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Hemispheric sea ice extent dynamics as observed from MSMR

NILAY SHARMA, M. K. DASH[†], P. C. PANDEY and N. K. VYAS*

Indian Institute of Technology, Kharagpur - 721 302, India

**Space Applications Centre, Ahmedabad - 380 015, India*

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[†]**e mail : mihir@coral.iitkgp.ernet.in; suryain_1999@yahoo.com**

सार – ध्रुवीय महासागरों के हिमाच्छादित क्षेत्र भूमंडलीय जलवायु को अनेक प्रकार से प्रभावित करते हैं। विकिरण प्रबलन के माडुलन, समुद्र तल में पानी बनने और वायुमंडल–क्रायोस्फेयर–महासागर प्रणाली के बीच द्रव्यमान और संवेग अंतरण की वजह से ध्रुवीय महासागरीय क्रायोस्फेयर में किसी भी प्रकार का विक्षोभ स्थानीय मौसम और भूमंडलीय जलवायु को प्रभावित करता है। ध्रुवीय क्षेत्र की शीत, कठिन और दुष्कर स्थितियाँ उस स्थान विशेष के स्थानिक और कालिक विभिन्नता के पर्याप्त गहन आँकड़ों के संग्रहण में रूकावट डालती हैं। तथापि ध्रुवीय क्षेत्रों जैसे क्षेत्रों का अध्ययन करने के लिए उपग्रह दूर संवेदन आदर्श तकनीक है जिससे उस क्षेत्र का सिनॉप्टिक अध्ययन किया जा सके और उस क्षेत्र के आँकड़े बार–बार लिए जा सकें। इस शोध पत्र में भारत के प्रथम महासागरीय उपग्रह ओशन सैट–1 के बहु–चैनल क्रमवीक्षण सूक्ष्म तरंग रेडियोमीटर (एम. एस. एम. आर) के उपयोग से जून 1999 – सितम्बर 2001 के दौरान ध्रुवीय महासागरीय क्षेत्रों से प्राप्त आँकड़ों के विश्लेषण का विवेचन किया गया है। एम. एस. एम. आर. प्रेक्षण से पता चला है कि एंटार्कटिक के सभी क्षेत्रों में समुद्र की बर्फ के पिघलने ओर जमने के लक्षण अलग –अलग है। हिन्द महासागर क्षेत्र में 1999 – 2000 में बर्फ के पिघलने के दौरान समुद्र की बर्फ के विस्तार में वृद्धि, वर्ष 2000 में बर्फ के जमने की अवधि में पश्चिमी प्रशान्त महासागर के क्षेत्र में समुद्र की बर्फ के विस्तार में 15–20 प्रतिशत तक की कमी, वर्ष 2000 में "बी" और "ए" सेक्टर में समुद्र में बर्फ के जमने की अवस्था के दौरान बर्फ के पिघलने जैसे कुछ विशेष लक्षण प्रेक्षित किए गए हैं। इसके विपरीत स्थलीय विशेषताओं की प्रधानता के कारण उत्तर ध्रुवीय महसागर में हिम का विस्तार रहा है। कारा और बेरंट सागरीय क्षेत्र में बर्फ के जमने का कारण महासागरीय तरंगों की प्रबलता है जबकि जापान में हिमावरण का कारण स्थलीय प्रक्रियाओं की प्रमुखता है। आर्कटिक महासागर में हिम का विस्तार जुलाई से अक्तूबर तक अस्थिर रहता है और अन्य महीनों मे लगभग स्थिर रहता है। भूमंडलीय हिमावरण के मार्च से जून तक जमने की अवस्था और नवंबर से फरवरी तक पिघलने की अवस्था होती है। अन्य महीनों, जैसे जुलाई से अक्तूबर तक के महीनों में भूमंडलीय महासागरीय हिम आवरण बर्फ के जमने और पिघलने के कारण गोलार्द्धीय विषमता रहती है।

ABSTRACT. The ice covered regions of the polar seas influence the global climate in several ways. Any perturbation in the polar oceanic cryosphere affects the local weather and the global climate through modulation of the radiative forcing, the bottom water formation and the mass & the momentum transfer between Atmosphere-Cryosphere-Ocean System. The cold, harsh and inhospitable conditions in the polar regions prohibit the collection of extensive *in situ* data with sufficient spatial and temporal variation. However, satellite remote sensing is an ideal technique for studying the areas like the polar regions with synoptic and repetitive coverage. This paper discusses the analysis of the data obtained over the polar oceanic regions during the period June 1999 – September 2001 through the use of Multi-channel Scanning Microwave Radiometer (MSMR), onboard India's first oceanographic satellite Oceansat-1. The MSMR observation shows that all the sectors in the Antarctic behave differently to the melting and formation of the sea ice. Certain peculiar features like the increase in sea ice extent during the melt season of 1999 – 2000 in the Indian Ocean sector, 15 – 20% decrease in the sea ice extent in the western Pacific sector during the ice formation period for the year 2000, melting spell within the formation phase of sea ice in B & A sector in the year 2000 were observed. On the other hand the northern polar sea ice extent is seen to be more dominated by the land characteristics. The ice formation in Kara and the Barent Sea sector is dominated by the ocean currents, where as the ice covered in the Japan and the Okhotsk Sea is dominated by the land processes. The sea ice extent in the Arctic Ocean show fluctuations from July to October and remain almost steady over other months. The global sea ice cover shows a formation phase from March to June and melting phase from November to February. In other months, *i.e.*, from July – October the global sea ice cover is dominated by the hemispheric asymmetry of the ice growth and retreat.

Key words – Sea ice, MSMR, Antarctic, Arctic.

1.   Introduction

The ice covered regions of the polar seas influence the global climate in several ways. The polar region acts as the heat sinks of the great global heat engine. The inter- and intra-annual variability of the polar ice cover greatly influences the heat, mass and momentum transfer between the atmosphere and the ocean, hence modifies both the oceanic and the atmospheric circulation in local as well as in the global scale. The heat flux from the open ocean to the atmosphere is nearly twice in magnitude to that of the area covered with ice (Badgley, 1966 and Maykut, 1978). In view of this, the distribution of open water and sea-ice is particularly important to regional heat balance. Also, the brine rejected during ice formation increases the density of water, thereby inducing convection that deepens the mixed layer and ultimately the formation of bottom water. This denser water then sinks to form the bottom water which very slowly moves equatorward as the bottom current and affects the global climate over very long time periods.

Very few long temporal *in situ* observations are available in the polar regions. The all weather day and night capability of the microwave observations from space have revolutionized the study of the polar sea ice. Since more than three decades, polar sea ice cover has been monitored through the Satellite Passive Microwave Observations (SPMO). The hemispheric asymmetry in the global sea ice trend is reported from the analysis of SPMO form 1978 – 1996 (Cavalieri *et al*., 1997). With more observational input from subsequent SPMO to the above data set Vinnikov *et al*., 2006 shown that sea ice extent in the northern hemisphere has a negative trend, with a mean rate of -0.32 million km^2 per decade and with mean deceleration -0.16 million $km^2/(10year)^2$. But, the southern hemisphere sea ice extent does not show any statistical significant trend. Decrease in sea ice thickness and extent in the northern hemisphere is also seen in model simulations (Vinnikov *et al*., 2006), whereas no significant trend is simulated by the models for the southern hemisphere (Vinnikov *et al*., 2006).

India has flown her first passive microwave radiometer, the Multifrequency Scanning Microwave Radiometer (MSMR) onboard the Indian Remote Sensing satellite, IRS - P4 (later renamed as Oceansat-1), on 26th May 1999 to collect data for oceanographic, coastal, atmospheric and cryospheric applications. The arrangement of MSMR payload in orbit is given in ISRO (1999). An extensive ground calibration experiment was conducted for MSMR prior to the launch of Oceansat-1 to

TABLE 1

Co-ordinates of the study area

Region	Latitude range		Longitude range	
Arctic	45° N	90° N	0° E	360° E
Antarctic	50° S	90° S	0° E	360° E

TABLE 2

Definition of different sectors in Southern Polar Ocean
(After Gloersen *et al*., 1992)

| No.	Sector	Longitude range	Remarks
1.	Weddell Sea sector	60° W to 20° E	Through 0° Meridian
2.	Indian Ocean sector	20° E to 90° E	
3.	Western Pacific sector	90° E to 160° E	
4.	Ross Sea sector	160° E to 130° W	Through 180° Meridian
5.	Bellingshausen and Amundsen Sea sector	130° W to 60° W	

evaluate the calibration coefficients. (Misra *et al*., 2002). The studies of Antarctic ice cover using these data sets have been carried out by Dash *et al.*, 2001, Vyas *et al.* 2003 and Bhandari *et al*., 2005. In present paper we have analyzed the observations form MSMR to study the global and hemispheric sea ice cover, its rate of advance and retreat in different sectors of the Antarctic and the Arctic for the MSMR period. Also, this paper describes the variation in global sea ice cover during the MSMR period.

2.   Study region, data and methodology

The area of our interest covers the entire southern ocean surrounding the Antarctica continent and Arctic region (Fig. 1). The geo-location of the study area is given in Table 1.

The MSMR brightness temperature images show a blind spot around the pole (not shown), which is not be visited by the satellite due to limitations arising out of its orbital inclination and sensor scanning geometry. The maximum coverage will be constrained by the maximum latitude reachable by the satellite along its orbital path.

For convenience, the whole Antarctic area is divided into five different sectors as per Gloresen *et al*., 1992 [Table 2, Fig. 1 (a)]. The Arctic region is divided into six different sectors [Table 3, Fig. 1 (b)].
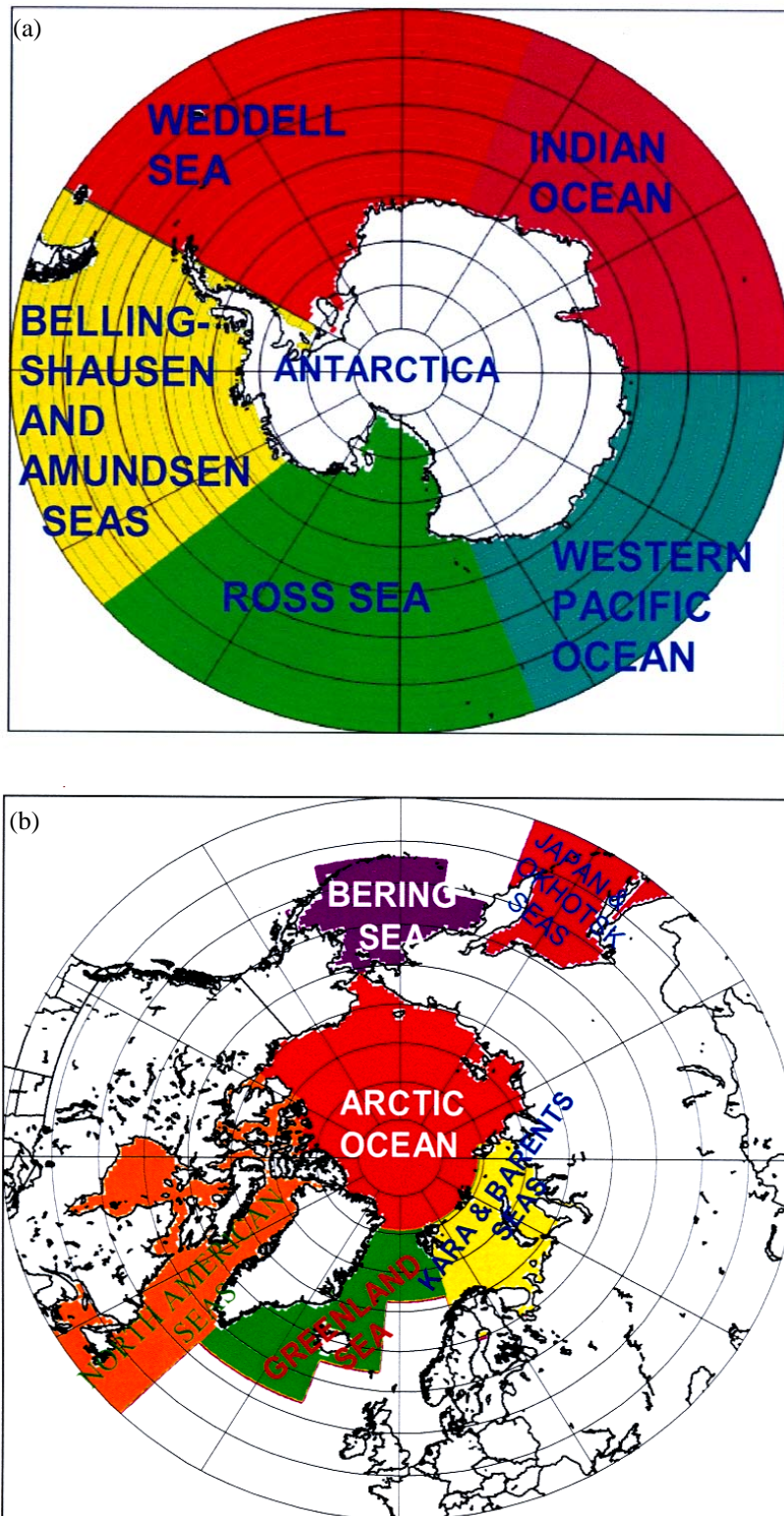
Figs. 1(a&b). View of different sectors (a) Southern Polar Ocean and (b) Northern Polar Ocean

TABLE 3

Definition of different sectors of the Northern Polar Ocean

S. No.	Name of the Sector	Latitude		Longitude	
		From	To	From	To
1.	Bering Sea sector	56.0° N	66.0° N	163.0° E	203.0° E
		52.0° N	56.0° N	172.0° E	195.0° E
2.	Seas of Japan and Okhotsk	45.0° N	63.0° N	140.0° E	160.0° E
		45.0° N	60.0° N	127. 0° E	140. 0° E
3.	Kara and Barents Seas	65.0° N	81.0° N	17.0° E	102.0° E
4.	Greenland Sea	57.0° N	62.5° N	315.0° E	340.0° E
		62.5° N	71.5° N	315.0° E	355.0° E
		71.5° N	81.0° N	315.0° E	17.0° E
5.	North American Sector				
5A		45.0° N	82.0° N	270.0° E	315.0° E
5B		55.0° N	78.5° N	247.0° E	270.0° E
5C		65.0° N	76.5° N	236.0° E	247.0° E
6.	Arctic Ocean				
6A		76.5° N	90.0° N	236.0° E	247.0° E
6B		78.5° N	90.0° N	247.0° E	270.0° E
6C		82.0° N	90.0° N	270.0° E	315.0° E
6D		81.0° N	90.0° N	315.0° E	16.0° E
6E		81.0° N	90.0° N	16.0° E	102.0° E
6F		70.0° N	90.0° N	102.0° E	163.0° E
6G		66.0° N	90.0° N	163.0° E	203.0° E
6H		68.0° N	90.0° N	203.0° E	236.0° E

The data from 18 GHz (H) channel of the MSMR payload onboard IRS -P4 have been used for this study. The 18 GHz (H) channel is chosen because of its higher spatial resolution of 50 km compared to 6 and 10 GHz channels, lesser influence of water vapor compared to 21 GHz channels and better distinction of sea ice features compared to 18 GHz (V) (Dash *et al.*, 2001).

Brightness Temperature (T_B) maps over polar regions were prepared from MSMR 18 GHz (H) observations for the period June 1999 - September 2001. These maps represent the average T_B for data collected between the 15th and the 22nd day (both days inclusive) of each calendar month. However, in the cases where problems of data non-availability existed, the dates have

been slightly adjusted to keep the observation period constant as 8 days for the averaging process.

The T_B observation from MSMR is available for the whole day combining all the 14.5 passes that occur on a given day. Each data point represents an average brightness temperature over an area of about 50 km × 50 km. However, this does not correspond to any standard geographic grid. The data for the study region is extracted and is gridded into a 0.5° × 0.5° latitude-longitude grid. Several data gaps are observed on displaying the smoothed gridded data through image display software GRADS. The data gaps are filled using a linear interpolation scheme in both the meridional and the zonal

directions. The data is also likely to have a certain amount of noise. To reduce the noise, averaging of the brightness temperatures for each grid cell is carried out over 4 repeat cycles of two days each. The data are then mapped on to the polar stereographic projection. This data is then displayed in the image form using GRADS Software. Ice and water regions are examined and transects (straight lines across the water - ice boundary) are selected and graphs of T_B are plotted along this line. The boundary between ice and water is derived through inspection of steep slope regions on the graphs. This boundary (for 18 GHz horizontal polarization) is then used later on for distinguishing between ice and water. The optimal boundary between sea ice and open water is found to be at $T_B = 130$ K & 150 K for Antarctic and Arctic respectively using this procedure. The classification procedure used between the sea ice and the open water involved the supervised technique where previously known areas of open water and sea ice were taken and separate clusters of brightness temperatures were formed. The analysis was extended to include different seasons of the year. As soon as a grid cell is identified as sea-ice, its area is computed and added to the calculation of total area. A detailed discussion of the comparison of near simultaneous MSMR observation with that of SSM/I at the brightness temperature level is described by Bhandari *et al.*, 2005.

3.   Results and discussions

The physiographical difference between the two polar regions is also very important hence the ice formation, retreat, minimum and the maximum ice cover in both the polar regions. Antarctic is a continent which is surrounded by southern ocean which is well connected with the Indian, Pacific and Atlantic oceans. On the other hand, the Arctic is a predominantly oceanic region surrounded by land with very few passages connecting it with world's other oceans. Arctic ocean has one third area with depth below 100 m and its mean depth is 1800 m (Cavalieri *et al.*, 1997) and on the other hand, southern ocean's depth lies in the range between 4000-6000 m. Here we have first described the results of the Sea Ice Extent (SIE) in the northern polar regions, then the southern polar region and then the global SIE. The section is followed by conclusions.

3.1. *Northern polar regions*

Bering sea

Bering sea is surrounded by the Bering Strait on the north, by the Aleutian islands on the south, by the Siberian coast on the west and by the Alaskan coast on the east. The westward flow of Alaska current carries relatively

warm Pacific water to the Bering Sea and limits the sea ice growth. Monthly variation in sea ice extent during MSMR period shows that during northern summer the sea remain ice free [Fig. 2(a)]. Maximum horizontal expansion ice occurs during the peak winter period. From the MSMR analysis it is found that during the year 1999 maximum rate of areal expansion (20 % of the sea area) of sea ice occurred during November – December months of the year. Similar result is also seen during 2000 – 2001, *i.e.*, maximum ice spatial expansion occurred in the months of December – January (17% of the sea area) [Fig. 3(a)]. Ocean currents moving in the North West – South East direction across the sea help in limiting the further growth of ice in winter time. For both the years it is found that maximum sea ice retreat occurred during the months of April- May [Figs. 2(a) and 3(a)].

Sea of Japan and Okhotsk

The Sea of Japan & Okhotsk (SJO) is bounded by the land masses from the three sides and other side is opened to the Pacific Ocean. The formation season lasts from middle of the November to middle of the March. The sea remains almost free from ice from July to October [Fig. 2(a)]. SJO has the peak of the ice extent in March. From MSMR observations it is found that rate of maximum ice advancement occurred during the January – February [Fig. 3(a)]. But during the year 1999 – 2000 maximum ice formation (31.5% of the sea area) occurred during January – February 2000, but in the year 2000 – 2001 rate of southward advancement of ice is distributed almost uniformly over the whole winter period [Fig. 3(a)]. The rate of advancement and retreat in SIE are slightly higher than Bering Sea but characteristics are same in this sector [Fig. 3(a)].

Kara and Barent Seas

The Kara & Barents seas (KBS) are located in the north of Scandinavia and western Russia and are separated by the island of Novaya Zemlya, which acts as a barrier between the cold Arctic waters in the Kara Sea and the warmer waters from Norwegian current in Barents Sea. As a result Kara Sea contains high concentration sea ice cover for most part of the year whereas the Barents Sea remains mostly ice free except for the pick winter months. The MSMR observations of the sea ice in this sector of the arctic shows that in this sector sea ice remains through out the year [Fig. 2(a)]. And the sea ice advancement lasts from September – January [Fig. 3(b)]. But maximum acceleration in SIE occurs during November – December, which is the peak winter time [Fig. 3(b)]. MSMR observation shows the presence of sea ice in this sector during peak summer months [Fig. 2(a)], which is due to
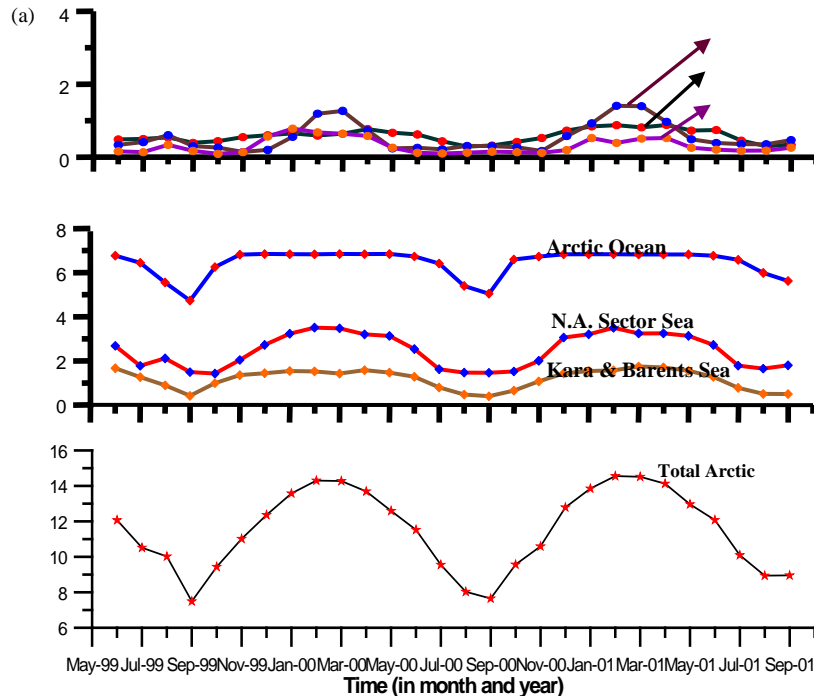
(a)

May-99 Jul-99 Sep-99 Nov-99 Jan-00 Mar-00 May-00 Jul-00 Sep-00 Nov-00 Jan-01 Mar-01 May-01 Jul-01 Sep-01
Time (in month and year)

Fig. 2(a). Monthly variation in sea ice extent (in million km^2) in different sectors of the Northern Polar region as observed from MSMR
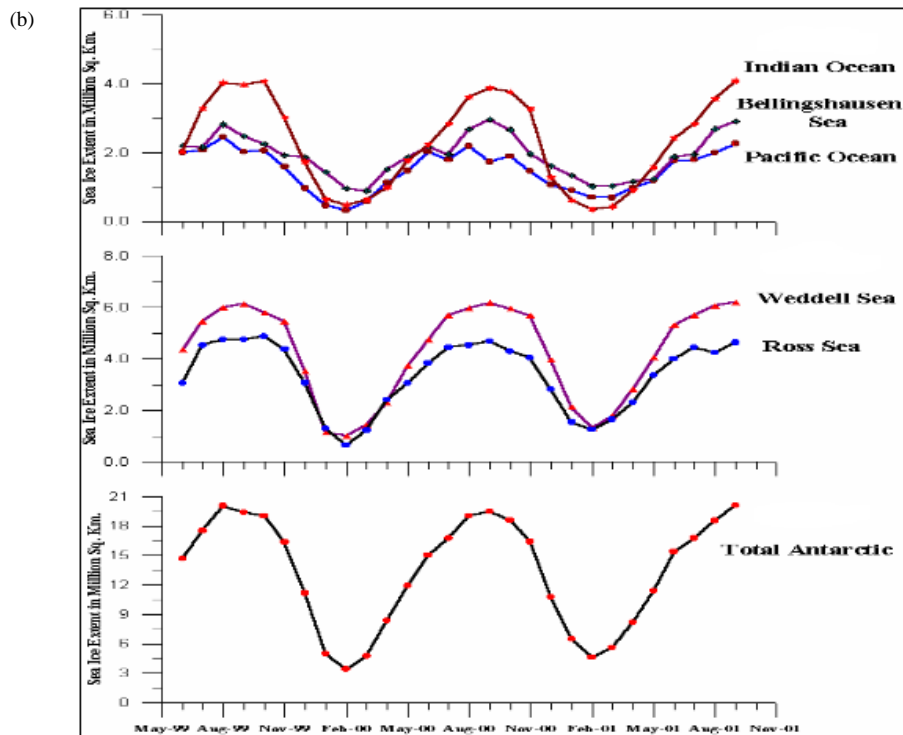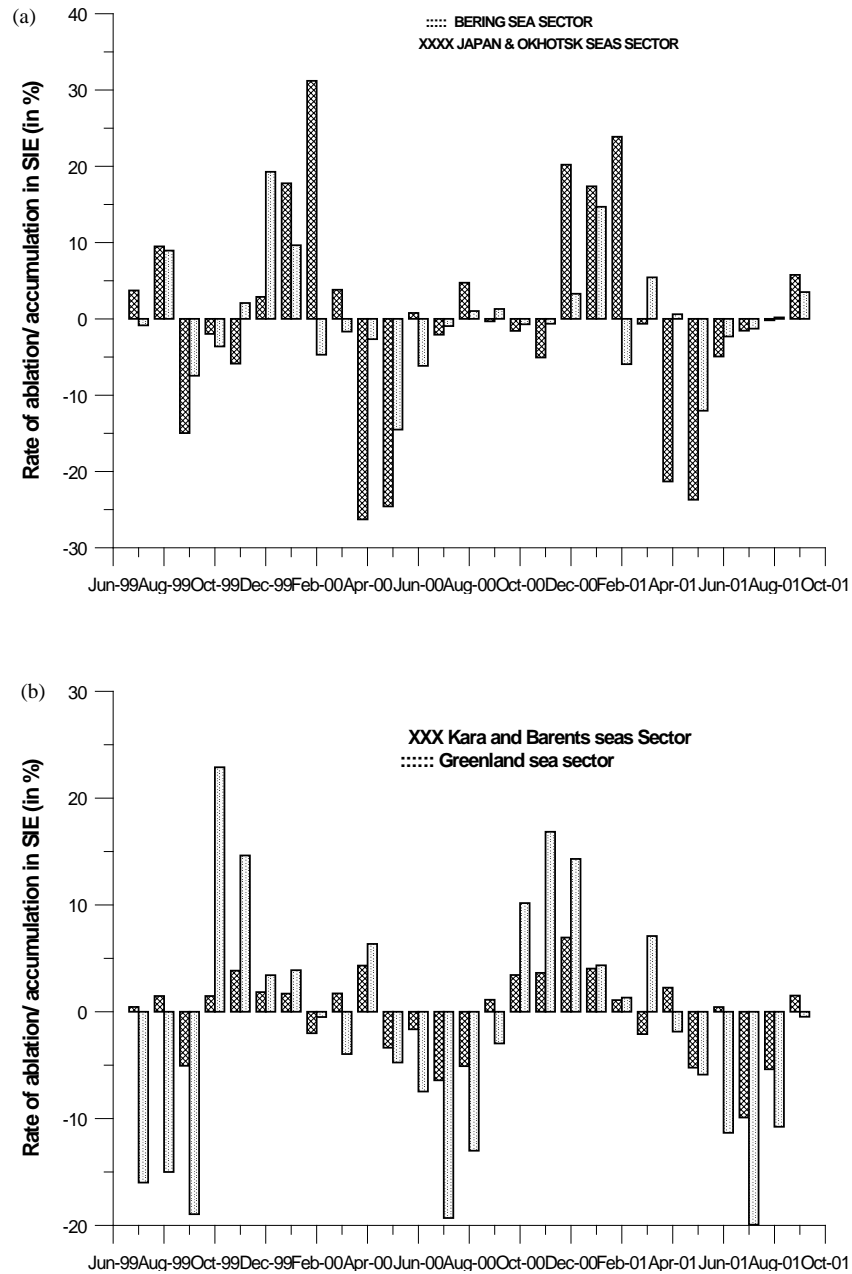
(b)

Fig. 2(b). Monthly variation in sea ice extent (in million km^2) in different sectors of the Southern Polar region as observed from MSMR

Figs 3(a&b). Advancement and retreat rate in the sea ice extent (in %) in different sectors of the Northern Polar region for the MSMR period (a) for Bering Sea sector and Japan & Okhotsk Sea sector (b) Kara & Barents sea sector and Greenland Sea sector

the intrusion of cold Arctic water in the Kara Sea. It shows minimum ice coverage in September which lies in its northernmost portion. During the northern autumn the ice edge moves southwards and by December, covers almost entire sea. By observing combined KBS, the total SIE shows an average seasonal cover expanding from a

minimum of 0.7×10^6 km^2 in September to a maximum of 1.9×10^6 km^2 in March [Fig. 2(a)]. The spatial variation in Barents Sea closely follows the variation in temperature from summer to winter. Variation in Kara Sea is observed less due to very little variation in sea surface temperature. It happens due to advection of heat from Kara to adjacent
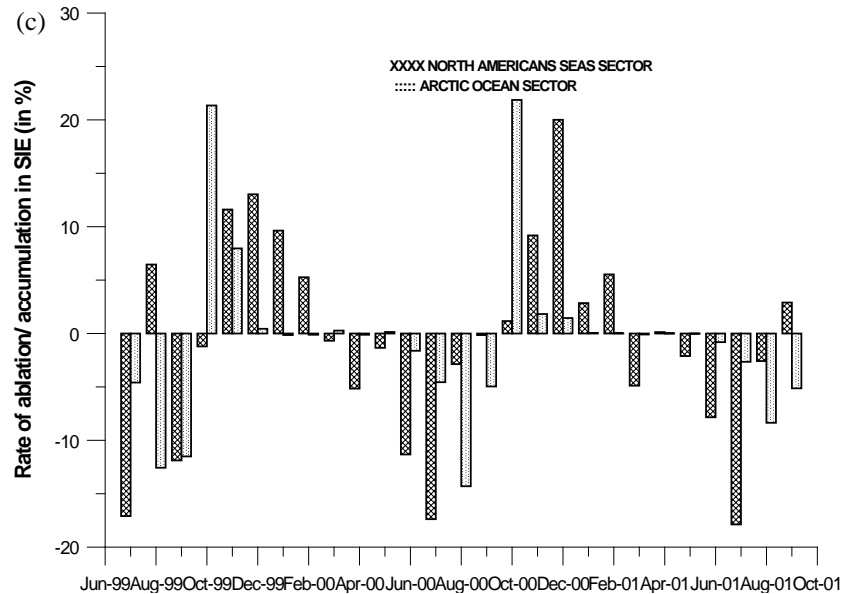
Fig. 3 (c).   Advancement and retreat rate in the sea ice extent (in %) in different sectors of the
Northern Polar region for the MSMR period for North American seas sector and
Arctic Ocean Sector

Arctic Ocean (Comiso 2000). Rate of spatial expansion of sea ice more than 50% from September to November then gradually decrease from January to August in this sector.

Greenland sea sector

Greenland Sea (GS) lies between the Arctic ocean and the Atlantic ocean and allows free movement of water between the two oceans. It is a very important area for the formation of the bottom water and acts as a ventilator of the world ocean circulation. GS ice extent shows very less seasonal variation [Fig. 2(a)]. Some pockets of the GS show presence of the sea ice through out the MSMR observation period suggesting that these regions contain multi year ice (not shown in the figure). Maximum rate of advancement occurs in the month of October – November. But the rate of areal expansion varies from year to year [Fig. 3(b)]. It is found from MSMR observation that during September-October 1999 southward advancement rate of sea ice is very high and almost covers 23% of the whole area. But in year 2000 it is found that advancement rate is distributed more or less uniformly between September to December [Fig. 3(b)]. The retreat in sea ice cover starts during February – March and attains the maximum during the June – July. But during year 1999 it

is found that retreat rate is more or less uniformly distributed June – September [Fig. 3(b)].

North-American seas sector

The North American sector includes two large regions. The first one includes Baffin Bay, Davis Strait and Labrodor Sea areas and the second one includes ocean north of Alaska and Canada surrounding the Canadian Archipelago. It also includes the Hudson Bay and the Gulf of Lawrence. Hudson Bay is almost ice covered for six month of the year from December to May. Ice starts melting during June-July-August. But during July-August 1999 MSMR observation shows advancement of sea ice in this sector which followed by retreat in subsequent months [Fig. 3(c)]. Ice formation in this sector mostly follows the temperature pattern of the surrounding continent. The advancement period starts in the month of November and extends upto February [Fig 3(c)]. During year 2000 -2001 maximum sea ice advancement occurred during December, whereas the rate of increase in SIE is distributed between November-December-January months. The retreat rate is very fast in this region and maximum melting of sea ice (16.5 % of the sea area) occurs during the June – July [Fig. 3(c)]. SIE is minimum during September [Fig 2(a)], which is just opposite to the Antarctic. The MSMR observation shows

that the year 1999 is an unusual year. The retreat is very fast the advancement is also very rapid [Fig. 3(c)].

Arctic ocean sector

The analysis of seasonal ice cover in the Arctic region shows, the ice coverage is lesser in September/ October than in June and large in February than in December. The central and western part of Arctic ocean is seen to be covered with ice throughout the year. In Arctic, during the MSMR observation period, the sea ice coverage is seen to have a minimum extent of 7 million km^2 in September and a maximum extent of nearly 14-15 million km^2 in March [Fig. 2(a)]. This compares reasonably well with the typical long-term average values reported in the literature (Hanna and Bamber, 2001).

Arctic Ocean remains fully covered by sea ice from November to May each year. The rate of advancement of sea ice is maximum during September – October [Fig. 3(c)]. Central Arctic Ocean always remains covered with sea ice. From November to March, the sea ice occupies almost entire Arctic Ocean. Maximum ice extent is observed in the month of March. During this time the average ice concentration is around 79%. The decrease in SIE starts in April and goes up to September [(Fig. 2(a)]. MSMR observation of sea ice for the three summers of 1999, 2000 and 2001 shows good agreement with that of SMMR and SSM/I.

3.2. *Southern Polar ocean*

The SIE in the southern polar ocean varies by 10 folds between its maximum and minimum values [Fig. 2(b)]. Intra-annual variation of the SIE in different sectors of the Southern Polar ocean; the Weddell Sea, the Ross Sea, the Indian Ocean, the Pacific Ocean, the Bellingshausen & Amundsen Seas sectors and the southern polar ocean as a whole is shown in Fig. 2(b). It can be noted that the seasonal trend derived from MSMR is in good agreement with those derived earlier from SMMR (Vyas *et al.*, 2003 and Bhandari *et al.*, 2005). We divided the southern polar ocean into five different sectors and studied the ice retreat and formation in each sectors separately and the southern polar ocean as a whole.

Weddell Sea sector

The Weddell Sea sector is identified as one of the major source of Antarctic bottom water. The bottom water formation process is greatly influenced by the large variability of the ice production in the region (Gordon, 1978). This sector is a very dynamic among all the five sectors of the Antarctic. The western part of the Weddell Sea remains ice covered during the entire year and most of the ice here is multi-year ice. The eastern Weddell Sea undergoes strong seasonal variability and is known to support formation of large Polynyas. During the two year of MSMR observation it is found that the formation season last for almost seven months from March to September [Fig. 4(a)]. The maximum rate of ice formation occurs during April – May (25% of the area) and the maximum ice extent occurred during September [Fig. 4(a) and Fig. 2(b)]. The melt season from the October and lasts till February. Almost 40% of the total area melted during mid January and mid February. It is the maximum melt rate observed during the MSMR period. The minimum ice cover around 1 million km^2 is observed during February [Fig. 2(b)]. It is found that there is a 2 – 3 months lag remain in the peak winter/summer and the maximum/minimum ice cover.

Ross Sea sector

It is another important sector in the Antarctic. The seasonal cycle of sea ice extent in Ross sea sector is different from that of other sectors. In this sector the lateral growth of sea ice occurs rapidly for four to five months (March – July) followed by a slow expansion until September. MSMR observation shows that the month of maximum ice formation varies from year to year [Fig. 4(a)]. The ice formation and decay almost follow similar pattern as that of Weddell Sea sector. The decay rate of sea ice is maximum during December - January. In the MSMR period maximum melting of 45% is observed during January 2000. During January and February, the western portion of Ross Sea and the Ross Ice Shelf edge becomes ice free. From MSMR observations it is found that the rate of decay is faster than formation rate in this sector. The minimum ice extent occurred during February [Fig. 2(b)]. This sector also shows 2-3 months lag in the maximum/minimum ice extent and peak winter/summer.

Indian Ocean, Western Pacific and Belligshausen & Amundsen Seas sectors

The definition of the Indian Ocean sector is given in the methodology section. The sea ice cover in Indian ocean sectors is less than the Weddell Sea and the Ross Sea sectors [Fig. 2 (b)]. The Indian Ocean region shows a relatively moderate rate of long term increase of sea ice extent although the annual average sea ice extent there is relatively low (Vyas *et al.*, 2001). It is the second warmest part of the SPO and has negligible ice cover throughout year. The MSMR observation shows that in this sector the sea ice formation starts in the months of March and lasts till September. May to June are the months when rapid sea ice formation occurs (35 % of the area observed by MSMR during 1999 June – July) [Fig. 4(a)]. The melt season lasts from September
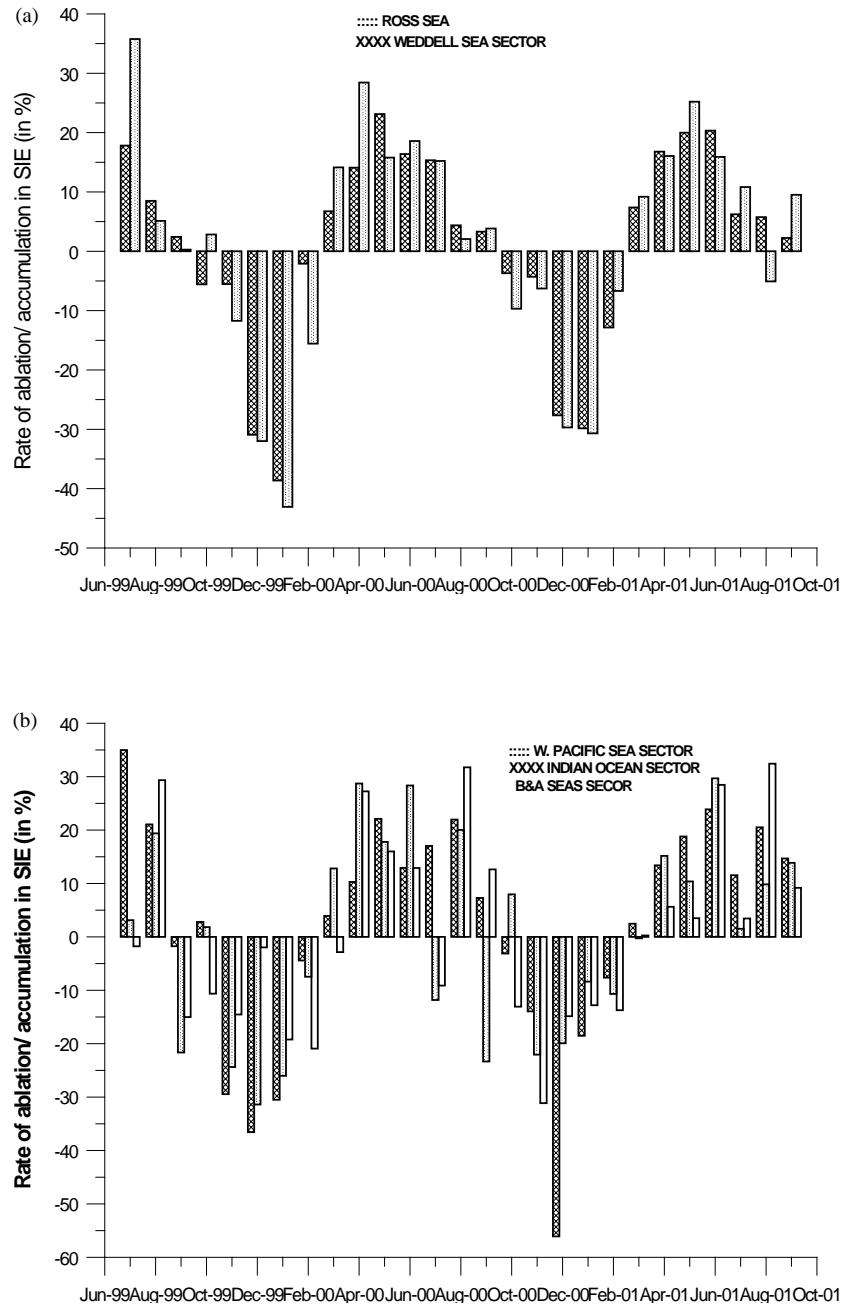
Figs. 4(a&b). Advancement and retreat rate in the sea ice extent (in %) in different sectors of the Southern Polar region for the MSMR period (a) Weddell Sea sector and Ross Sea Sector (b) Western Pacific Sector, Indian Ocean Sector and Bellingshausen and Amundsen Seas sector.

February. During MSMR period it is found that the minimum sea ice extent occurs during February [Fig. 2(b)]. A very peculiar signature, increase in ice extent is noticed during 1999 – 2000 melt seasons. This may be due to the advection of sea ice from the Weddell Sea to the Indian Ocean region during that period.

Western Pacific ocean is farthest from the south pole. Pacific Ocean sector is the warmest among all the sectors of the southern polar ocean. The sea ice extent is very less throughout the year in this sector. During the summer time the sea ice margin recedes towards the coast and most part of the coastline remains ice-free. The
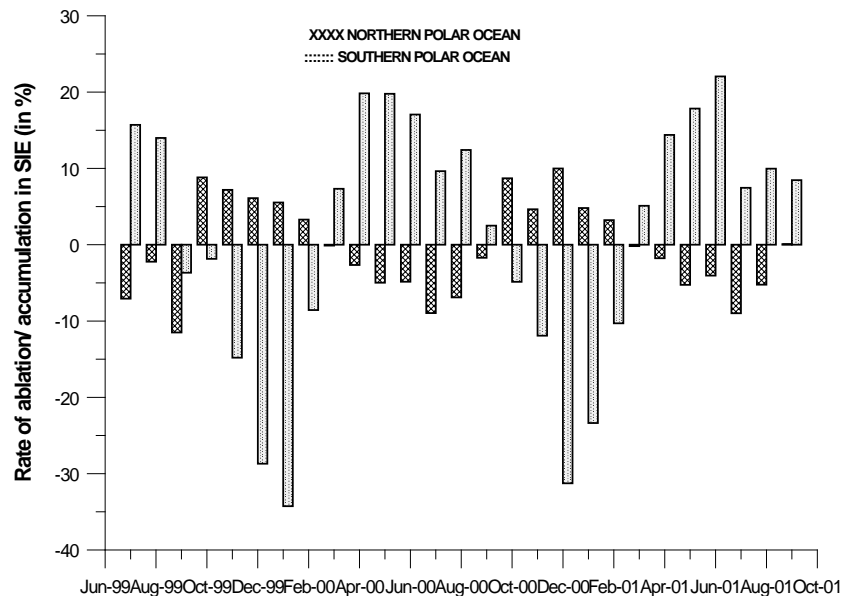
Fig. 5. Hemispheric advancement and retreat rate in the sea ice extent (in %) in for the MSMR period, Northern Polar region and the Southern Polar region are shown separately

maximum sea ice extent occurs in the month of August [Fig 2(b)]. During the MSMR period it is observed that in this sector the melting season lasts from mid August to February [Fig. 4(b)]. A very peculiar signature is noticed during 1999 – 2000 melt season like the Indian Ocean. It is found that in between the melt season sea ice formation occurred during September – October, 1999. The formation period extends from March to October. This sector shows again a very peculiar signature during the year 2000. The MSMR observation shows a high melting rate of the order of 15 – 25% has occurred during melt season of year 2000 [Fig. 4(b)]. This may be due to the some external forcing. The sea ice formation and melting signatures match almost of that of the Indian ocean sector.

The atmospheric circulation in the Bellingshausen and Amundsen Seas (B&A seas sector) sector with that of Weddell Sea sector forms the Antarctic dipole (Lieu *et. al.*, 2004 and Turner 2004). The MSMR observation of the B & A sea sector shows that and it has the largest ice cover during the month of August – September and the minimum ice cover during the month of February [Fig. 2(b)]. This matched well with that from SMMR and SSMI. The melting season starts in the month of

September and last up to March. Maximum retreat in SIE occurs in the month of October – November [Fig. 4(b)]. The expansion in ice extent lasts from April to September. Maximum area expansion ice occurs during the month of July and August. During MSMR observation period, a melting spell is noticed within the formation phase of sea ice in this sector [Fig. 4(b)].

3.3. *Global Sea ice extent*

The seasonal cycle of sea ice cover in Southern ocean is characterized by minimum ice cover in the month of February. The MSMR records sea ice extent of the order of 2 - 3 million km^2 during February [Fig. 2(b)] (Vyas *et al.* 2003). The retreat ice extent in the SPO spreads over the months November to February (Fig. 5). The maximum retreat occurs during the month of January – February. It is followed by expansion of the ice cover in successive months until the maximum ice coverage is reached during August to October. The most rapid expansion of the ice cover occurs during the period July – August and then asymptotically reaches the maximum during September/October in the SPO. The MSMR observed maximum sea ice cover over the SPO about 21 million km^2 (Vyas *et al.,* 2003). As may be thought off the sea ice situation in the Northern Polar Ocean (NPO) is not

(a)

(b)
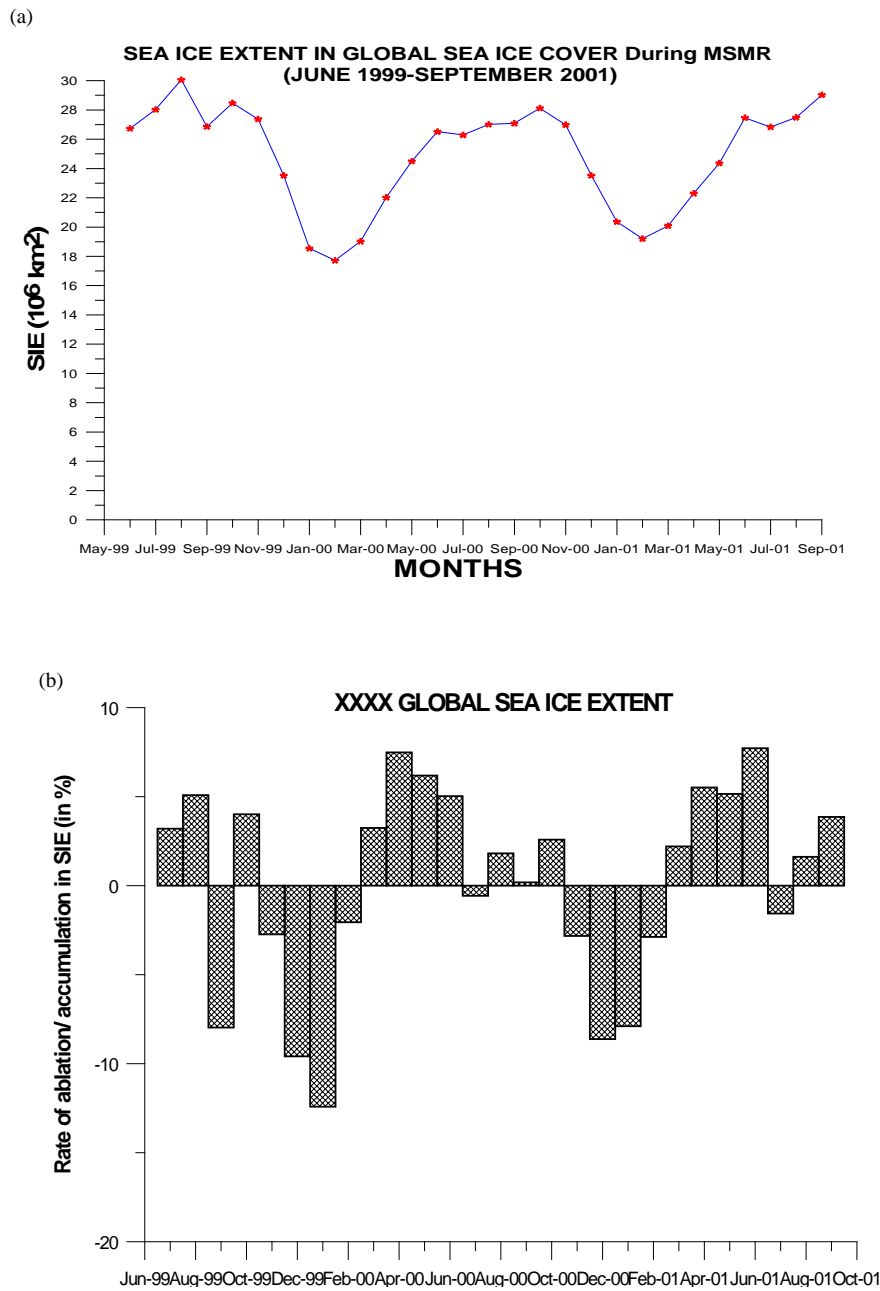
Figs. 6(a&b).   (a) Monthly variation in global sea ice extent (in million km²) as observed from MSMR
and (b) Advancement and retreat rate in the global sea ice extent (in %) for the MSMR
period

totally opposite to that of the SPO. The months having high melting rate in the SPO is not the month of high ice formation in the NPO. The situation varies from year to year. As observed by MSMR the maximum sea ice

formation in the NPO occurred during September – October in the year 1999 and it shifts to November – December in the year 2000 (Fig. 5). Whereas the sea ice retreat rate is spread over September to January. The

Global ice cover shows a formation phase from March to June and melting phase from November to February [Figs. 6 (a&b)]. The global ice cover in months from July – October is dominated by the hemispheric asymmetry of the ice growth and retreat.

4.   Conclusions

The geographical positions of two polar regions are very important hence the ice formation, retreat, minimum and the maximum ice extent in both the polar regions. It is found that all the sectors of the NPO behave more or less similarly to each other, whereas the sectors of the SPO behave differently. During February to March growth of ice extent occurs in all the sectors of the SPO except the B & A seas sector in the Antarctic. The initial sea ice growth phase after the melt season is high during February to March in the Ross Sea and Weddell Sea sectors than the other sectors of SPO. Very interesting features, slower ice growth in July compared to other ice formation months, is marked in the Pacific ocean and the Bellingshausen and Amundsen seas sectors during MSMR period. The cause of this is not known yet; it may be due to the influence of atmospheric circulation on the sea ice extent. A very peculiar signature, the growth in SIE in the Indian Ocean Sector is observed during the 1999 – 2000 melt season. The MSMR observation shows SIE retreat rate of the order of 15 – 25% in the Western Pacific sector during ice formation season in the year 2000. Also, During MSMR observation period, a melting spell is noticed within the formation phase of sea ice in B & A sector in the year 2000.

It is also apparent that the build up and decay of sea ice cover lags in time with respect to the months of peak winter and summer. In SPO the ice coverage is larger in September / October than in June, and less in February than in December. Most of the area of the southern ocean northward of 55° S is seen to be free of ice throughout the year. In SPO, during the MSMR observation period, the sea ice coverage is seen to have a minimum extent of 3.42 million km^2 in February and a maximum extent of nearly 21 million km^2 in September.

On the other hand the North Polar sea ice extent is seen to be more dominated by the land characteristics in the Arctic. The peculiar signatures which are seen in the SPO is not seen in the NPO during the MSMR observation period. Although the MSMR observation covers a period of only 28 months (from June 1999 – September 2001), bring out the nature of seasonal and secular variations in a very consistent manner. During the MSMR period it is found that the global sea ice extent varies from 7.35 million km^2 to 15 million km^2. More

studies are required to understand the nature of ice formation and retreat of sea ice in both the polar regions.

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