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Review Article

Physical Process Influencing the Ecosystem of the Indian Sector of Southern Ocean-An Overview

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The Antarctic Circumpolar Current (ACC) is the key current system in the Southern Ocean (SO) which connects three major oceans. The eastward flowing ACC in the Indian sector of SO (IOSO) influences by the southwest Indian ridge and Weddell gyre which results a southward shift of the core of ACC. This brings warm water to the coastal Antarctica and may cause glacier/sea-ice melting and further warming and freshening of bottom water masses. Additionally eddies in IOSO are the principal mechanism which transfer heat, salt, and carbon poleward across the zonal ACC and contribute to the mixing of water masses. The southward intrusions of Subtropical Surface Water as well as the upward movement of Antarctic Intermediate Water are attributed to the influence of anticyclonic and cyclonic eddies respectively. Presence of upwelling in the coastal waters of Antarctica (Prydz Bay), increased sea ice extant and subsequent enhanced melting in positive Southern Annular Mode (SAM) events causes high chlorophyll *a* in the coastal waters as well as south of Polar Front during austral summer, which perhaps makes the IOSO a potential site for CO_2 sink. Further, the bottom waters from this region may bring the dissolved CO_2 which is getting ventilated in subtropics. However detailed investigations covering seasons are required to be implemented using Models and Observations (Both satellite and in-situ) for a better understanding about the IOSO ecosystem and it's links to Tropical Ocean.

Keywords: Antarctic Circumpolar Current; Antarctic Bottom Water; Melt Water; Eddies; Chlorophyll; Southern Ocean

Introduction

Southern Ocean (SO) is a unique region which tends to have a global scientific relevance in terms of its circulation, water masses, other distinct physical, chemical and related biological processes and it's response to climate change. In the light of the above perspectives, the SO in general and the Indian Ocean sector of the SO (IOSO) in particular, is still an understudied region. Further the IOSO circulation is linked with the Indian Ocean circulation through Agulhas current, Antarctic Circumploar Current (ACC), West Australian current and South Equatorial current systems. Hence the exchange of heat and mass through these currents shall affect the variabilities of the Indian monsoon.

The major current in the SO is the ACC, which is the major conduit for inter ocean transport of heat and fresh water fluxes (Rintoul and Sokolov, 2001; Sokolov and Rintoul, 2002; Rintoul *et al*., 2002; Yuan *et al*., 2004). ACC transforms the hydrographic conditions in the SO, which is entrenched with copious circumpolar fronts, jets, high-speed filaments and eddies (Sokolov and Rintoul 2007; Lenn *et al*., 2011; Nowlin and Klinck, 1986; Stammer 1998; Hughes 2005). The IOSO has complex quasi-zonal frontal systems and the individual branches of these fronts often merge and diverge in response to interactions with the bathymetry (Sokolov and Rintoul 2007, 2009).

In some region of the IOSO the front allied with the Agulhas retroflection, known as Agulhas Return Front (ARF), merges with the Subtropical Front (STF) (Belkin & Gordon 1996; Lutjeharms and Ansorge 2001; Kostianoy *et al*., 2004) which is the boundary between subtropical and subantarctic waters (Deacon 1937; Hamilton 2006). The fronts southwards of STF

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*Author for Correspondence: E-mail: anil@ncaor.gov.in are Subantarctic Front (SAF), Polar Front (PF), Southern ACC Front (SACCF) and southern boundary of the ACC (SB). These fronts extend through the water column since ACC is a deep-reaching barotropic current, (Belkin and Gordon 1996; Meijers *et al*., 2010). The topographic influences and discrepancies in hydrographic as well as biological characteristics in various frontal systems have been reported (Orsi *et al*., 1995; Belkin and Gordon 1996; Sparrow *et al*., 1996; Holliday and Read 1998; Kostianoy *et al*., 2004; Sokolov and Rintoul 2007; Swart *et al*., 2008; Sokolov and Rintoul, 2009; Swart and Speich 2010). Also, previous studies in the Indian IOSO have reported frontal variability, water masses and their influence on the phyto- and zooplankton biomass during austral summer (Jasmine *et al*., 2009; Gandhi *et al*., 2012).

The IOSO encompasses several deep and intermediate water masses which ventilate the abyssal and intermediate depths of the world oceans. The major water masses in the IOSO are Subtropical surface Water (STSW), Subantarctic Surface Water (SASW), Mode Water, Antarctic Surface Water (AASW), Antarctic Intermediate Water (AAIW), Circumpolar Deep Water (CDW) and Antarctic Bottom Water (AABW). Among these AABW is one of the most significant water masses which brings the dissolved inorganic carbon (DIC) from the polar regions to tropics and causes the deterioration of DIC due to the occurrence of warm water. The high degree of freshening and warming of AABW has been reported by earlier investigators (Whitworth, 2002; Rintoul, 2007). Another peculiar feature observed in the IOSO is the presence of Winter Water (WW) which has a close relationship with the heat budget as well as the freshening due to ice melt in the SO and is a major source of micronutrients which regulates the Chlorophyll (Chl a) blooms (Deacon, 1937; Park *et al*., 1998; Yuan *et al*., 2004; Boyd and Ellwood, 2010).

With the existing knowledge of IOSO it is quite impractical to derive a proper understanding useful for scientific indulgent or societal benefits. Hence more systematic investigations are required to be carried out to study the atmospheric, physical, biogeochemical and palaeoclimatic processes in IOSO to understand its role in the global climate change scenario. In view of this, the Ministry of Earth Sciences (Govt. of India) has initiated a national scientific program in the IOSO since 2004 with National Centre for Antarctic and Ocean Research (NCAOR), Goa as the nodal agency. So far eight multi-institutional and multidisciplinary expeditions have been completed with the active participation from several national and international research organizations and universities. In the present review paper we discuss about the major results in the aspect of hydrodynamics of the IOSO published so far from the studies carried out by the Indian expeditions.

Data and Methods

The surveys were carried out along two meridional sections, one above the southwest Indian ridge (between 45°E and 48°E) and the other above a relatively flat bottom (57° 30′E). The observations were carried out as far south as 69°19’S to understand the hydrodynamics of the study region and for this the atmospheric and physical parameters were measured (Fig. 1). The observations were mainly concentrated between the subtropical (40°S) and coastal waters of Antarctica. Data and samples were collected during the austral summer (January-February) onboard ORV Sagar Kanya in 2004, Akademic Boris Petrov in 2006 and 2009 and ORV Sagar Nidhi, in 2010, 2011, 2012, 2013 and 2015. In

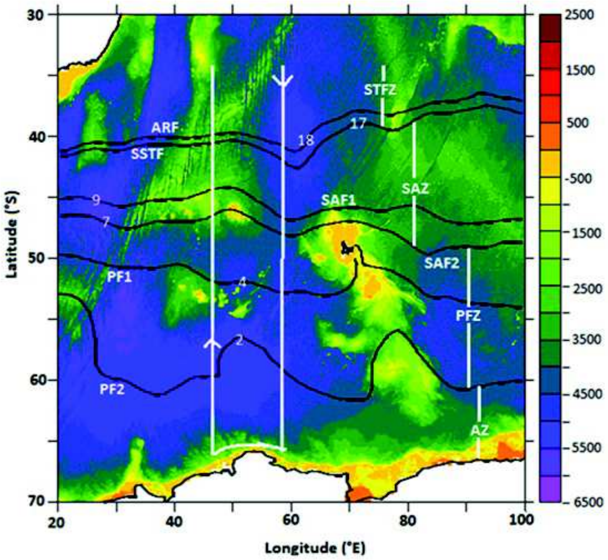

Fig. 1: IOSO study region. Fronts are marked using WOA climatology. Background colour represents the bathymetry of the study area from the high resolution ETOPO1 data [STFZ- Subtropical Frontal Zone, SAZ-Subantarctic Zone, PFZ-Polar Frontal Zone and AZ-Antarctic Zone]

2006 expedion, a time series observations were also carried out in the Prydz Bay (69°19’S, 76°E). During the above expeditions except in 2009, a CTD (Sea-Bird Electronics, USA) and XCTDs (Tsurumi-Seiki Co. TSK Ltd, Yokohama, Japan) were deployed to collect the temperature and salinity profiles. XCTD probes were launched at ~ 0.5° nautical mile intervals between the CTD stations. In 2009, a MARK III-B CTD (Neil Brown Instrument Systems) was used to collect the vertical profiles of temperature and salinity. The XCTD profiles were quality controlled by following the guidelines in the CSIRO Cookbook (1993). The salinity data from the CTD were calibrated against water samples analysed using a high-precision salinometer (Guildline AUTOSAL). Oceanic fronts were identified using the characteristic property indicators following the criteria listed by Belkin and Gordon (1996), Sparrow *et al*. (1996), Holliday & Read (1998) and Kostianoy *et al*. (2004). The thickness of the fresh water input in the surface layer relative to the WW in the study region was estimated using the formula of Park *et al*. (1998):

$$h = \frac{D_C(S_W - S^{bar})}{S_W}, S^{bar} = \frac{1}{D_C}\left[\int_{-D_C}^{0} Sdz\right],$$

where *h* is the thickness of the fresh water input per unit surface area, *Dc* is the WW depth, *Sw* is the WW salinity, and S^{bar} is the depth-averaged salinity between the surface and WW depth. Surface ocean currents from Ocean Surface Current Analysis–Realtime data (Bonjean and Lagerloef, 2002), monthly ASCAT wind stress (Bentamy and Fillon, 2012), Ekman current and AMSR-E ice coverage data from ERDDAP, (https://coastwatch.pfeg.noaa.gov/erddap), Argo data from the Coriolis Data Center (http://www.coriolis.eu.org/cdc) and sea surface height anomaly data AVISO (http://atoll-motu.aviso.oceanobs.com) were used. ECMWF (ORAS4,) reanalysis data (Balmaseda *et al*., 2013) was also used to understand the freshening of AABW in the study area.

Results and Discussion

Major Physical Processes in the IOSO

Frontal Variability: During southern summer, the position and structure of the SO fronts during austral summer 2004 (ARF, STF, SAF and PF) along 45°E has been discussed by Anilkumar *et al*. (2005). ARF was observed with a width of ~ 110 km in the region between 40°15’ and 41° 15’S, the surface temperature ranges from 19° to 17°C and the depth of the 10°C isotherm ranges from 300 to 750m, contrary to narrower (44 and 73 km) ARF reported in an earlier study (Holliday and Read, 1998). However, STF identified between 41°15’ and 42°15’S which was narrower (~ 110 km) compared to previous studies (> 220 km). On the other hand, the SAF was identified as a broader front (~ 500 km) between 42° 30’ and 47°S compared to 165-275 km width reported by earlier studies (Holliday and Read, 1998; Lujeharms and Valentine, 1984). Between these latitudes, the surface temperature reduced from 9.7 to 6.3°C and surface salinity varied from 34.0 to 33.85. The differences in frontal positions based on the data from previous investigation are discussed by Anilkumar *et al.* (2005). The PF was identified as Surface PF (SPF) and Subsurface PF (SSPF), and the SPF was identified between 48 and 52°S, with a width of ~ 440 km, while the SSPF was identified by the northern limit of 2°C isotherm below 200 m. Anilkumar *et al.* (2014a) identified the positions of the Southern ACC Front and Southern Boundary of ACC between 60°S

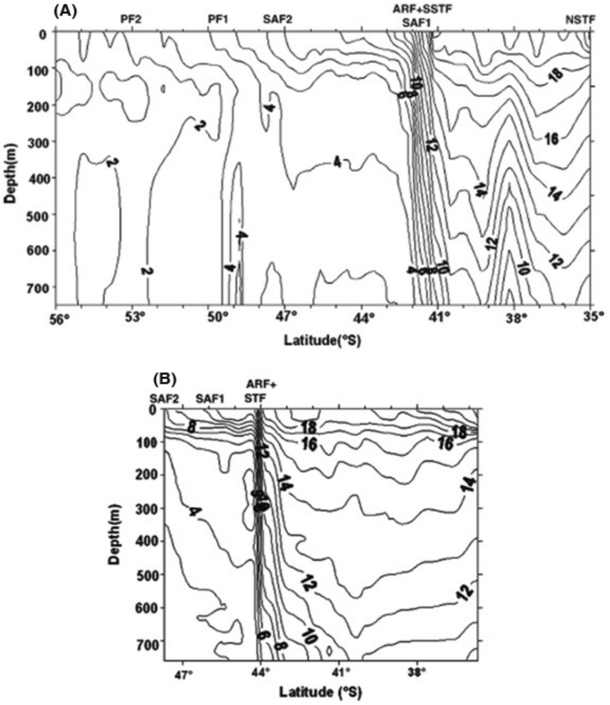

Fig. 2: Vertical structure of temperature (a) along 45°E and (b) along 57°30’E (1°C contour interval)

and 61°S and between 64°S and 64°30’S, respectively. A shifting of the merged fronts ARF+STF +SAF by >2° latitude towards south from 45°E to 57°30’E, has been demarcated (Fig. 2) by Anilkumar *et al.* (2006, 2007) and this shift could be due to the bottom topographic influence. The results of this analysis brought out the surface as well as subsurface manifestation of various oceanic fronts in IOSO, which was not intensively examined earlier.

Water Masses: The water masses in the IOSO have been demarcated (Fig. 3) by Anilkumar *et al.* (2006). STSW, SASW, and AASW were identified from 37 to 40°S, between 43° and 45°S and from 44° to 56°S respectively. STSW is characterized by relatively high temperature and salinity. The SASW always found near the southern boundary of the frontal zone and it is characterized by the lower temperature and salinity (9°C, <34). While nearing the PF region from the subtropics the surface water becomes colder and fresher indicating the presence of AASW. Cold and fresh Mode Water in a depth between 400 and 700 m from 31° to 41°S has also been reported by them and it as a subtropical Mode Water concurring with the earlier findings (Park *et al.*, 1991 & 1993; McCartney, 1977). North of the ACC, this water mass is formed by deep winter convection and appears in summer sections as a pycnostad (or thermostad) beneath the seasonal thermocline (Park *et al.*, 1993; Stramma and Lutjeharms, 1997). This Mode Water is not concatenated with the argument of McCartney (1977, 1982) who suggested all Mode Waters are associated with the circumpolar SAF. Between 31° and 41°S from ~1150 and ~1200 m depth, the features of AAIW characterized by its properties (q~ 4.4°C; salinity minimum ~ 34.42 and s_q ~ 27.24 kg m^{-3}) were identified which was reported earlier at 1100 m (Blindoff and McDougall, 1999) and 1300 m (Park *et al.*, 1998). This could be due to impact of eddies present in this region as reported by Sabu *et al.* (2015). AAIW, as indicated by a salinity minimum at about 1000 m depth, spreads northward to about 10°S below the subantarctic Mode Water (Stramma and Lutjeharms, 1997) which has a strong circulation in the western Indian Ocean (Harris, 1972; Toole and Warren, 1993). Circumpolar Deep Water (CDW), occupies the depth range 2000-3800 m, has been identified with its remarkable feature (q~ 2°C; S~ 34.77 and s_q ~ 27.8 kg m^{-3}) in the IOSO, this concatenate with the characteristics of the North Atlantic Deep water (NADW) reported by Park *et al.* (1993), which rises sharply to shallower depths north of 45°S. The Antarctic Bottom water (AABW) was identified below CDW at 4100 to 4700 m depth. Along the deep western boundary of Madagascar (Warren, 1981), AABW enters the Madagascar Basin through the fractures in the Southwest Indian Ridge (Warren, 1978) and flows further north and this agrees with the characteristics of AABW identified upto 49°S.

Further Anilkumar *et al.* (2015) reported that AABW in the IOSO became warmer (~0.04°C) fresher (~0.01) and lighter (0.01 kg m^{-3}) in a time span of four years, from 2006 to 2010 (Fig. 4). A high degree of freshening was indicated by them from 2006 to 2010 in the IOSO (~0.01 in four years) compared to the freshening observed by Rintoul (2007) from 1990 to 2005 (~0.01 in 15 years). The increased influence of melt water from continental ice also may cause the freshening of bottom waters (Jacobs, 2002, 2006, Jacobs and Giulivi, 2010; Pritchard *et al.*, 2012). In addition to the role of Amery Ice Shelf, indeed the nearby Cape Darnley Polynya was reported as a significant source of new bottom water (Ohshima *et al.*, 2013). From the above discussions it can be noted that high degree of freshening and warming of AABW has been observed in the recent years could be due to the increased glacier melting as an impact of global warming.

Winter Water (WW): The WW is believed to be a key source of micronutrients (Boyd and Ellwood 2010), which controls the blooms of chlorophyll (Chl a) in the region. Freshwater layer thickness relative to the WW in 2010 and 2011 was compared (Fig. 5 and 6) and observed higher thickness and cooler WW during 2011 (Anilkumar *et al.*, 2014a). This could be due to the increased presence of sea ice in the winter of 2010, which subsequently melted, resulting in the advection of melt water from the south and west of the study region. WW, temperature minimum layer in the subsurface, is the remnant of the mixed layer of the previous winter capped by seasonal warming and freshening (Deacon 1937; Park *et al.* 1998). The ocean surface is exposed to winds during the ice-free period, which augments the mixing, further this temperature minimum layer becoming mixed with the surface and subsurface layers, and subsequent changes shall be made in the heat budget of the region (Yuan *et al.*, 2004).

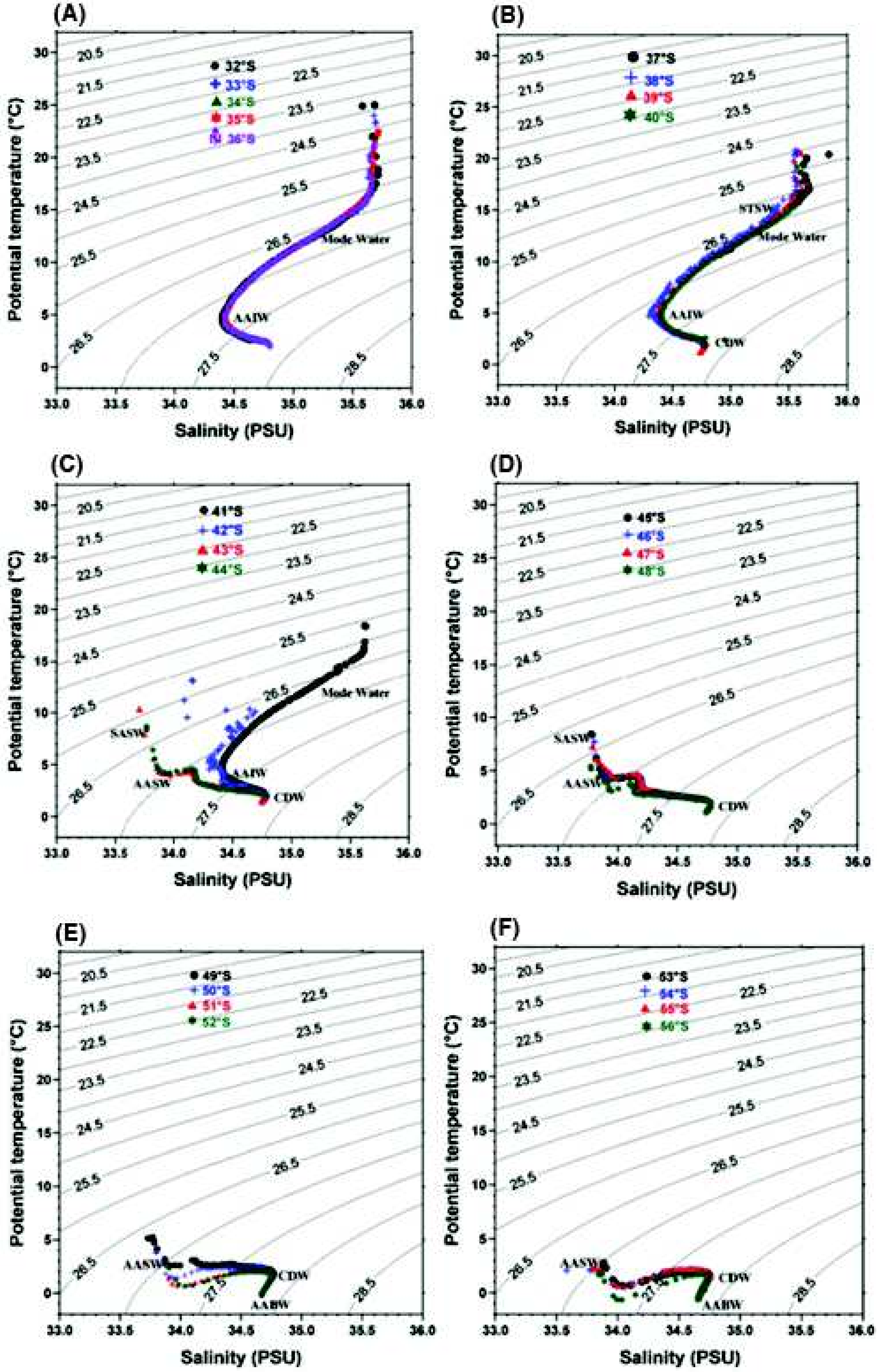

Fig. 3: TS diagram along 45°E. (a) 32–36°S, (b) 37–40°S, (c) 41–44°S, (d) 45–48°S, (e) 49–52°S, (f) 53-56°S (Anilkumar *et al.*, 2006)

Eddies: The SO is one of the most energetic regions of the world ocean in terms of the eddy activity (Fu *et al.*, 2010) in which mesoscale eddies play an important role in the dynamics and thermodynamics

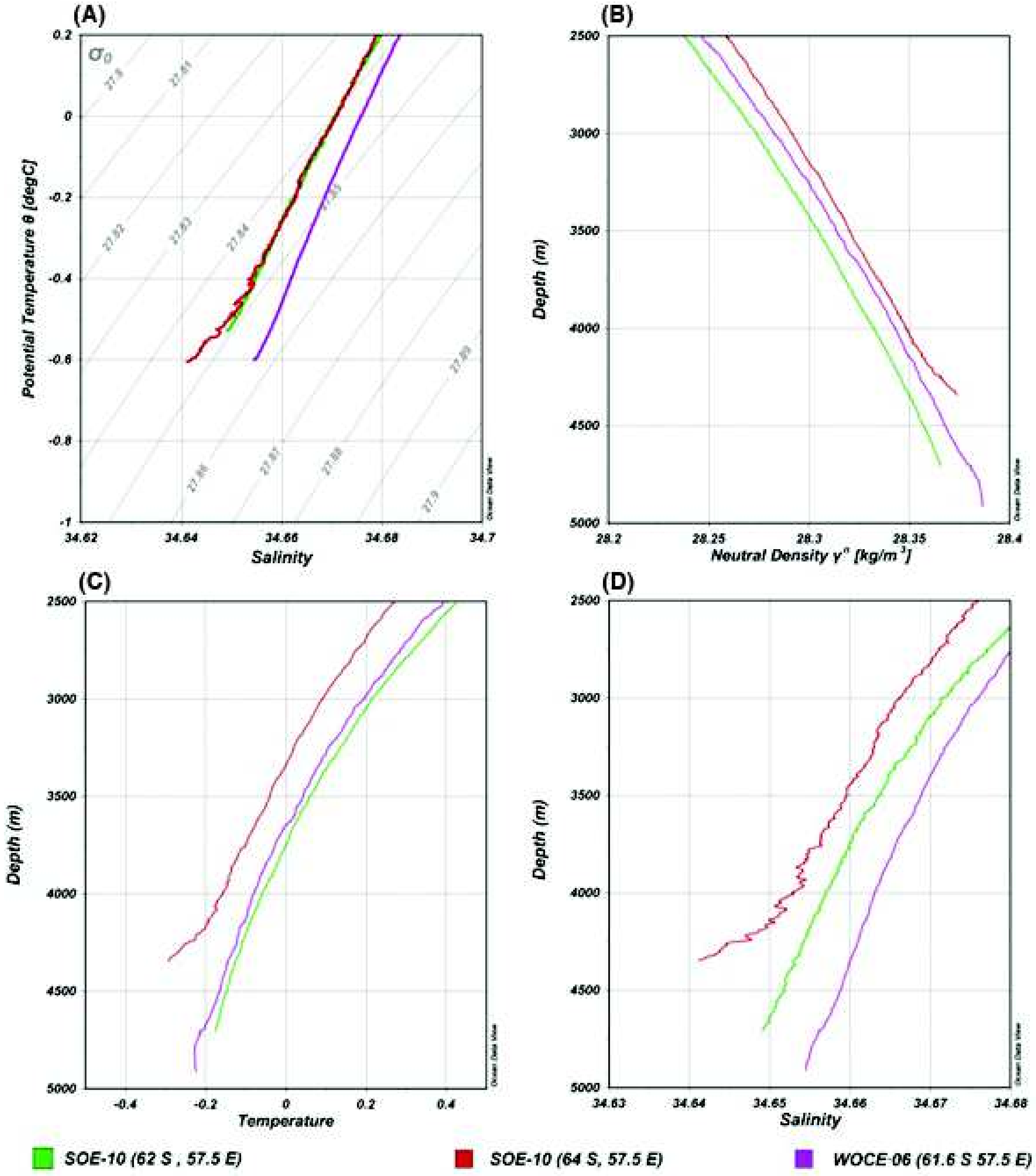

Fig. 4: Comparison between IOSO Expedition 2010 (SOE-10) and WOCE 2006 (a) è-S plot showing the presence of AABW (b) vertical structure of neutral density (c) vertical structure of temperature (d) vertical structure of salinity (Anilkumar *et al*., 2015)

(Marshall and Radko, 2003). Alternate cyclonic and anticyclonic eddies are common features in STF due to high mesoscale variability (Garrett, 1981). A southward shifting STSW in 2011 compared to 2010 (Fig. 7) is attributed to the dominance of eddies in 2011 (Chacko *et al*. 2014). The cyclonic eddy transports cold, fresh and deeper AAIW to much shallower depths (Fig. 8) but the anticyclonic eddy pushes the warm, more saline STSW to deeper depths (Sabu *et al*., 2015). Large change in water mass characteristics was noticed in the eddy regions which is more significant in the cyclonic eddy. STSW, Subtropical Mode Water, and AAIW were also significantly modified in the cyclonic eddy. It is

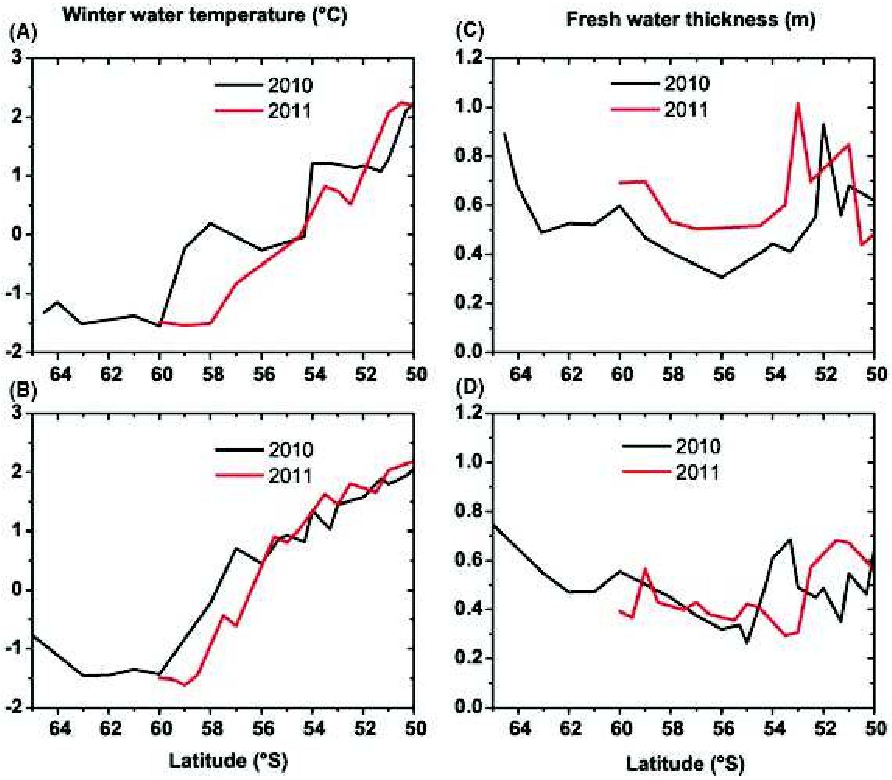

Fig. 5: (A) WW temperature (°C) in 2010 and 2011, along 47°E and (B), in 2010 and 2011 along 57°30'E (C) Freshwater thickness (m), in 2010 and 2011 along 47°E and (D), in 2010 and 2011 along 57°30'E

hypothesized that the freshening in the AAIW at a given depth in the cyclonic eddy is due to shoaling of the pycnocline, causing further intrusion of fresh saline water from deeper depths whereas the corresponding freshening in the anticyclonic eddy is due to the conservation of potential vorticity.

Costal Upwelling: Anilkumar *et al*. (2010) reported the signatures of coastal upwelling in the Prydz Bay (69°192 S 76°E) and its influence on the on phytoplankton abundance during the austral summer 2006 (Fig. 9). In earlier studies it was mentioned that Prydz Bay, is characterized by horizontal distributions of meltwater, suggesting a strong upwelling of warm water with the signatures of CDW, this causes the formation of sensible heat polynyas, perhaps it results in melting the existing ice and/or prevents new ice formation (Stagg *et al*., 1985; Cai *et al*., 2003; Flocco, 2005). Depends on oceanic conditions, the physical processes allied with the meltwater have varying impact on the growth of phytoplankton (Jansen *et al*., 2007). These studies signify the importance of upwelling processes on the phytoplankton community structure in the coastal waters of the Southern Ocean.

Physical Processes and Phytoplankton Bloom: Eventhough SO is considered as a high nutrient low-chlorophyll (Chl) region, the studies carried out by Sabu *et al*. (2014) and Anilkumar et.al. (2014a) showed the occurrence of an anomalous phytoplankton bloom in this area during the austral summer, 2011. The bloom, which formed in January 2011, intensified during February and weakened by March. High surface Chl concentrations (0.76 mg m^{-3}) were observed in the area of the bloom (60°S, 47°E) with a Deep Chlorophyll Maximum (DCM) of 1.15 mgm^{-3} at a depth of 40-60 m (Fig. 10). During 2011, both the concentration and spatial extent of sea ice were high on the western side of the bloom, between 0°E and 40°E, and enhanced freshwater influx was observed in the study area, as a result of ice-melt this probably causes the enhanced Chl *a* in the Antarctic Zone. A positive Southern Annular Mode and an intense La Nina during 2010-2011 are possible reasons for the high sea-ice. The presence of such blooms

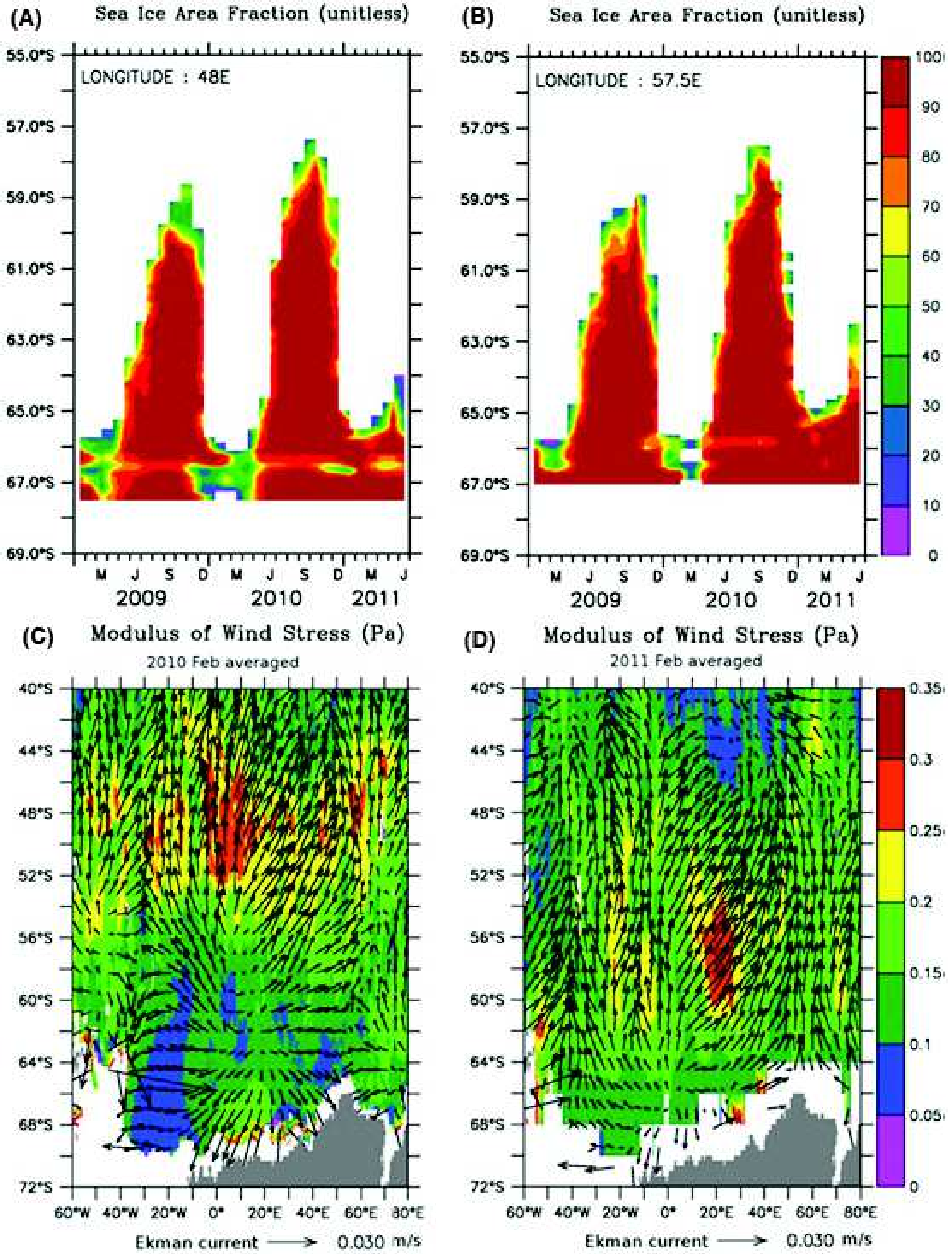

Fig. 6: Sea ice fraction derived from AMSRE along A, 48°E and B, 57°302 E; and wind stress (Pa) overlaid by Ekman currents (m s^{-1}) derived from ASCAT during C, February 2010 and D, February 2011 (Anilkumar *et al*., 2014)

can play major role in drawing down atmospheric CO_2, exporting carbon to the ocean interior, enhancing annual biological productivity, and influencing trophic dynamics and biogeochemical cycles of the IOSO.

CO_2 Ventilation: Dissolution and dissociation of bicarbonate ions are the factors controlling the CO_2 exchange south of 50°S, where the productivity is limited. Supply of deep water with high DIC content

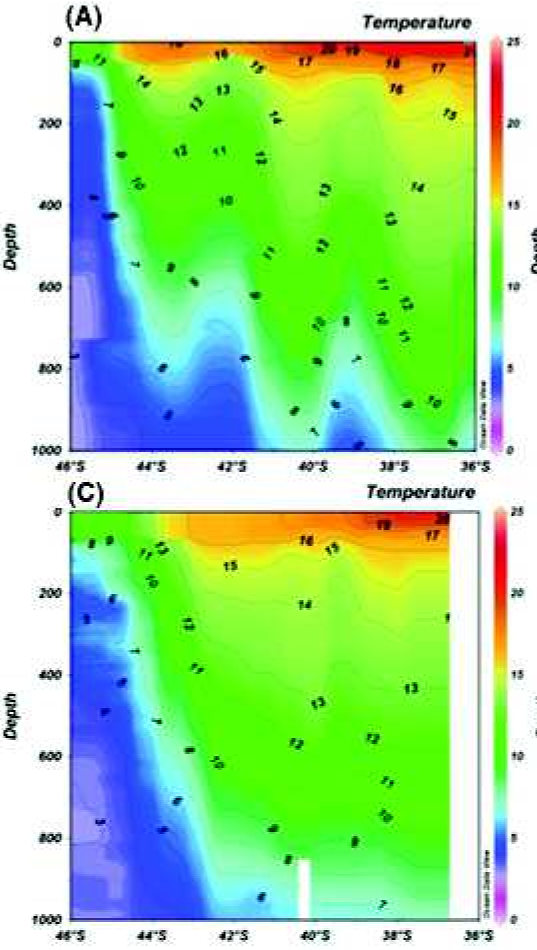

Fig. 7: Vertical section of temperature and salinity in 2011 (a, b) and 2010 (c, d) [Racheal *et al*., 2014]

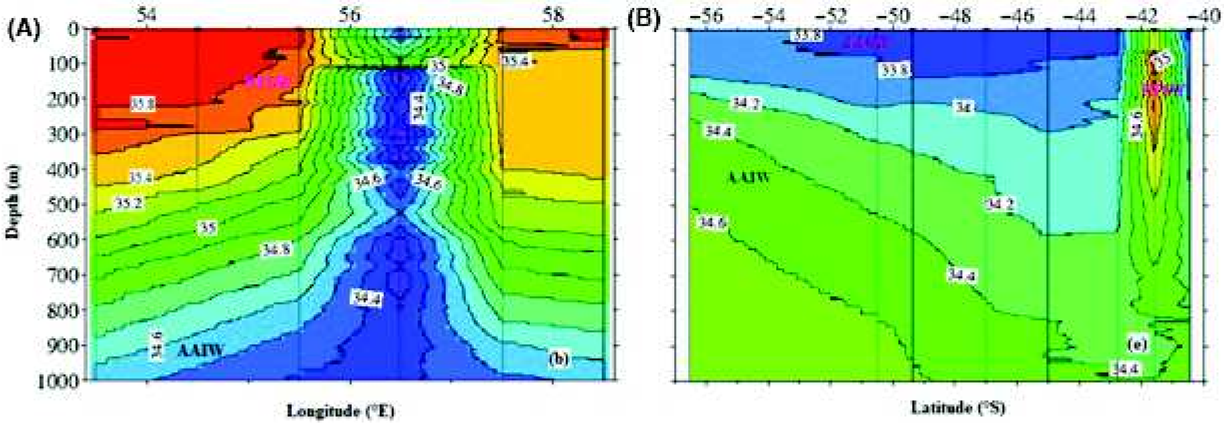

Fig. 8: Vertical section of salinity in the (a) cyclonic eddy along 40°S section and (b) anticyclonic eddy along 57° 30' E section. Black vertical lines in the figure represent the CTD locations [Sabu *et al*., 2015]

to the surface layer and then to the atmosphere (Fig. 11) is attributed to the occurrence of upwelling in the subtropical region and further to the deterioration of the dissolved inorganic carbon due to the occurrence of warm water (Prasanna *et al*., 2015). South of 44æ%S has been identified as major sink of global carbon in the SO region (Caldeira and Duffy, 2000; Fletcher *et al*., 2006) where one third of the total

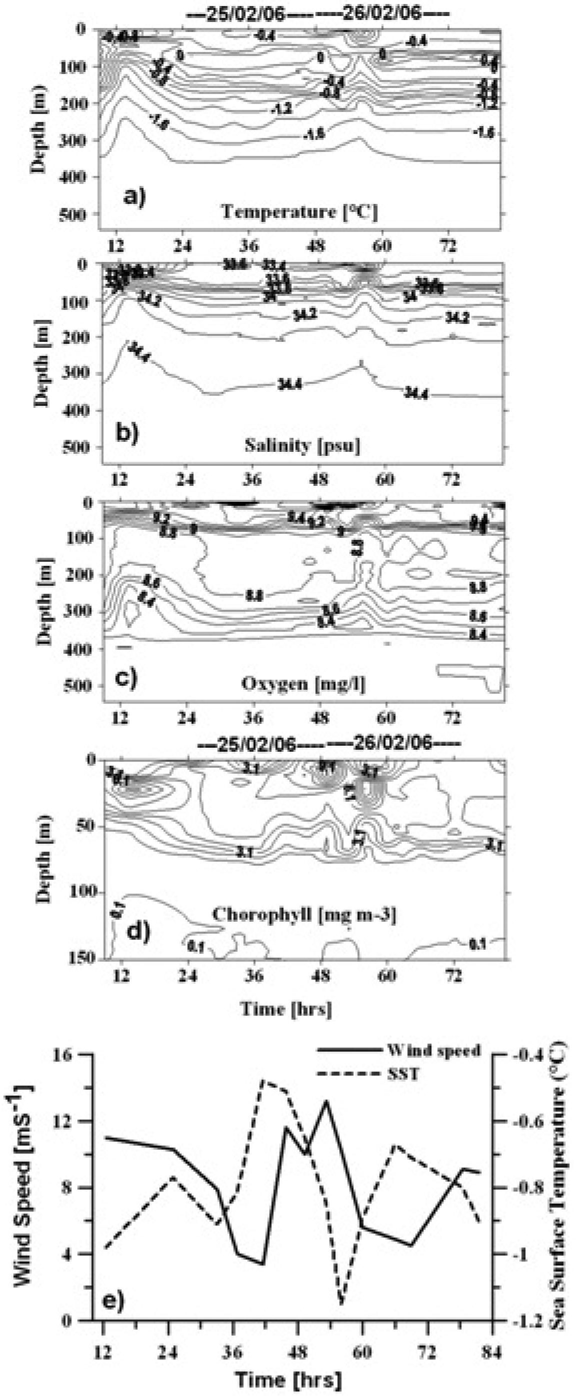

Fig. 9: Vertical structure of (*a*) temperature; (*b*) salinity; (*c*) oxygen; (*d*) chlorophyll and (*e*) wind speed and SST at 69°19'S, 76°E (Anilkumar *et al.*, 2010)

global ocean uptake of anthropogenic CO_2 takes places (c.a. 0.7 PgC yr^{-1}) (Fletcher *et al.*, 2006). Eventhough the efficiency of sinking of CO_2 reduces with time in SO predictions suggest that the region may remain as an important sink of atmospheric CO_2, (Roy *et al.*, 2011) and it can be considered as a net sink for anthropogenic CO_2 (Takahashi *et al.*, 2012). Although the role of temperature and wind in the CO_2 uptake process was renowned, the process of CO_2 uptake in SO is not completely understood (Longinelli *et al.*, 2012). In the sub-Antarctic zone (SAZ) between 48°S and 51°S deep penetration of anthropogenic CO_2 (<1900 m) was observed with modest accumulation (<400 m) in south of 53°S (McNeil *et al.*, 2001). In some particular zones in SO, the net flux of CO_2 is positive during summer time in an year although the SO has a net negative flux of CO_2 (Metzl, 2009) and these regions are significant to monitor in the event of climate change. To understand the factors responsible for the variability of CO_2 concentration in air and ocean, studies on physical and biological variables in this region are more significant (Valsala *et al.*, 2012). Detailed observations on air and ocean CO_2 concentration in both the Indian Ocean and IOSO are imperative to link the prominent role of IOSO with the tropical climatic changes.

Way Forward

The IOSO behaves differently in terms of circulation due to its enclosure in the north with continental Asian landmasses hence anthropologically induced climate change is much faster. Hence future long term hydrodynamic studies (both Modeling and Observations) in the IOSO are imperative to address the following major scientific and societal questions.

- How the Southern Ocean circulation, thermohaline structure, bottom water masses, sea level and sea ice extent varies during different scales and how it is linked to Tropical Indian Ocean?
- What is the role of CO_2 dynamics/acidification rate, biogeochemistry and biodiversity of the Southern Ocean in modulating the physical characteristics of the water and vice versa?
- What are the atmospheric and ocean tele-connection between Southern Ocean and Tropical Ocean both in seasonal and inter-annual time scale? How these oceans responding to climate change?

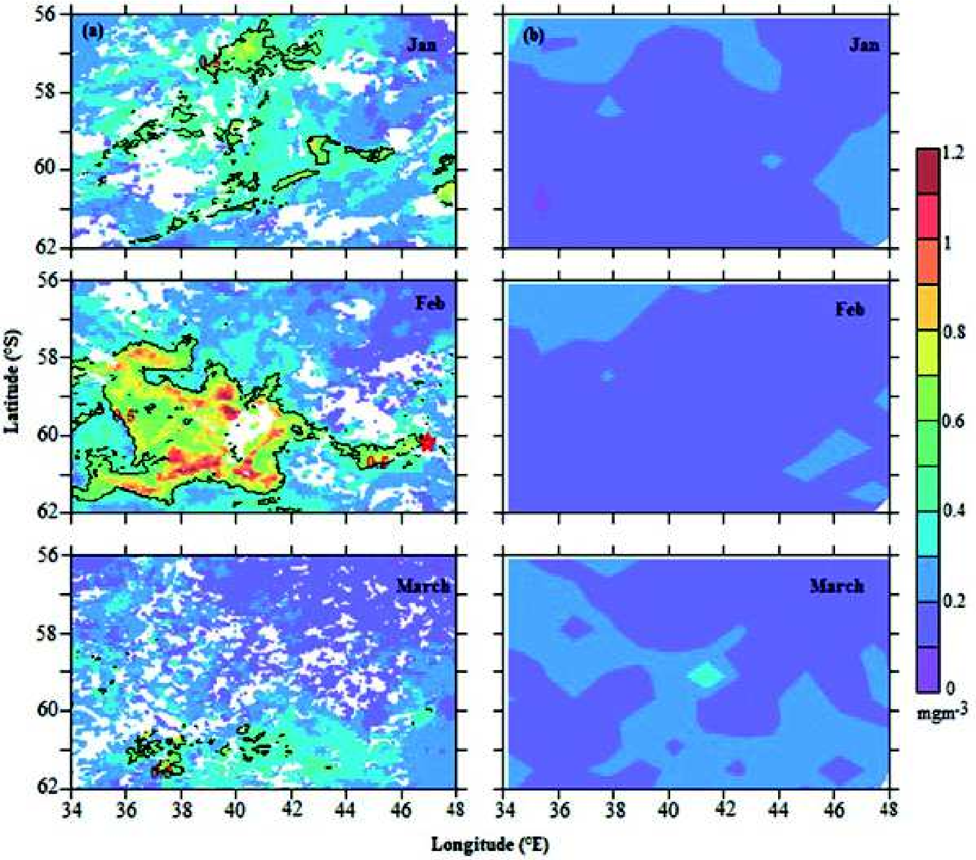

Fig. 10: Monthly variation of satellite Chl *a* during 2011(a) and long term mean (1997-2002) of Chl *a* (b) in the Indian sector of AZ [Sabu *et al*., 2014]

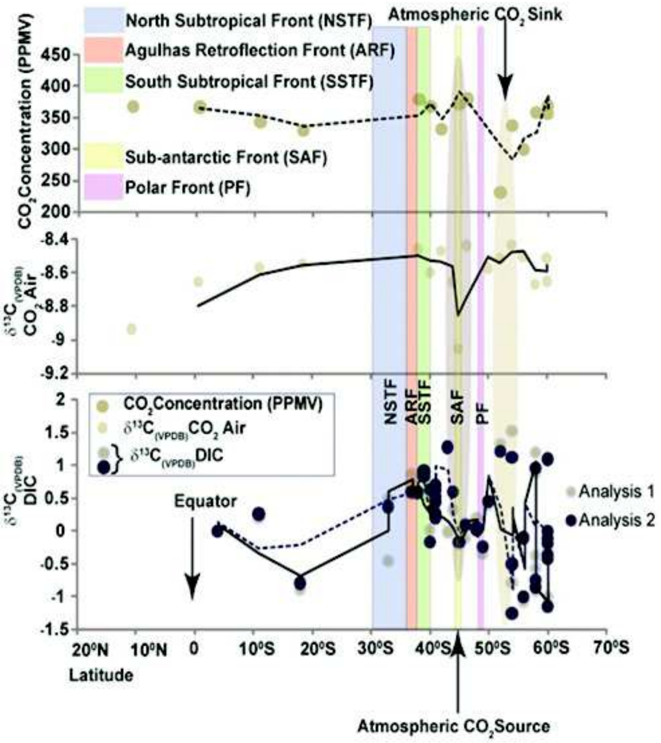

Fig. 11: A zone of CO_2 sink has been identified near 52°S, a zone of CO_2 ventilation has been identified near 45°S. Productivity being the main driving force for CO_2 sinking in southern ocean (Prasanna *et al*., 2015)

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