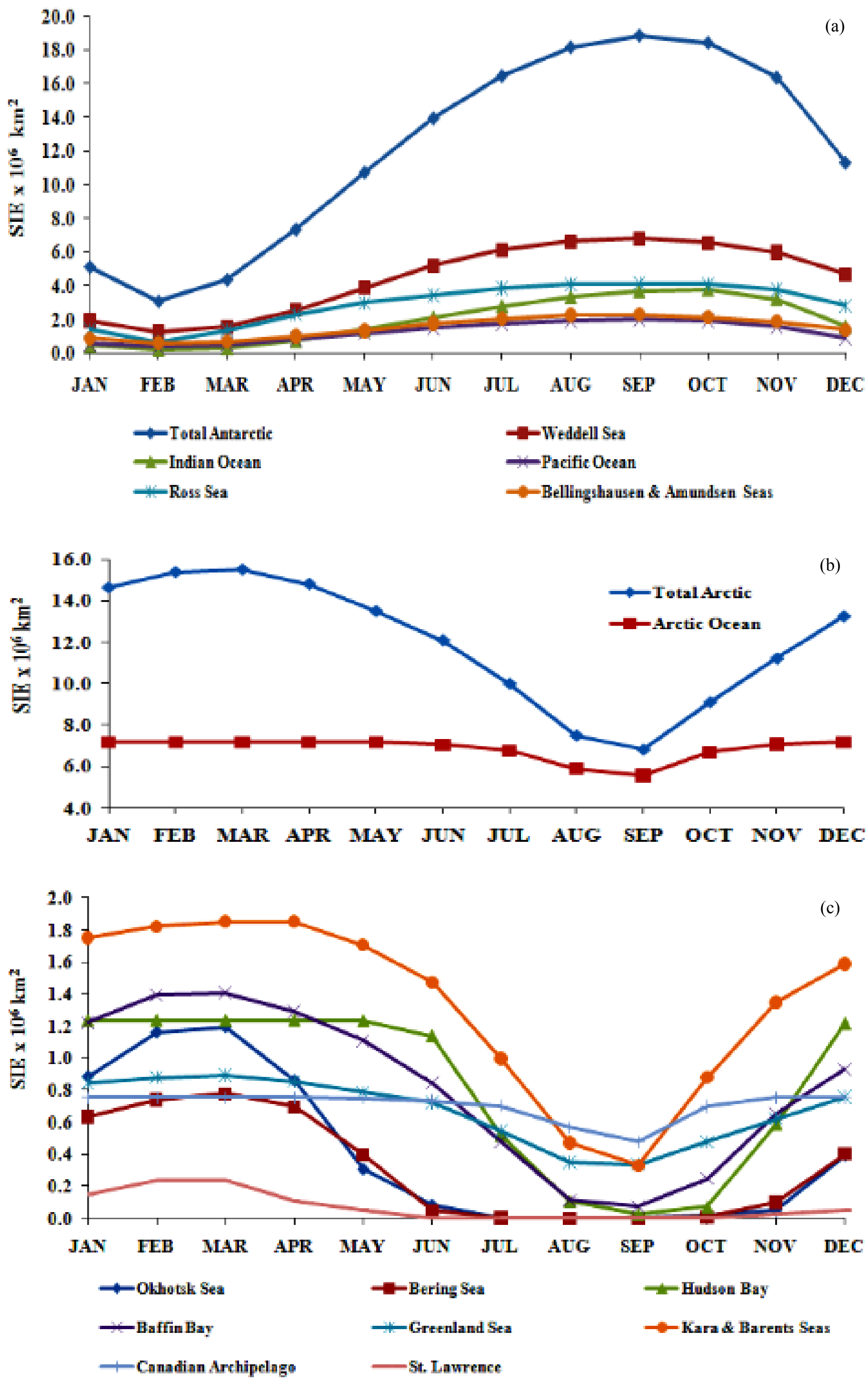
Figs. 1(a&b). Maps of (a) five sectors of Antarctic and (b) nine sectors of Arctic (*Source* : NSIDC website)

warming scenario of increasing temperature caused due to substantial rise in greenhouse gases (IPCC, 2007).

2. Data and methodology

To carry out this study, the SIE data provided by the National Snow and Ice Data Center (NSIDC) (website: ftp.sidads.colorado.edu) is used. The SIE is defined as the amount of ice area covered (in km^2) from the continental boundary to the ice edge in the open water. It is constructed from the Sea Ice Concentration (SIC) defined as the fractional sea ice cover lying within one resolution cell of the satellite sensor, which is primarily developed using NASA Team Algorithm (Steffen and Schweiger, 1991) employing the dually polarized brightness temperature data that is obtained using the sensors Scanning Multi-channel Microwave Radiometer (SMMR) onboard NIMBUS-7 and Defense Meteorological Satellite Program's (DMSP) Special Sensor Microwave/Imager (SSM/I) (Comiso and Steffen, 2001). The definitions of SIC and SIE along with the procedures to generate them have been obtained from Gloersen *et al*., (1992). This SIC based algorithm was selected because of their relative insensitivity to the ice surface temperature variations. In general, open water has the lowest brightness temperature values due to its low emissivity (Lamb, 1982). Over the regions known to be covered with sea ice, emissivity is observed to be very high ranging from 0.5 to 0.9 depending upon various levels of concentration in sea ice (Grenfell, 1983). Higher the value of SIC, higher is the emissivity and therefore, higher is the brightness temperature. A threshold value of 15% of SIC is fixed, which means that if a pixel value having a spatial resolution of 25 km × 25 km has a SIC value above this threshold value, then it goes into the calculation of SIE (Cavalieri *et al*., 1999). It is known from literature (Parkinson *et al*., 1999; Gloersen *et al*., 1992) that the derived SIE is not very sensitive to the threshold value used to derive it.

The variability of both the Antarctic and Arctic SIEs as seen from the sea ice data series combining SMMR and SSM/I is described in the form of time series of yearly ice extents, monthly ice deviations and monthly ice extents. The monthly deviations are calculated as deviations of the monthly sea ice extent from the 29-year (1979-2007) average values for the particular month. Trends for the yearly ice extents are further calculated by using linear least squares regression through the SIE values for the above period. The slopes of b of the least square lines as given by the linear equation $y = a + bx$, are calculated along with their estimated standard deviations (or standard errors) following Draper and Smith (1981). For each trend line, a standard F test (Pollard, 1981) was performed, testing the null hypothesis of 0 slope, and all the cases in which the null hypotheses can be rejected atleast for confidence level of 95% are identified. In the present study, the inter-regional and inter-hemispheric comparisons of SIE for the different polar sectors, including the Total Antarctic and Total Arctic, which is the cumulative area of SIE for all the five sectors in the Southern Hemisphere (SH) and nine sectors in the Northern Hemisphere (NH) respectively, are focused upon. Further, the SIE trends that are annually averaged over the SMMR-SSM/I would be discussed. Similar trend analysis is also done for the months of extrema of sea ice extent for the various polar sectors. The outcome of the



Figs. 2(a-c). Seasonal cycles obtained from averaging the monthly sea ice extents for the polar sectors for the SMMR-SSM/I period 1979-2007

analysis is likely to provide a useful quantitative measure to look into the most burning issue of our planet - the global warming. Finally, we will be presenting the summary of the global sea ice cover.

TABLE 1

Slopes of the yearly SIE trends using Linear Least Squares fit for the period 1979-2007 along with its decadal analysis over the Antarctic region

Various sectors of Southern Hemisphere				
Region	Yearly			
	10^3 km^2/year	S	% / decade	
			A	B
Total Antarctic	12.5 ± 4.5	99	1.3	1.1
Weddell Sea (WS)	4.0 ± 5.5	-	2.9	-1.1
Indian Ocean (IO)	3.2 ± 2.5	-	1.0	3.5
Pacific Ocean (PO)	1.0 ± 2.1	-	1.7	0.2
Ross Sea (RS)	13.2 ± 4.3	99	5.2	5.1
Bellingshausen and Amundsen Seas (BAS)	-8.9 ± 2.8	99	-9.6	-2.8

where 'S' indicates statistical significance and identifies the cases in which the null hypothesis of 0 slope is rejected with a 95% confidence level (95) and a 99% confidence level (99) using a standard *F* test. Decade 1: 1979-1987, Decade 2: 1988-1997 and Decade 3:1998-2007. 'A' represents behaviour of Decade 2 with respect to 1 and 'B' represents behaviour of Decade 3 with respect to 2

TABLE 2

Slopes of the yearly SIE trends using Linear Least Squares Fit for the period 1979-2007 along with its decadal analysis over the Arctic region

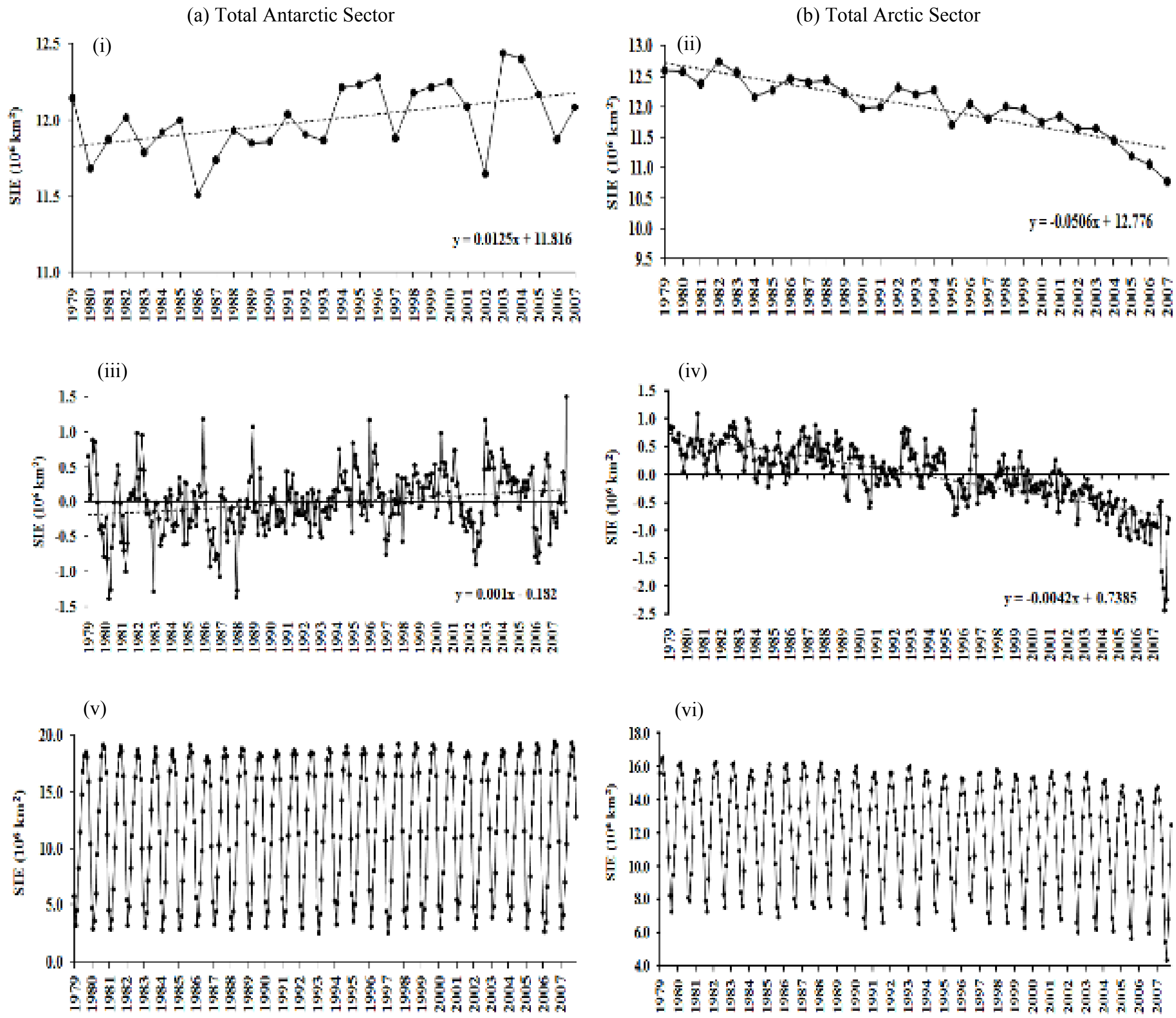
Various sectors of Northern Hemisphere				
Region	Yearly			
	10^3 km^2/year	S	%/decade	
			A	B
Total Arctic	-50.6 ± 4.8	99	-2.9	-4.7
Seas of Okhotsk and Japan (SOJ)	-4.3 ± 1.5	99	-21.8	10.7
Bering Sea (BS)	-0.4 ± 1.0	-	4.2	-3.4
Hudson Bay (HB)	-4.1 ± 0.8	99	-2.2	-8.3
Baffin Bay/Labrador Sea (BLS)	-8.2 ± 2.0	99	1.5	-20.7
Gulf of St. Lawrence (GSL)	-0.6 ± 0.4	-	22.3	-33.7
Greenland Sea (GS)	-6.5 ± 1.4	99	-1.6	-16.0
Kara and Barents Seas (KBS)	-11.6 ± 2.8	99	-7.7	-5.4
Arctic Ocean (AO)	-11.6 ± 2.4	99	-1.4	-1.8
Canadian Archipelago (CA)	-1.2 ± 0.3	99	-2.1	-1.6

3. Results and discussion

3.1. *Seasonal cycle of polar SIE*

The perennially attached sea ice cover around the polar sectors, amounting to millions of square kilometers, has the potential to impact the oceanic and atmospheric circulation through the large-scale oceanic heat and mass transport (Park *et al.*, 1998; Brix and Gerdes, 2003). The seasonal cycle of total Antarctic Sea Ice Extent (AnSIE), wherein SIE for each month is averaged over the period 1979-2007 is brought out in Fig. 2 (a). It has a minimum of 3.1×10^6 km^2/yr in February and a maximum of 18.84×10^6 km^2/yr in September. Growth is fast from March to September and so is the rate of decay from September to February, with maximum contribution to the total AnSIE coming from WS and RS sectors.

On the other side of the globe, the seasonal sea ice coverage behaviour of the Arctic sea ice extent (ArSIE)

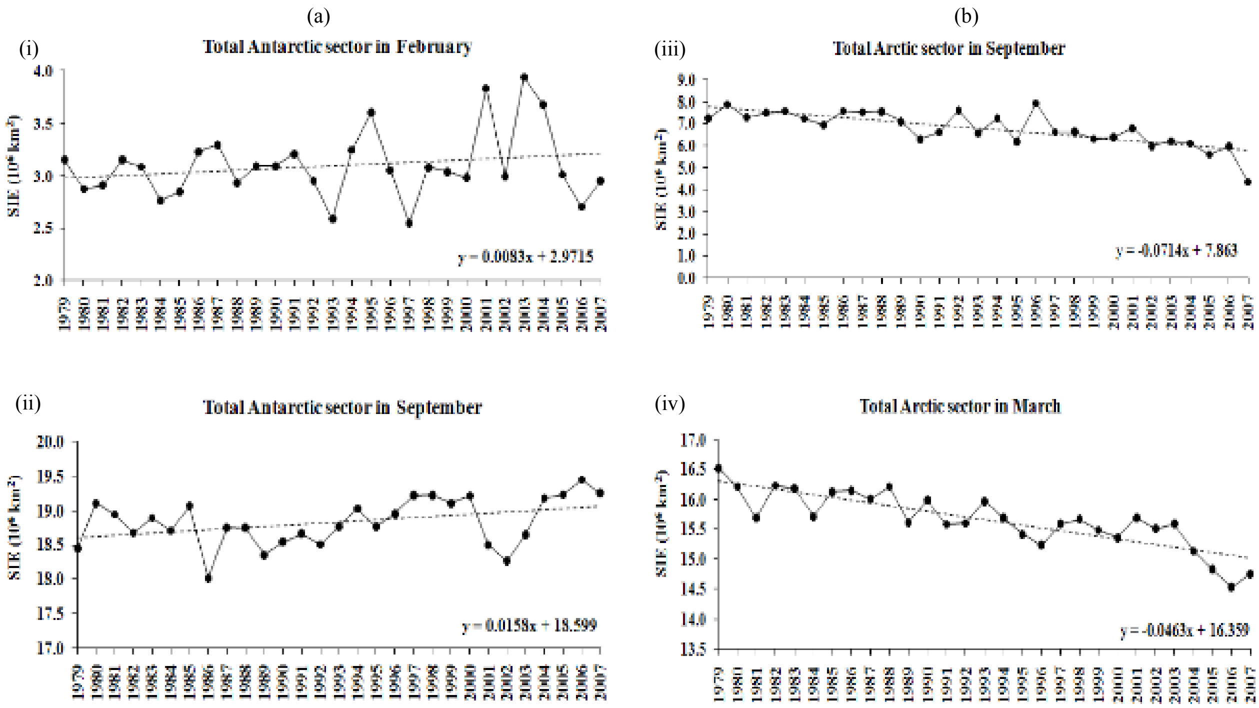


Figs. 3(a&b). The interannual variation of (a) Antarctic and (b) Arctic as a whole using SMMR-SSM/I data for the period January 1979 through December 2007. (i) and (ii) gives the interannual variation of yearly averaged SIE; (iii) and (iv) displays the monthly deviations; (v) and (vi) gives the monthly averaged SIE

shows a maximum in March (15.5×10^6 km^2/yr) and a minimum in September (6.8×10^6 km^2/yr) with maximum contribution coming from AO and KBS sectors [Figs. 2 (b&c)]. Although this behaviour of (hemisphere dependent) maxima and minima occur consistently for all the years and uniformly for all the sectors, the scale of variability in the ice coverage varies for each sector.

3.2. *Time series of the total Antarctic and Arctic region*

Some of the previous studies related to Antarctic trends reveal that SIE trend for SMMR period (1979-1987) shows an increasing ice boundary of 3000 km^2/year (Gloersen *et al*., 1992). A recent study of secular trends in the sea ice extent over the polar regions based on SMMR and SSM/I measurements extending up to the end of 1996 (US-GCRP, 2001), indicated an increasing trend of 1.3 ± 0.2% per decade for the Antarctic region. A significantly higher estimate of the trend (3.0 ± 0.3% per decade) for the period 1987-1997, based on independent analysis of SSM/I data, have also been derived in the recent past (Hanna and Bamber, 2001). These rates are distinctly higher than those found during the SMMR observation period. In the case of Arctic region, there are several earlier findings by Gloersen and Campbell (1991),



Figs 4(a&b). (a) Trends of total Antarctic (i) minima in February and (ii) maxima in September and (b) Trends of total Arctic (iii) minima in September and (iv) maxima in March

TABLE 3

Slopes of the yearly SIE trends for extrema using Linear Least Squares Fit for the period 1979-2007 along with its decadal analysis over the Polar region

Region	Minimum SIE					Maximum SIE				
	Month	10^3 km^2/yr	S	%/decade		Month	10^3 km^2/yr	S	%/decade	
				A	B				A	B
(a) Total Antarctic	Feb	8.3±7.3	-	-0.11	6.32	Sep	15.8±7.2	95	0.11	1.34
(b) Total Arctic	Sep	-71.4±11.5	99	-5.97	-13.42	Mar	-46.3±5.8	99	-2.49	-2.77

Johannessen *et al*., (1995), Bjorgo *et al*., (1997) indicating decrease in total Arctic SIE, though they were all on a shorter timescales and therefore the results could not be tested for its statistical significance.

From our study, using SMMR-SSM/I derived SIE for the period 1979-2007, we observe that the trend of yearly averaged total AnSIE is increasing at the rate of 12,500 ± 4,500 km^2/year and is significant at 99% level [Fig. 3 a(i), Table 1]. Strangely, out of all the five SH Polar sectors, only the BAS sector shows a prominent decreasing trend of -8,900 ± 2,800 (Table 1). Conversely, the total ArSIE trend is having a negative slope of -50,600 ± 4,800 km^2/year significant at 99% level [Fig. 3 b(ii), Table 2], which means that there is further accelerated decrease to an overall decreasing rate of -34,000 ± 8,300 km^2/year found by Parkinson *et al*., (1999) over the 18 year period from 1979-1996 of their study. The nature of trends obtained for both Antarctic and Arctic SIE as a whole seems to correspond well with the previous studies. The yearly trends for the other SH and NH polar sectors are shown in (Tables 1 and 2). The behaviour of the yearly trends for AnSIE and ArSIE is partly due to contribution from its local sectors specifically the RS in the Antarctic (Table 1) and the KBS in the Arctic (Table 2). Further, the trend lines of the monthly deviations of SIE for the aforementioned period for the Antarctic and Arctic as a whole give a positive trend of 1,043 ± 227 km^2/year [Fig. 3 a(iii)] and a negative trend of -4,230 ± 181 km^2/year [Fig. 3 b(iv)], both being significant at 99% level. The visual impact of the monthly averaged SIE for the 29 year period is quiet consistent for the total Antarctic sector [Fig. 3 a(v)] but slightly tilts downward for the Total Arctic sector [Fig. 3 b(vi)].

It is observed that the interannual variability of SIE, for certain sectors in both the Antarctic and Arctic regions, has a relationship with the All-India Summer Monsoon Rainfall (AISMR). These studies revealed that over the Antarctic region, the SIE of the WPO sector (Long. 90° E to 160° E) in the month of March (same year) (Prabhu *et al*., 2009) and the BAS sector's sea ice extent (Long. 90° W to 120° W) averaged over the months of October through December of the previous year (Prabhu *et al*., 2010) show strong positive and negative relationships respectively with the AISMR. Likewise, over the Arctic region, the KBS SIE (Long. 30° E to 90° E) during the month of October shows a significant positive relationship with the ensuing monsoon (Prabhu *et al*., 2011).

The decadal analysis have been carried out over the various sectors of the polar regions including the Antarctic and the Arctic as a whole by assigning Decades 1, 2 and 3 as 1979-1987, 1988-1997 and 1998-2007 respectively. Interestingly, we see that rate of increase in the total Antarctic SIE has slowed down over the last decade (1998-2007) as compared to the previous ones (Table 1), whereas in the case of total Arctic SIE, the rate of decrease has been intensified over the same time frame (Table 2). These results of rate of growth and decay over the last decade might be perturbing in the context of global warming.

3.3. *The analyses of extrema over the Polar regions*

In the analyses of extrema over the polar region during the SMMR-SSM/I period, we see for the total Antarctic sector that although the yearly increase in the maximum months of September at the rate of 15,800 ± 7200 km^2/yr is significant at 95% level, there is no marked increase seen during the minimum months of February, which means that the increase is not uniformly prominent during extrema [Table 3(a)]. However, in case of Arctic, we see a uniform decrease that is significant at 99% level for both the maxima and the minima, wherein the last decade from 1998-2007 has seen the total Arctic to be deceasing at an alarming rate of -13.42% per decade.

4. Summary and conclusion

The dominant characteristic of polar SIE as revealed from the SMMR-SSM/I sea ice data is the large scale regional variability. Another characteristic is the low interannual variability for each hemisphere as a whole, given the large regional variability of the amount of SIE from year to year. The polar sectors showing the largest interannual variability, for instance the sectors of BAS and KBS in the Antarctic and Arctic regions respectively, are the areas particularly vulnerable to large scale atmospheric or oceanic forcing. The SIE estimates during the period 1979-2007 bring out the nature of seasonal and secular variations in a very consistent manner. In case of all the sectors of Antarctic, the months of September and February give the maximum and minimum sea ice coverage respectively. Whilst in the Arctic, it is just the opposite. Within a year, the range of flux in SIE over the Antarctica as a whole swings almost twice in magnitude then that of its counterpart. In the SH, the first two contributors in its total ice coverage are the WS and the RS sectors while in the NH, the sectors of AO and KBS play a major role.

Finally, the results obtained using the SMMR and SSM/I observations on SIE can be synthesized into a scenario wherein the positive trend in the Antarctic is slowly decreasing though not significantly and the negative trend in the Arctic is notably accelerating in time, particularly in the last decade. This signal could be considered as an indicator of global warming caused due to increase in greenhouse gases.

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