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Antarctic sea ice variability in recent years and its relationship with Indian Ocean Sea Surface Temperature

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ABSTRACT
Antarctic sea ice edge variability is analyzed for 23 years (1982-2004) data of satellite passive microwave observation. Sea ice edge anomaly averaged around Antarctica shows nearly zero trend in the time domain. The positive trend of Ross, Weddell seas and Indian Ocean is reduced and the sea ice accumulation in Pacific Ocean region is increased but the sea ice variability in Bellingshausen/Amundsen seas is unaffected in recent years. Maximum Antarctic Sea ice concentration trend of 0.01 degrees/year is found during summer season for the period 1982-1998 but the same season shows a negative trend for the period 1982-2004. On the regional scale the trend differs from season to season. Ross and Weddell seas show positive trend whereas Bellingshausen/Amundsen sea shows negative trend for all the seasons. The relationship of Antarctic sea ice variability with Indian Ocean SST is studied and found that the most persistent positive relation exists for the southeast Indian Ocean region, off Australia.

INTRODUCTION

Antarctic sea ice, through their vast cover and source of deep water formation/ventilation have the potential to influence global climate over a range of time scales (Fletcher 1969, Walsh 1983). The fact that sea ice covers about 7% of the earth's surface at any time and varies seasonally in extent, emphasizes the importance of monitoring and understanding the variability of the sea ice extent. Antarctic sea ice is an important feature of the global climate system because it exists as a thin layer at the air-ocean interface and affects heat, mass, and momentum fluxes between the ocean and atmosphere.

Variability of the Antarctic sea ice has been investigated by a number of researchers. It has been shown in most of the studies that the increasing trend for the Antarctic sea ice concentration is about 0.01 degrees/year (Yuan & Martinson 2000; Zwally et al., 2002; Kwok & Comiso 2002). The variability study has also been done for regional and seasonal time scales using data-set up to 1998 (Zwally et al., 2002). However, there is a need to study the trends of sea ice concentration in Antarctic region from time to time because the polar regions being an important component of the earth's climate system may exert strong control on global climate changes e.g. a result of the accumulation of greenhouse gases in the atmosphere.

Linear covariance between Antarctic sea ice field variability and other climate indices such as tropical Pacific El Nino – Southern Oscillation (ENSO) has been reported in many observational studies (Simmonds & Jacka 1995; White & Peterson 1996; Yuan, Cane & Martinson 1996). These relationships occur in the key areas such as Ross, Bellingshausen, Weddell seas and some parts of Southern Indian Ocean (SIO). The statistical significance of the earlier studies can not be considered good since the length of the data set for the sea ice concentration under investigation was limited. Due to significant efforts in the accumulation of sea ice data in recent years the study for possible teleconnection of sea ice with the climate indices such as ENSO becomes statistically significant (Yuan & Martinson 2000; Martinson & Iannuzzi 2003).

Much work have also been done for the extra polar to tropical connection for the Pacific and Atlantic Oceans due to large variability of sea ice concentration in the Bellingshausen and Ross seas of South Pacific and Weddell Sea of South Atlantic. Yuan & Martinson (2000,2001) discovered the Antarctic Dipole (ADP) which is a quasi stationary wave in sea ice, Sea Surface Temperature (SST) and Surface Air Temperature (SAT) and linked to the ENSO variability. The proposed mechanism of ENSO and ADP teleconnection that linked the tropics with polar seas with both the South Pacific and South Atlantic have rapidly advanced our understanding of the ENSO teleconnection in the Southern Ocean (Yuan 2004).

In addition to the ENSO teleconnection with Antarctic sea ice there are other climate parameters linked with sea ice concentration variability. Yuan and Martinson 2000 found that the sea ice is linked with preferred climate indices such as tropical Indian Ocean SST, the tropical Pacific precipitation. The length of the data set used in above study was 1979 to 1996 and the geographical region for tropical Indian Ocean SST index was between 2.5°N to 12.5°S and 62.5°E to 82.5°E.

It is supposed that the SST Anomaly (SSTA) over Indian Ocean plays a major role in determining the monsoon rainfall variability. A General Circulation Model (GCM) study shows that the annual cycle of SST in the Indian Ocean is important in establishing the monsoon circulation and rainfall (Shukla & Fennessy 1994). Strong positive correlation occurs between the All India Rainfall Index (AIRI) and tropical SSTA in the preceding December-February (Clark, Cole & Webster 2000) season. Thus the Indian Ocean SST variability is important for the improved prediction of monsoon rainfall. The variability of sea ice concentration and connection with tropical Indian Ocean SST has been studied by Yuan & Martinson (2000) but with the scanty data set till December 1996. So there is a need to check the consistency of this relationship using the data set of longer temporal coverage.

In this paper we attempt to document the variability of Antarctic sea ice concentration. This variability study has been done for different geographical locations and their seasonal variation. We have also tried to establish linear relationships between the sea ice variability and extrapolar climate variables specially the Indian Ocean SST. Identification of geographic location in Indian Ocean that has persistence relationship with Antarctic sea ice variability was also attempted.

Sea Ice and Climate Data

Satellite measurements of polar sea ice enables us for the variability study from seasonal to interannual time scales. In the present study we have used sea ice concentration data for 23 years (January 1982 to December 2004) downloaded from http://www.cdc.noaa.gov/. The data set for the period January 1982 through November 1999 is available through United Kingdom (UK) Meteorological Office and is based on datasets of Spatial Sensor Microwave Imagers (SSM/I) and its subjective analysis by the US National Ice Center. From Dec 1999 onwards, NCEP ice analysis fields based on SSM/I data has been used. These data sets are provided on monthly time scale and spatial resolution of 1^ox1^o.

Sea Ice Edge (SIE) is defined as equator-most position of the 30% isopleth of ice concentration in each degree of longitude. The SIE monthly anomaly (SIE′) is calculated by removing monthly climatology defined at each grid point, which will eventually remove any seasonal cycle present.

To investigate the possible teleconnection between Antarctic sea ice and global climate the NOAA's optimal interpolated version 2 SST (OISST) monthly fields for 23 years period (1982-2004) has been used which are derived by a linear interpolation of the weekly optimum interpolation version 2 fields to daily fields and then averaging the daily values over a period of month (http://www.cdc.noaa.gov/; Reynolds et al., 2002). Monthly anomaly series is calculated by subtracting monthly mean climatology from the data, which effectively removes the seasonal and monthly cycles present.

To study the regional variability the seas around Antarctic are divided in five regional sectors as defined by Zwally et al., (1982) and Gloerson et.al. (1992). These five sectors are Indian Ocean (20°E-90°E), Pacific Ocean (90°E – 160°E), Ross sea (160°E-140°W), Bellingshausen/Amundsen seas (140°W-60°W) and Weddell sea (60°W-20°E). The SIE′ time series for the months of January-March (JFM), April-June (AMJ), July-September (JAS) and October-December (OND) were averaged to obtain the time series for four seasons as summer (JFM), autumn (AMJ), winter (JAS) and spring (OND).

RESULTS AND DISCUSSION

A linear regression is applied to the SIE′ as function of longitude for two temporal domains (1982-1998, 1982-2004) as shown in figs 1(a-f). The division facilitates in capturing the sea ice concentration in recent years and for the comparing the trends with that of previous studies. For the Period 1982-1998, a net increase in trend for SIE′ is found of 0.01 ± 0.004 degrees/year, which is in agreement with the other studies (Cavalieri et al., 1997; Yuan & Martinson, 2000 and Zwally et al., 2002). SIE′ on regional scale displays maximum increasing trend of 0.1 ± 0.016 degree/year and maximum negative trend of –0.04 ± 0.009 degrees/year for Ross and Bellingshausen-Amundsun seas respectively (Table 1). Weddell sea and Pacific Ocean shows equatorward expansion of sea ice whereas for Indian Ocean slightly negative trend of SIE′ is found (Table 1). These trends are in agreement with earlier studies (Zwally et al., 2002).

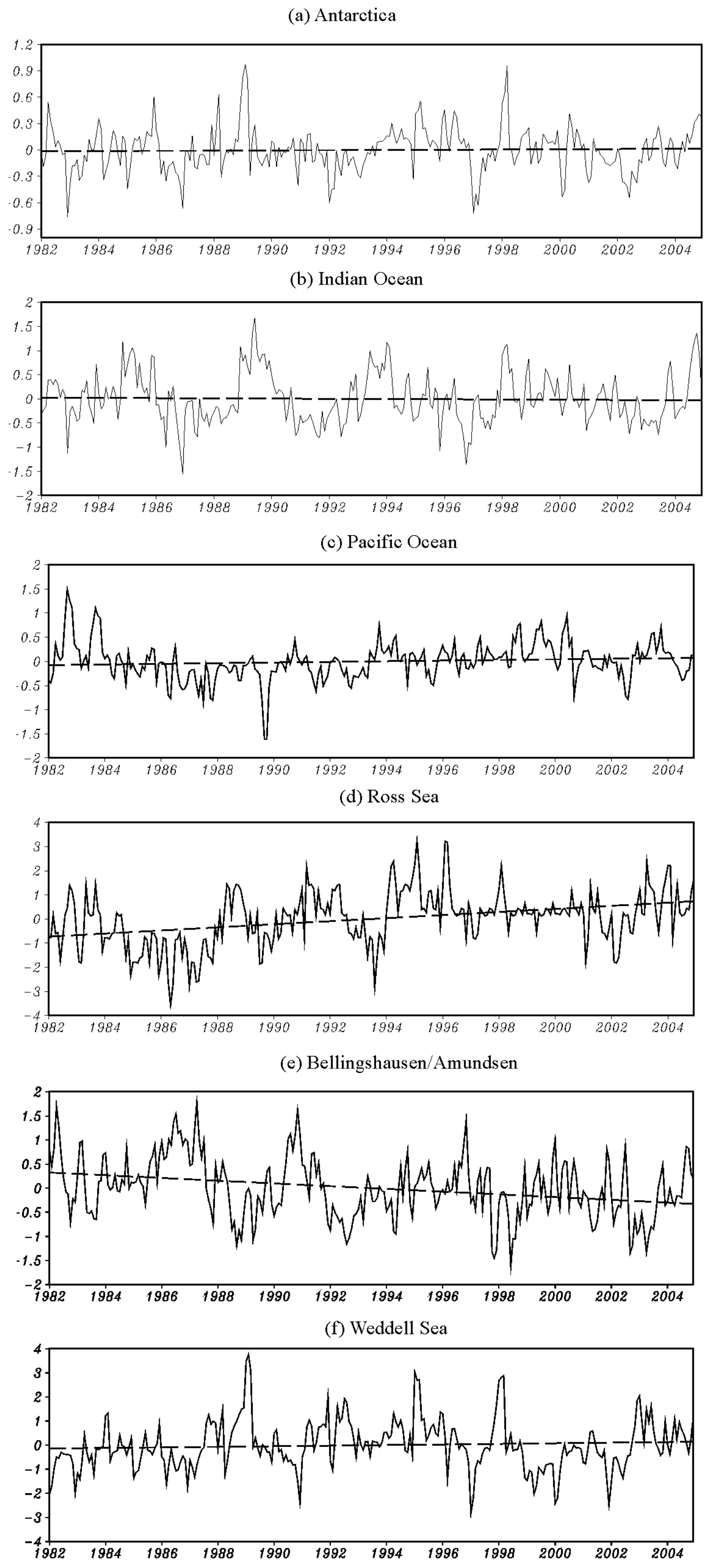

Figure 1. The 23 year (1982-2004) trend in sea ice edge anomaly (degrees/ year) averaged over **(a)** Antarctica **(b)** Indian Ocean (20°E-90°E) **(c)** Pacific Ocean (90°E – 160°E) **(d)** Ross sea (160°E-140°W) **(e)** Bellingshausen/Amundsen sea (140°W-60°W) and **(f)** Weddell sea (60°W-20°E) regions.

Table 1: Regional sea ice edge anomaly trend

Region	Linear trend for the time domain 1982-1998 (degrees/year)	Linear trend for the time domain 1982-2004 (degrees/year)
Antarctic	0.010 ± 0.004	0.001 ± 0.002
Indian Ocean	0.005 ± 0.008	-0.002 ± 0.005
Pacific Ocean	0.002 ± 0.005	0.006 ± 0.003
Ross sea	0.100 ± 0.016	0.064 ± 0.009
Belligshaushan/ Amundsen sea	-0.040 ± 0.009	-0.03 ± 0.005
Weddell sea	0.060 ± 0.014	0.01 ± 0.009

The analysis has been extended for 23 years period (1982-2004) to capture the recent trends of Antarctic sea ice edge variability. The positive trend of sea ice concentration is reduced by ten times and nearly zero positive trend is found (0.001 ± 0.002 degrees/year) for the Southern Ocean (Fig.1a and Table 1). Indian Ocean, which had slightly positive trend for the period 1982-1998 is evidenced by a small negative trend (-0.002 ± 0.005) (Fig.1b and Table 1). The positive trend of Ross sea and Weddell seas is reduced as compared to the results of previous time domain (Fig.1d, 1e and Table 1) whereas the trend of Pacific Ocean is slightly increased (Fig.1c). The negative trend of Bellingshausen-Amundsen seas is nearly uneffected in recent years (Fig. 1f).

Another aspect of the results is the seasonality being positive but nearly zero for autumn, winter and

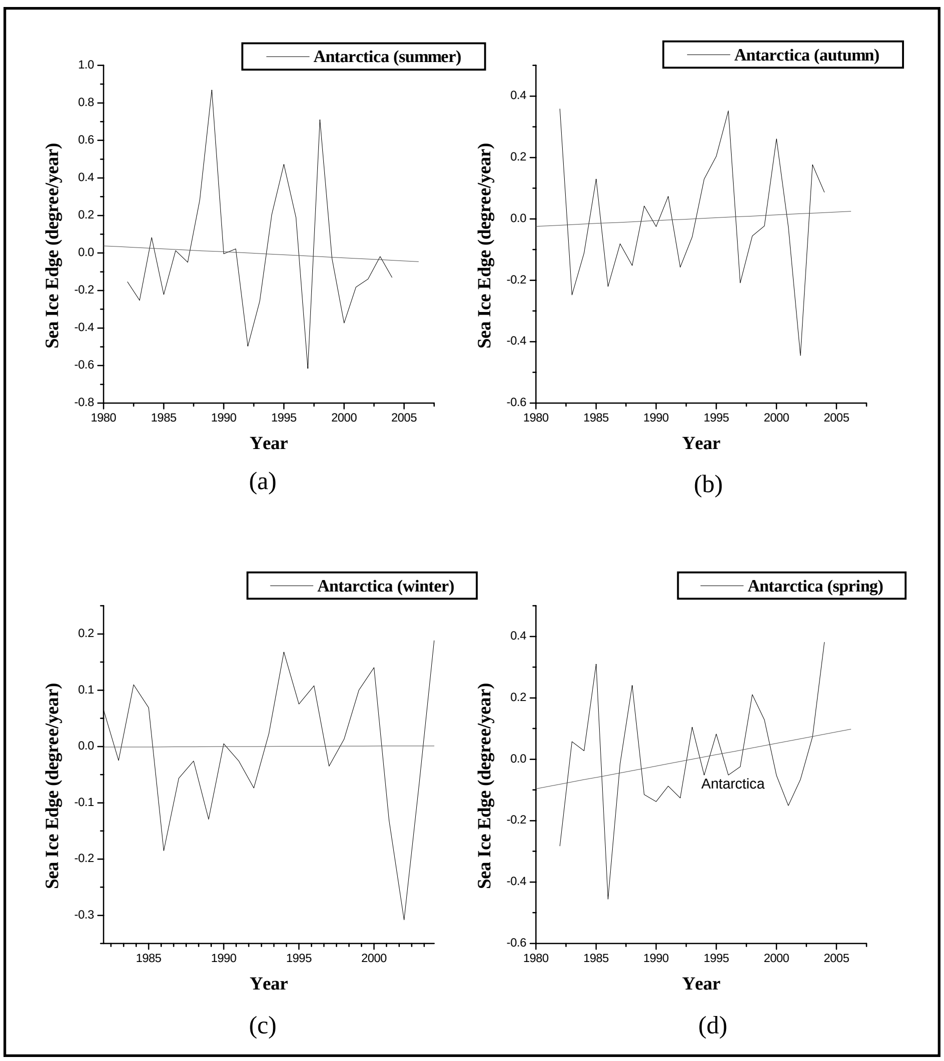

Figure 2. Antarctic sea ice edge anomaly trend for the seasons **(a)** Summer (JFM), **(b)** Autumn (AMJ), **(c)** Winter (JAS) and **(d)** Spring (OND).

spring seasons and negligible negative trend for summer season (figs 2a,b,c and d). On the regional basis trend changes from season to season. Although the trends are positive for Ross and Weddell seas whereas Bellingshausen-Amundsen seas shows negative trends for all the seasons (figs 6 and 7 and Table 2), yet the positive trend of Weddell sea is considerable for summer (0.016 ± 0.047 degrees/year) and autumn (0.02 ± 0.023 degrees/year) but insignificant for winter and spring seasons (figs 7a,b,c and d and table 2). Positive trend of about 0.1 ± 0.03 degrees/year is found to be maximum in Ross sea for summer and autumn (figs 5a and 5b and Table 2) and negative trend of –0.06 ± 0.03 degrees/year is found in Bellingshausen-Amundsen for summer, autumn and spring seasons figs 6a, 6b and 6d and Table 2). Equatorward expansion of sea ice in Indian ocean is seen for spring (0.012 ± 0.017 degrees/year) and retreat of sea ice (-0.01 degrees/year) for summer and autumn seasons (figs3a, 3b and 3d). Similarily, Pacific ocean also shows equatorward expansion of sea ice for all the seasons exept in winter (-0.01 ± 0.013 degrees/year) with maximum positive trend of 0.02 ± 0.008 degrees/year for fall (Fig 4). Recent trends are quite different from that of earlier studies for regional as well as seasonal time scales (Zwally et al., 2002).

Table 2. Seasonal sea ice edge anomaly trend on the regional basis

Region	Season	Linear trend for the time domain1982-1998 (degrees/year)	Linear trend for the time domain1982-2004the (degrees/year)
Antarctica	Summer (JFM)	0.01 ± 0.019	-0.003 ± 0.011
	Autumn (AMJ)	0.004 ± 0.009	0.002 ± 0.006
	Winter (JAS)	0.003 ± 0.004	0.0
	Spring (OND)	0.007 ± 0.009	0.007 ± 0.006
Indian Ocean	Summer (JFM)	0.02 ± 0.024	-0.01 ± 0.014
	Autumn (AMJ)	-0.003 ± 0.024	-0.01 ± 0.014
	Winter (JAS)	-0.03 ± 0.020	0.0
	Spring (OND)	-0.01 ± 0.029	0.012 ± 0.017
Pacific Ocean	Summer (JFM)	0.013 ± 0.007	0.01 ± 0.004
	Autumn (AMJ)	0.02 ± 0.011	0.02 ± 0.008
	Winter (JAS)	-0.02 ± 0.022	-0.01 ± 0.013
	Spring (OND)	-0.007 ± 0.023	0.007 ± 0.013
Ross Sea	Summer (JFM)	0.2 ± 0.048	0.10 ± 0.036
	Autumn (AMJ)	0.1 ± 0.056	0.10 ± 0.032
	Winter (JAS)	0.05 ± 0.042	0.03 ± 0.023
	Spring (OND)	0.07 ± 0.045	0.06 ± 0.026
Bellingshausan / Amundsen	Summer (JFM)	-0.06 ± 0.057	-0.06 ± 0.031
	Autumn (AMJ)	-0.04 ± 0.047	-0.06 ± 0.027
	Winter (JAS)	0.07 ± 0.096	-0.04 ± 0.059
	Spring (OND)	-0.02 ± 0.053	-0.06 ± 0.031
Weddell Sea	Summer (JFM)	0.11 ± 0.074	0.016 ± 0.047
	Autumn (AMJ)	0.05 ± 0.026	0.02 ± 0.023
	Winter (JAS)	0.04 ± 0.031	0.0
	Spring (OND)	0.03 ± 0.041	0.007 ± 0.026

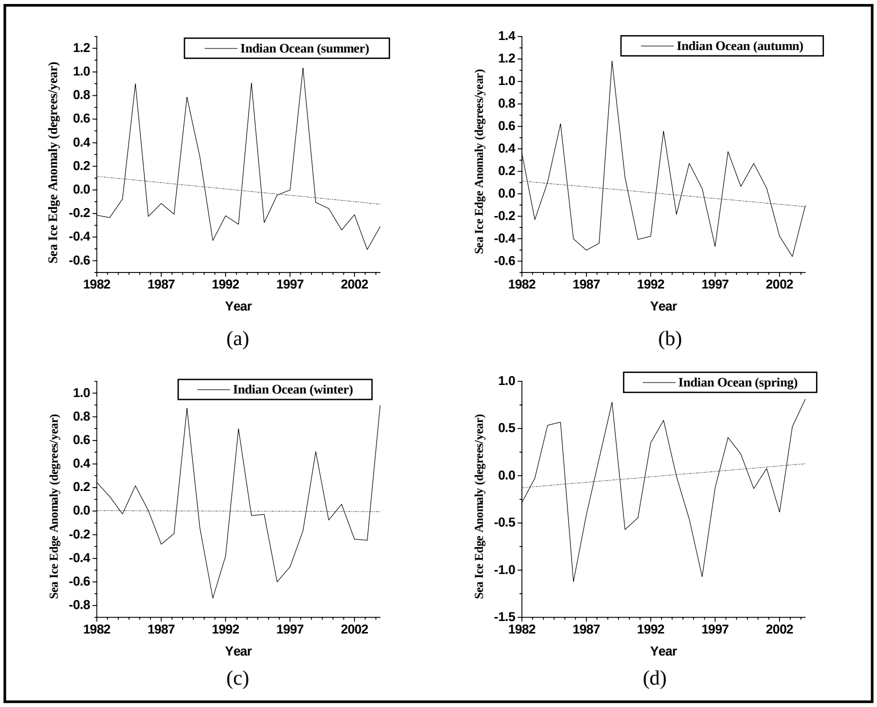

Figure 3. Sea ice edge anomaly trend in Indian Ocean 20°E-90°E) for the seasons **(a)** Summer (JFM), **(b)** Autumn (AMJ), **(c)** Winter (JAS) and **(d)** Spring (OND).

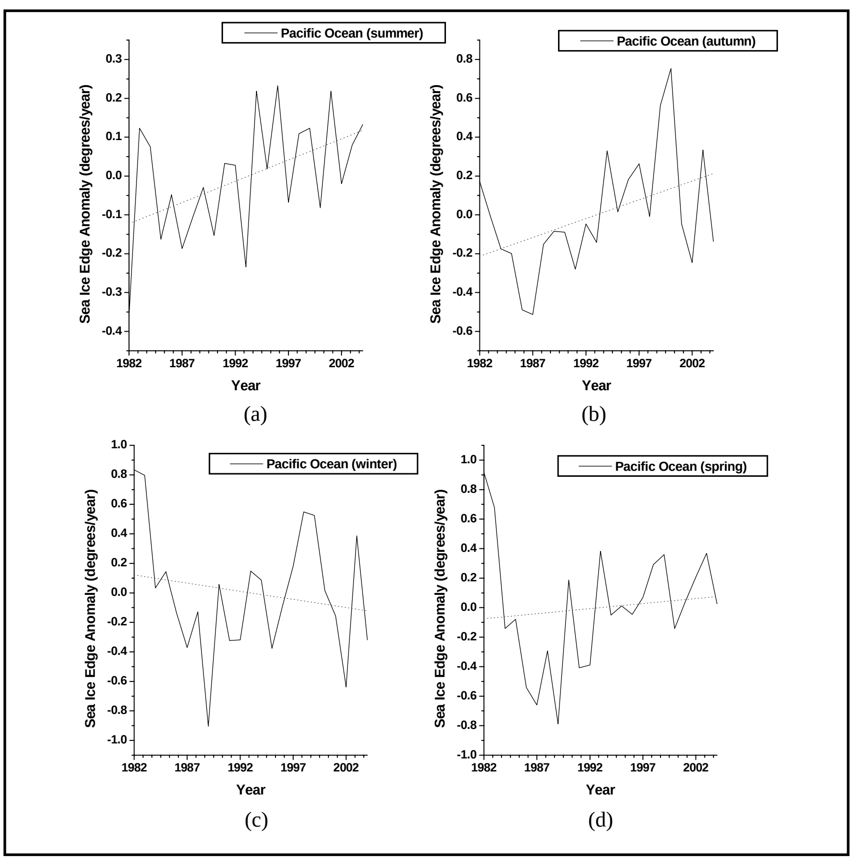

Figure 4. Sea ice edge anomaly trend in Pacific Ocean (90°E – 160°E) for the seasons **(a)** Summer (JFM), **(b)** Autumn (AMJ), **(c)** Winter (JAS) and **(d)** Spring (OND).

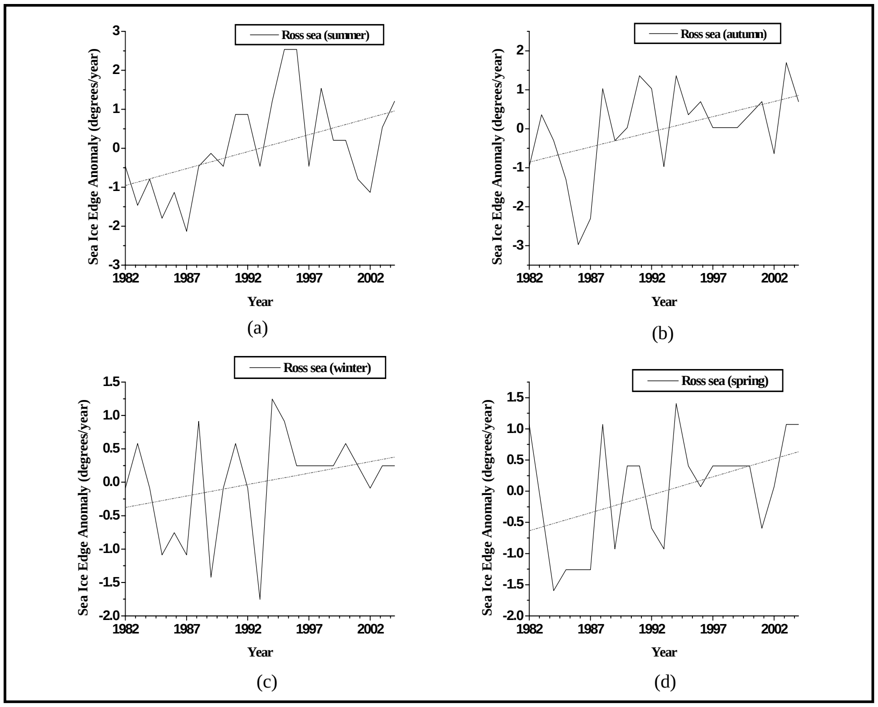

Figure 5. Sea ice edge anomaly trend in Ross sea (160°E-140°W) for the seasons **(a)** Summer (JFM), **(b)** Autumn (AMJ), **(c)** Winter (JAS) and **(d)** Spring (OND).

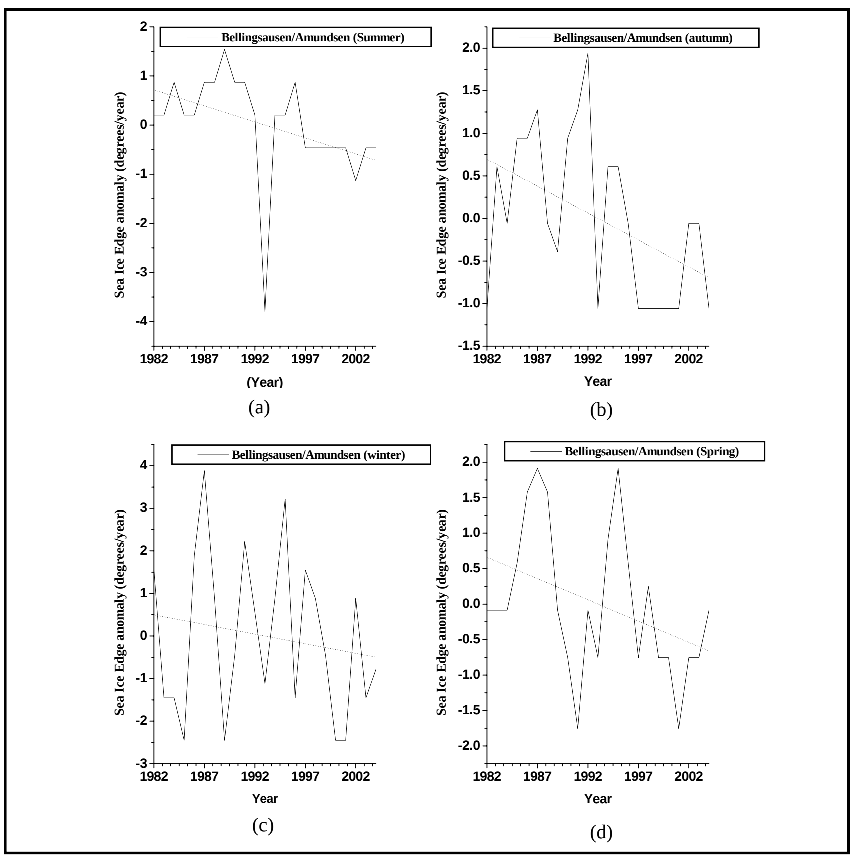

Figure 6. Sea ice edge anomaly trend in Bellingshausen/Amundsen sea (140°W-60°W) for the seasons **(a)** Summer (JFM), **(b)** Autumn (AMJ), **(c)** Winter (JAS) and **(d)** Spring (OND).

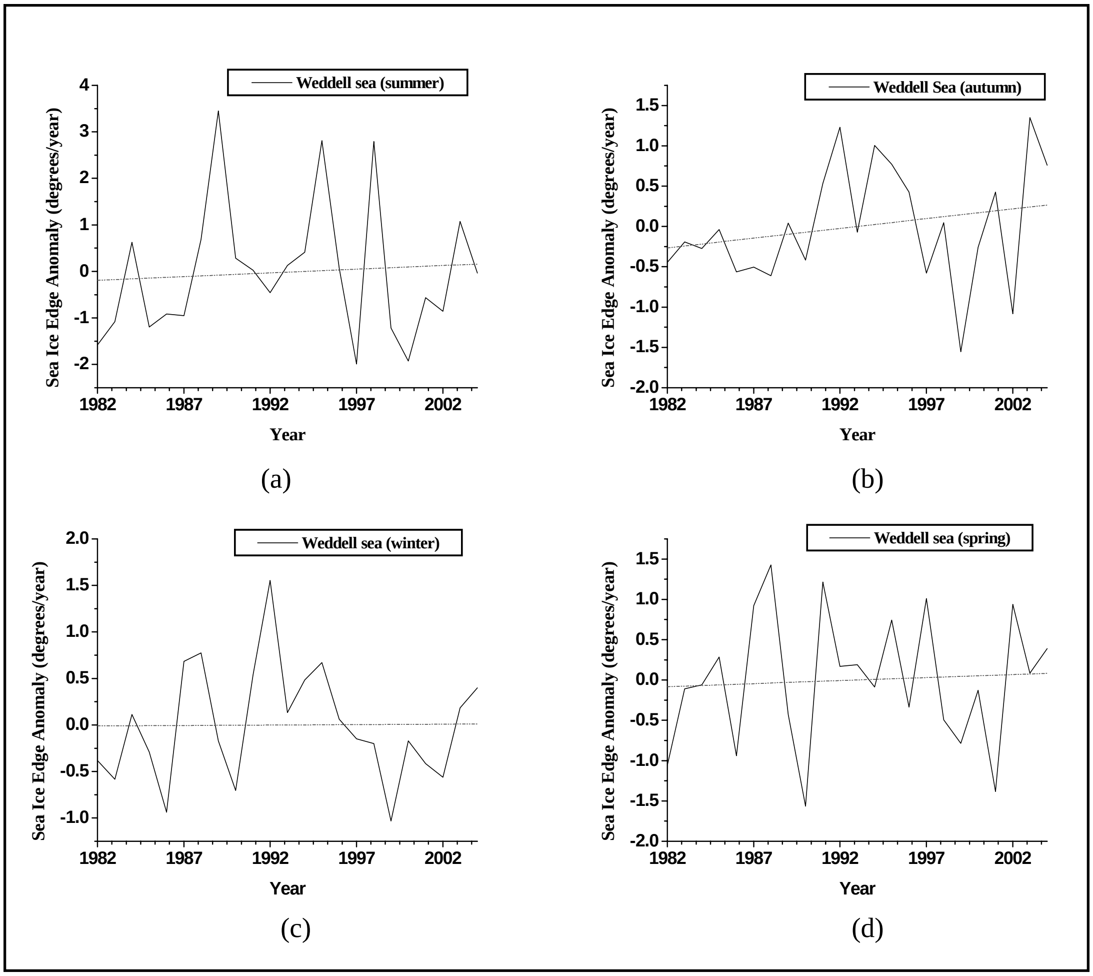

Figure 7. Sea ice edge anomaly trend in Weddell sea (140°W-60°W) for the seasons **(a)** Summer (JFM), **(b)** Autumn (AMJ), **(c)** Winter (JAS) and **(d)** Spring (OND).

To explore the sea ice variation and its possible connection with the tropical climate indices, the Indian Ocean SST indices for various geographical locations is chosen. The correlation between SIE′ and tropical Indian Ocean SST index is found to be 0.39 in the present domain when time domain is taken as 1982-2004 as against the findings of Yuan and Martinson, 2000 that shows 0.61 for the time domain 1979-1996 (Fig 8). The result may not have been to utter surprise had the change been small. The significant change is not only due to the change in time domain but to the choice of the region 2.5°N to 12.5°S and 62.5°E to 82.5°E for which consistancy in relationship with sea ice edge variability is questionable. To check the consistancy of the relatioship with Indian Ocean SST and sea ice variation we then calculated the correlation of SIE′ at each grid point of Indian Ocean SST with lead-lag time scale of 3 years and found that the region showing most consistent relationship is southeast Indian Ocean, off Australia. The southeast Indian Ocean SST index (SEIOI) was evaluated by averaging the SST Anomaly for the region 72°E to 122°E and 4°S to 26°S in view of its strong influnce on the transition of the whole monsoon-ENSO system (Terray, Dominiak and Delecluse, 2005). A significant positive correlation (above 95% significant level) is found between SEIOI and variability of sea ice in the Ross and Bellingshausan/Amundsen seas which reaches to 0.45 with ice leading months of 6 (Fig 9). Keeping the spatial domain same the study was also repeated for the time domain 1982-1996 giving rise to same result.

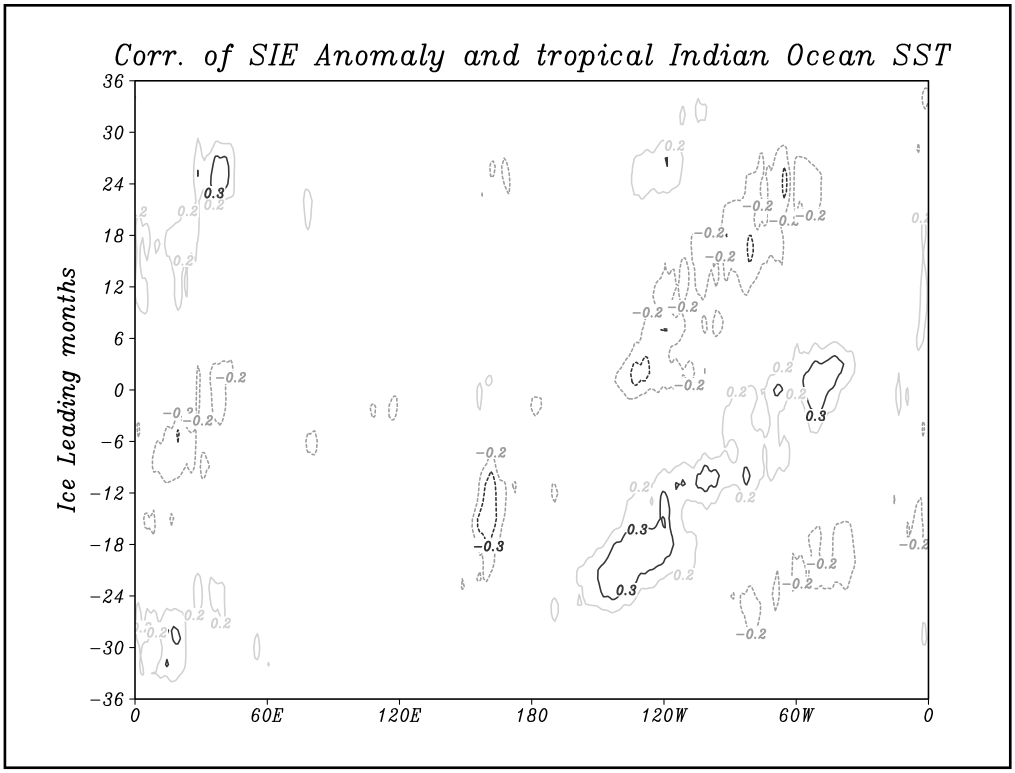

Figure 8. Spatial correlation between sea ice edge anomaly and tropical Indian Ocean (2.5°N-12.5°S and 62.5°E - 82.5°E) SST index for the time domain 1982-2004.

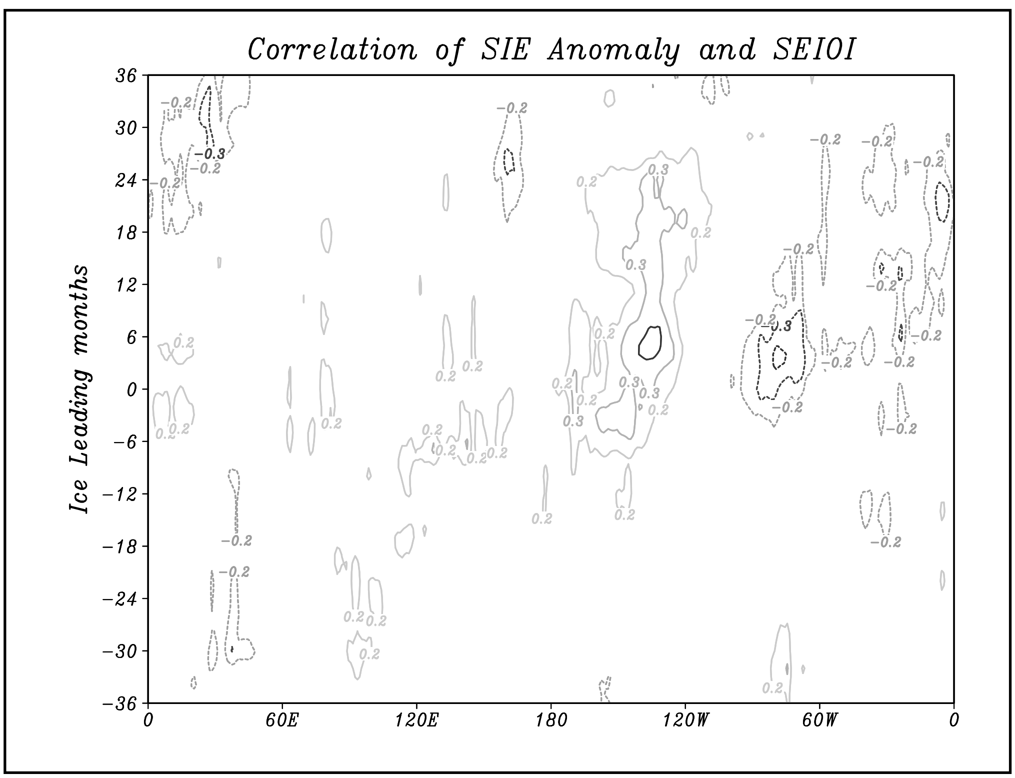

Figure 9. Spatial coefficient between sea ice edge anomaly and southeast India Ocean SST Index during the time period 1982-2004.

CONCLUSIONS

The antarctic sea ice edge variability till very recently is discussed for regional and seasonal time scales and its relationship with Indian Ocean SST is studied. It has been found that the sea ice accumulation in Ross, Weddell seas and Indian Ocean region is reduced whereas it has increased in Pacific Ocean and remains unaffected in Belligshaushan/Amundsen seas. On the seasonal time scale the trend of SIE′ is reduced considerably for summer and winter seasons. The trend for the time domain 1982-2004 for summer is negative and nearly zero for winter whereas both the seasons showed positive trend for 1982-1998.

The positive significant correlation of SIE′ with southeast Indian Ocean SST persists for both the time domains. The SST of this region is unique precurser for the Australian summer monsoon, Indian summer monsoon and ENSO phenomenon after the 1976-1977 regime shift and is also linked with recently discovered Indian Ocean Dipole event of subtropical Indian Ocean by Behera & Yamagata, 2001 (Terray, Dominiak and Delecluse, 2005). The physical mechanism of teleconnection between high latitudes of Antarctic and low latitude of Pacific and Atlantic Oceans have been advanced much in recent years (White & Chen 2002; Yuan 2004) but the studies to find any connection between polar to low latitude of Indian Ocean is still in primitive stage. In order to get stable relationship or teleconnection between low latitudes of Indian Ocean and polar latitudes, the present study for one ocean variable shall be extended to other atmospheric and ocean variables over the Indian Ocean for the better understanding of underlying physical mechanism that drives the observed correlation between SEIOI and SIE′. Moreover, as the transition of whole monsoon-ENSO system is influenced by SST anomaly of southeast Indian Ocean region, besides the above, modelling study shall also be employed for establishing the teleconnection, if any and understanding the physical mechanism.

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