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Title: **The link between tropical Indian Ocean processes, Indian Ocean Dipole (IOD), and sea-ice**

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Sea-ice in the Polar Regions is influenced by various processes. The local heat flux from the ocean to atmosphere results in the cooling of sea surface which subsequently leads to ice formation. However these fluxes can be modified by various mechanisms operating within and away from the region of ice formations. Recent studies (Liu et al., 2002; Liu et al., 2004; Yuan, 2004; Stammerjohn et al., 2008) highlighted the role of El Niño-Southern Oscillation (ENSO) in Antarctic sea-ice variability. The influence of ENSO, which varies in different Antarctic sectors (Bertler et al*.,* 2006) underlines the role of tropical ocean processes in regulating the high latitude variability. One of the most studied phenomena in the Indian ocean is the Indian Ocean Dipole (IOD) (Saji, et al, 1999). Occasionally the western and eastern Indian Ocean will be characterized by opposite sea surface temperature (SST) anomalies. A positive IOD results when the western Indian Ocean is characterized by positive and the eastern Indian Ocean is characterized by negative SST anomalies, whereas a negative IOD results when the western Indian Ocean is characterized by negative and eastern Indian ocean is characterized by positive SST anomalies. Impact of IOD can be traced in to the extra-tropical southern hemisphere. (Saji et al., 2005) found IOD induce Rossby wave trains with its source in the eastern tropical Indian Ocean which then get trapped in the westerly jet and propagate around the Antarctica and influence the southern hemisphere surface temperature anomalies. This exerts a significant influence on the weather pattern in remote regions as far as South America, where the rainfall is modified by anomalous anticyclonic wind pattern induced by the Rossby wave trains generated by IOD (Chan et al., 2008). However, how this phenomena influence the sea-ice of the southern hemisphere has not been investigated. This forms the motivations for the present study.

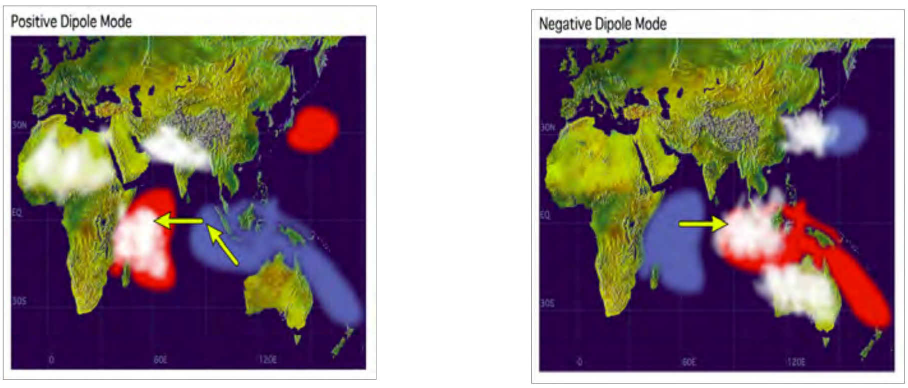

Figure.1. *Schematics of Indian Ocean Dipole (www.jamstec.go.jp), blue and red patches indicate negative and positive SST anomalies. Arrow Indicate the direction of the wind anomalies.*

In order to understand the variability of sea-ice in Antarctica in relation to the IOD, the Dipole mode Index (DMI), defined as the difference between the sea-surface temperature anomalies in the region 60E- 80E, 10S-10N and 90E-110E, 10S-0 (Saji and Yamagata, 2003) was constructed using Hadley centre sea-surface temperature data set (Rayner, et al., 2003) Passive microwave sea-ice concentrations computed using bootstrap method was obtained from National Snow and Ice data centre (NSIDC), USA (Comiso, 1999). This data, in polar stereographic grid, was initially re-gridded to 1 x 0.25 degree Longitude - Latitude grid. A monthly mean climatology of sea-ice concentration was constructed using this 28 years of data spanning November 1978 to December 2006. This climatology was used to construct sea-ice concentration anomalies, which is obtained by subtracting the monthly means from the actual observations. Since monthly sea-ice concentration anomalies are noisy, both the time series are smoothed by a 13 point running mean and correlation between these two variables are computed at various lag.

However IOD is also correlated with the ENSO at various time scales as well. Hence the smoothed ice anomalies are also correlated with the NINO3 index at various lags (-24 to 24). Partial correlation between DMI and ice concentrations anomalies were derived as following.

$$R_{di} \quad = \quad r_{xz} - (r_{xy} \times r_{yz}) / \mathrm{sqrt}(1 - r^2 xy)(1 - r^2 yz)$$

where R_{di} is the partial correlation between DMI and sea-ice concentration anomalies
r_{xz} is the correlation between DMI and sea-ice concentration anomaly
r_{xy} is the correlation between DMI and NINO3 index
r_{yz} is the correlation between NINO3 index and sea-ice concentration anomalies

Statistical tests were conducted to assert the significance of such a relationship (Yuan and Martinson, 2000)

Most remarkable correlations were obtained when the ice concentration anomalies lag DMI by 2 years (Figure.2) and when the ice concentration anomalies lead the DMI by one year.

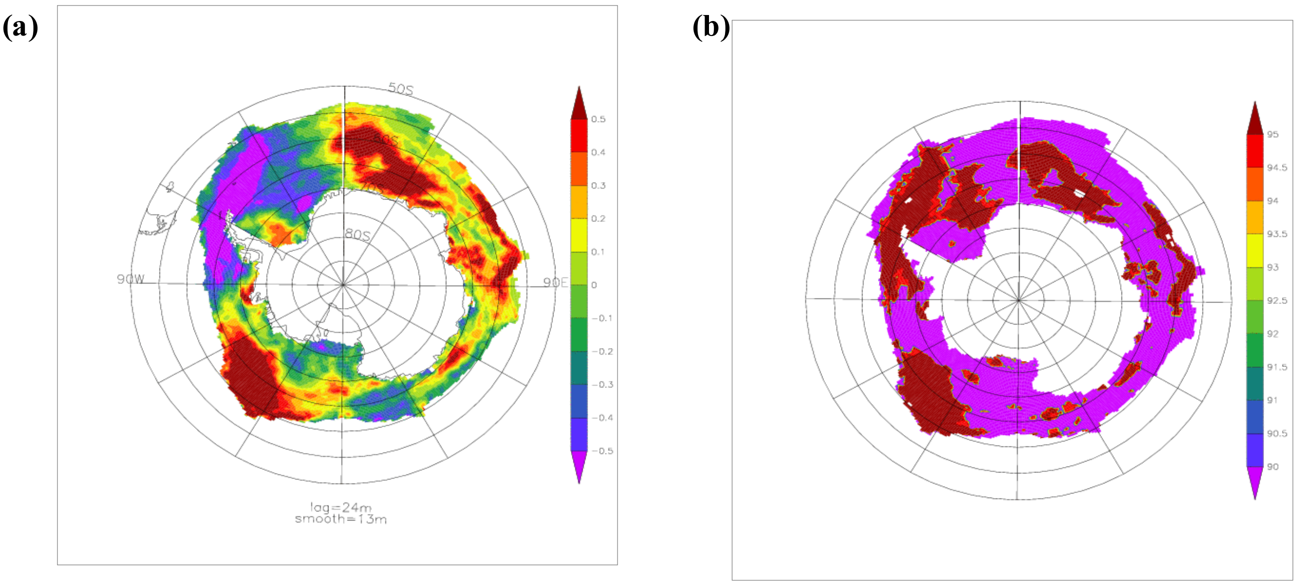

Figure.2. **(a)** *Partial Correlation between Sea-ice anomalies and DMI when sea-ice lags by 24 months and (b) significance levels.*

(a) **(b)**

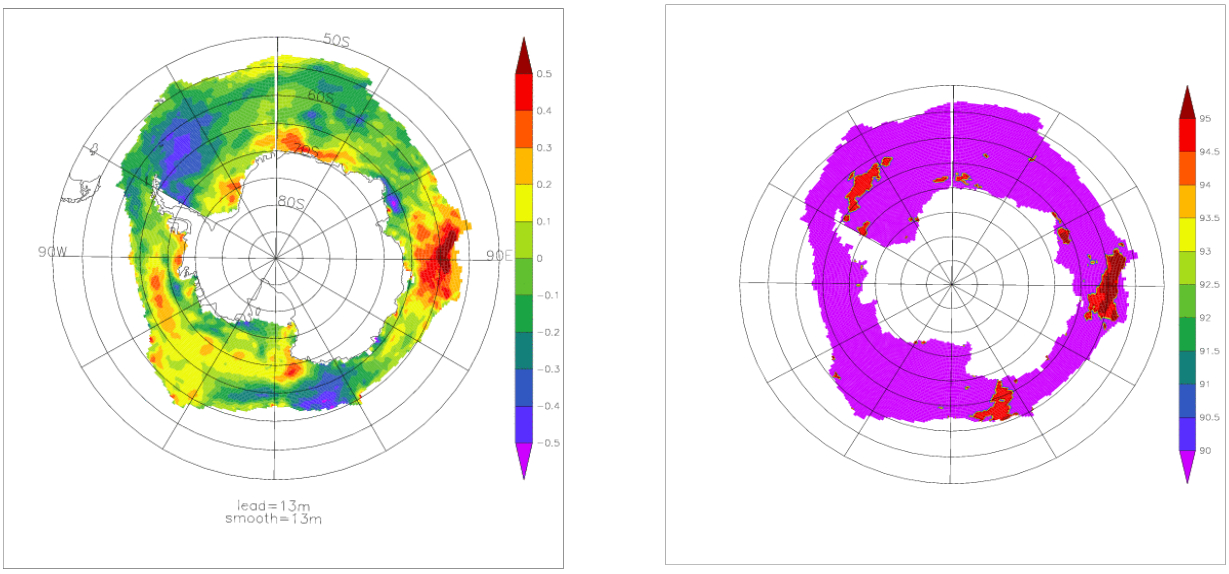

Figure.3. **(a)** *Partial Correlation between Sea-ice anomalies and DMI when sea-ice lead by 13 months and (b) significance levels.*

In the southern Ocean such lead lag correlations with tropical processes such as Indian Ocean Dipole can be spurious as there are climate anomalies propagating along with the ACC, called the Antarctic circumpolar wave. However, a short study conducted on this aspect showed that the ACW in the ice-ocean-Atmosphere system terminates at 40°E in the Indian Ocean region (Nuncio et al, 2011). This is due to the topographic meandering of the Antarctic Circumpolar current when it encounters deep bottom topography and associated changes in the air sea interaction. Here the meandering will result in the warming up of sea surface. This in turn will enhance the atmospheric vertical velocity. Hence the east ward propagating atmospheric ACW anomalies will be lifted up and the oceanic anomalies will be diverted southward. This will result in the decoupling of the atmospheric and oceanic anomalies and the termination of ACW (Figure. 4). Hence the correlations at 90°E (Figure.3a.) could be least influenced by the ACW and there may exists physical mechanisms that links the southern Hemisphere sea-ice and IOD at one year lead time.

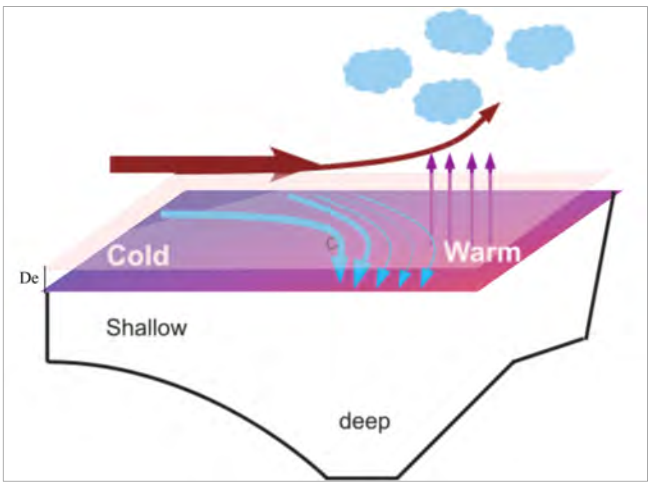

Figure.4 *Schematics for topographic meandering of ACC and associated changes in the eastward propagating ACW. The southward meandering will warm the ocean east of 40E, resulting in anomalous upward vertical velocity. This will divert the atmospheric ACW up while the southward steering of ACC will drive the oceanic anomalies southward, resulting in decoupling of oceanic and atmospheric anomalies and the termination of the ACW in the coupled ice-tmosphere-ocean system in the Indian ocean region of southern ocean. De, is the Ekman depth.*

A singular value decomposition of the SST and the sea-ice concentration anomaly for September-November, were also conducted to examine whether Indian Ocean dipole is a component of the southern hemisphere ice-ocean-atmosphere system. As expected the leading modes depicted the ENSO in the Pacific (Figure.5, top panel). Correlation of the first mode with the SST anomalies showed ENSO in the Pacific and Indian Ocean Dipole in the equatorial Indian Ocean with SSTs of opposite phases in the eastern and western Indian Ocean region (Figure. 6 top panel). This is similar to the Indo-Pacific tripole as described by Chen [2010], with warm SSTs in the western Indian Ocean, and eastern Pacific and cool SSTs in the eastern Indian Ocean. The corresponding sea ice pattern reflects the Antarctic Dipole (ADP) anomalies in responding to ENSO warm events. The time series of mode-1 is well correlated with the NINO3 and NINO3.4 indices with a maximum correlation coefficient of 0.9. The second mode displays a pattern characterized by negative SST anomalies near the tropics and warm SST anomalies at the subtropical gyre of the Indian Ocean (Figure. 5 and 6 middle panels). The north-south out-of-phase SST anomalies in the Indian Ocean are likely a pattern that is related to sea ice in the Indian Ocean in the second mode of the SVD. However, it is interesting that the sea-ice field is similar to the response to the La Nina phase of the ADP. In addition, a wave-3 pattern exists in mid-high latitudes around Antarctica and eastern tropical Pacific SST is relatively cold (Figure 5 middle panel). In contrast with the leading mode with maximum sea ice responses in the western hemisphere, mode-2 and 3 have more influence on sea ice in the Indian Ocean and western Pacific sectors of the Antarctic (Figure. 5 middle and bottom panels).

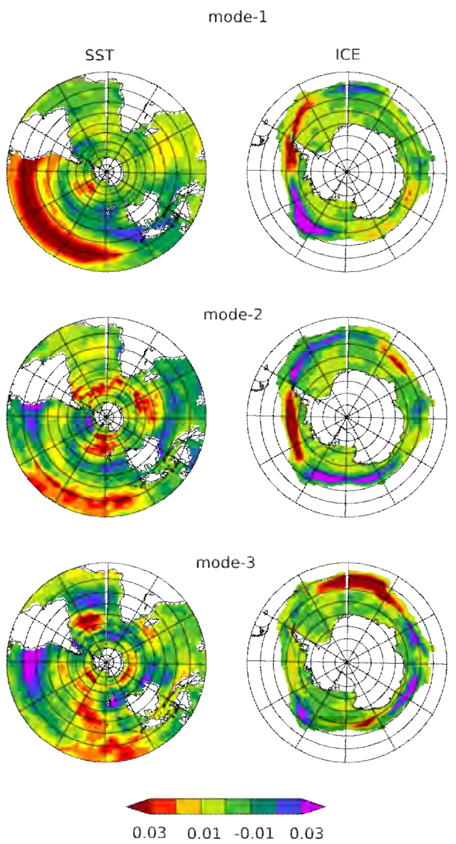

Figure.5. *Coupled SVD between sea-ice and SST anomalies for SON. Latitude circle starts at 10N for SST and 55 S for sea-ice anomalies*

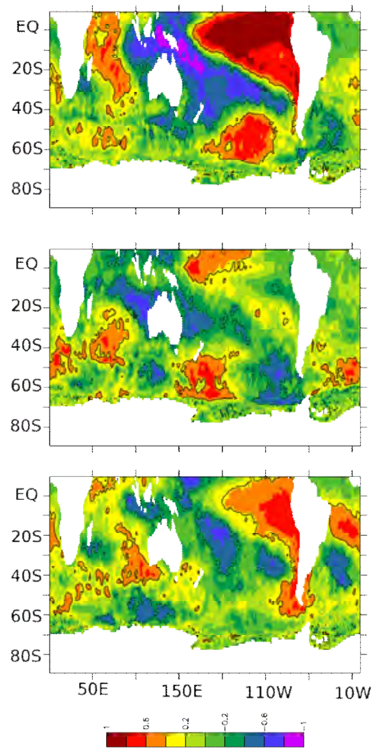

Figure.6. *Correlation between PC s of SST anomalies in figure5 and SST anomalies. Correlations > 0.36 significant at 95 % level.*

Present research identified significant statistical correlations between Antarctic sea-ice and the Indian Ocean dipole. The diminishing ACW signals in the ice-ocean-atmosphere system of the Indian Ocean region suggests that the one year lead correlations between ice and IOD can be meaningful and will help predicting the IOD ahead of a year. The relevance of this lies in the fact that IOD has numerous socio-economic consequences related to rainfall and drought in the Indian ocean rim countries. At the same time coupled SVDs reveal Indian Ocean sea-ice is more influenced by mode-2 and mode-3 pattern, where as the leading mode characterized by an Indo-Pacific tripole with IOD in the Indian Ocean and ENSO in the Pacific. However it has been found in the analysis that this mode is correlated maximum to the NINO03 and NINO34 SST anomalies. Thus, though IOD is present in this mode its effect is not evident in the sea-ice.

A total of 9600 USD was allotted for the study. About 1200 USD were utilized for travel and obtaining a US j1 visa. Housing in Palisades, New York cost about 3865 USD for three months. A new external hard disk was brought for the purpose of storing the work and data. Remaining amount was spend on living in New York.

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