

*Research Paper***Hydrographic Characteristics of a Coastal Antarctic Transect in the Indian Ocean Sector**

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(Received on 07 June 2016; Accepted on 29 November 2016)

We address results of the hydrographic measurements obtained from Expendable CTD (XCTD) probes deployed along a coastal Antarctic transect between Prydz Bay and India Bay during austral summer of 2013. The thermal structure indicated two upwelling zones: one centered at 38°E and another at 60°E; these entrain Circumpolar Deep Water (CDW) to shallow depths. The two bays are influenced by cyclonic circulation adjacent to the Amery Ice Shelf and in the Weddell Sea. The former promotes a cold front at 70°E which extends to deeper depths, while the latter promotes a cold front at 40°E in the upper 400 m. We encountered deep mixed layer (> 100 m) in low weak wind speed condition. The temperature and salinity profiles capture signatures of super cooled water in the Prydz Bay between 90-164 m and Antarctic Bottom Water at deeper depths (> 900m). CDW is the voluminous water mass detected in the study area. The research work, which is first of its kind pertaining to the coastal Antarctic sector by deploying XCTDs, will serve as benchmark for planning a detail survey in this region using a dedicated research vessel for deeper penetration of hydrographic recording instruments for a broader and 3-dimensional picture of the circulation and water mass transformation.

Keywords: XCTD Observations; Water Masses; Thermohaline Structure; Mixed Layer Depth; Coastal Antarctica

Introduction

The Southern Ocean (SO) has a profound influence on the world's ocean and the global climate system (Deacon, 1937). It connects global oceans and acts as a major conduit for ocean circulation (Rintoul *et al.*, 2001; Iudicone *et al.*, 2008). The Antarctic Bottom Water (AABW), which is one of the most important water masses of the global ocean, is formed at a few regions of the Antarctic shelf. AABW descends the shelf and flows northward, together with the Antarctic Intermediate Water and the Lower Circumpolar Deep Water, both of which are generated within the SO. They constitute the counter-clockwise part of the Meridional Overturning Circulation (MOC) and have significant effects on the ventilation and heat transport at abyssal and intermediate depths of the world's oceans. The southward flux of the MOC is driven by the North Atlantic Deep Water (NADW).

The dense AABW, which refers to several varieties of bottom waters produced and exported around the Antarctic continental margins, is generated around some areas of the Antarctic shelf (Orsi *et al.*, 1999; Gordon *et al.*, 2004). The different varieties of bottom waters are the Weddell Sea Bottom Water formed in the Weddell Sea, the Ross Sea Bottom Water formed in the western Ross Sea, and the Adélie Bottom Water formed along the Adélie coast of Wilkes Land (Orsi *et al.*, 1999, 2002). AABW formation is rather complicated as it involves poorly understood shelf processes and mixing of different water masses (Gill, 1973; Foster and Carmack, 1976). During austral winter, sea ice is formed within the Antarctic coastal polynyas due to convection facilitated by cold and strong offshore winds (Arrigo and Van Dijken, 2003), leaving behind high salinity dense water (brine). The brine sinks, driving deep convection bringing water with high nutrients and CO₂ to the surface (Arrigo *et al.*, 2008). Finally, on

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Antarctic shelf, the Circumpolar Deep Water (CDW) mixes with younger waters of local origin, producing ventilated water which is known as Modified Circumpolar Deep Water (mCDW; Withworth *et al.*, 1998). It is injected into mid-depths and contributes to the formation of the different types of AABW. Sea ice formation within the Antarctic shelf converts local upper waters like the Antarctic Surface Water (AASW) or the shoaling mCDW into the densest Shelf Water (SW) (Whitworth *et al.*, 1998). The SW is divided into Low Salinity Shelf Water (LSSW), and High Salinity Shelf Water (HSSW), which are discriminated by salinity of 34.6 psu (Smith *et al.*, 1984). The HSSW is recognized by its core salinity of ~ 34.8 (Orsi *et al.*, 2002).

The region between the eastern limb of the Weddell Sea and western edge of the Prydz Bay (black contour labeled by letter 'A' in Fig 1) is the focus of this study because of the following reasons: (i) this region is the site of an important confluence between the region west of Weddell-Enderby Land, Kerguelen Plateau to the north and the Australian-Antarctic Basin to the east. As a consequence, the resulting signature of water masses, circulation and biogeochemistry of this area is significantly influenced by this confluence. (ii) The Prydz Bay has been widely suggested as a region for AABW formation (Jacobs and Georgi, 1977; Orsi *et al.*, 1999; Yabuki *et al.*, 2006), thereby meriting a investigation of hydrographic features and the role of adjacent cyclonic circulation in the Weddell Sea and circulation adjacent to the Amery Ice Shelf on vertical thermohaline structure. The oceanographic features are cursory in the region from 10° to 77° E, so we address the water masses distribution and thermohaline structure during the austral summer period of 2013. The hydrographic data was collected using expendable CTD (XCTD) probes deployed during the Indian Scientific Expedition to Antarctica. Though the results are preliminary in nature, they help to gain insight into the oceanographic features of the study area, as well as in facilitating the development of sampling strategy using a dedicated oceanographic vessel in the near future.

Oceanographic Features of the Study Area

The study area extends from 9.55° E to 76° E, from India Bay, the berthing site which is about 100 km north of the Indian Research base Maitri to Prydz

Bay (the region marked by letter 'A' in Fig. 1). The region lies inside the Weddell-Enderby basin, with the Kerguelen Plateau to the north-east and the shallowest point of the Princess Elizabeth Trough (PET) to the east of Prydz Bay. The survey area can broadly be divided into two regimes: the region west of 50° E, which is dominated by the eastward extension of the Weddell Gyre (Gordon, 1998; Park *et al.*, 2001), while to the east of 50° E, the Antarctic Circumpolar Current (ACC) and its southern fronts, comprising southern ACC front (sACCF) and Southern Boundary (SB) (Orsi *et al.*, 1995), influence the region from the north. The fronts are forced southward by the Kerguelen Plateau, and flow eastward through the PET. The Amery Ice shelf is also an important feature, feeding shelf and ice-shelf water into the study region.

Two important features that are identified at the margin of Antarctica are the Antarctic Slope Front

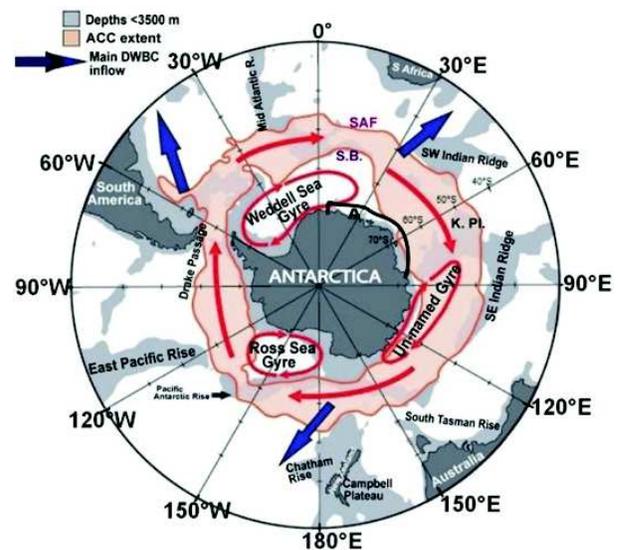


Fig. 1: The main oceanographic elements of the Southern Ocean including: (i) the ACC contained by the Subantarctic Front (SAF) and southern limit of southern boundary (SB) or Upper Circumpolar Deep Water; (ii) the Ross, Weddell and unnamed subpolar gyres; and (iii) the main exit points of deep western boundary currents from the Southern Ocean (deep blue arrows). The general path for the ACC is from Orsi *et al.* (1995) with modifications based on Heath (1985) and Morris *et al.* (2001). The coverage of the XCTD sampling area lies within the black contour indicated by letter 'A'. Bathymetric elevations are Annotated as R - ridge; and K. Pl. - Kerguelen Plateau. The base chart is modified from Orsi and Whitworth (2005)

(ASF) and the Antarctic Coastal Current (ACoC). The ASF defines the boundary between cold, relatively fresh waters encountered at the Antarctic continental shelf and the warmer, more saline waters farther offshore, which are found below the near-surface layer (Jacobs, 1991). It is associated with a westward transport around Antarctica, which is considered to be a consequence of the prevailing westward winds near the Antarctic continent, which induce an Ekman transport of cold, relatively fresh surface water toward the continent, thereby setting up a geostrophic westward flow around Antarctica (Deacon, 1937; Sverdrup, 1953). This flow is constrained to the continental slope depths of 500–1000 m on the eastern side of the Antarctic Peninsula (Muench and Gordon, 1995). The ACoC is a fast, shallow flow over the continental shelf, which is often associated with the front of the ice shelf (Jacobs, 1991). The transport of the ACoC, and that associated with the ASF, is important for the advection of nutrients and krill, for preconditioning the shelf waters for the formation of AABW through their associated heat and freshwater fluxes, and for supplying waters beneath ice shelves, thus melting the underside of the ice shelf (Heywood *et al.*, 2004).

In the Indian Ocean sector, negative wind stress curl associated with the Antarctic Divergence promotes cyclonic oceanic sub-structure. Zeverev (1963) reported the presence of a series of cyclonic gyres between 20° and 100°E, while Smith *et al.* (1984) showed that the subsurface cyclonic eddies of 500 km diameter were located at 67° and 80°E, along 65°S. Other researchers reported the presence of cyclonic eddies at 67°, 100°, and 115°E, and the zonal diameter of the eddies was estimated to be about 500 km (Wakatsuchi *et al.*, 1994). In the present study area, the Antarctic Divergence is located relatively close to the continent and some stations are placed hundreds of kilometers away from the coast, and so the topographic features of the continental shelf and slope could influence the water mass properties (Wakatsuchi *et al.*, 1994).

Data Processing

The XCTD deployments were carried out from 19th–25th February, 2013 (Fig. 2), from the Indian Antarctic Expedition vessel M V Ivan Papanin plying between Prydz Bay and India Bay. The hydrographic stations

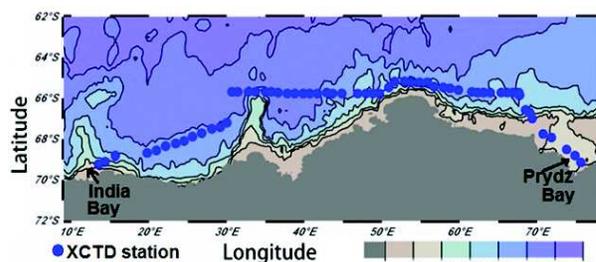


Fig. 2: The XCTD sampling locations during 19th–25th February, 2013. The bathymetry is shown in the background

were spaced 30–32 nautical miles apart. The XCTD probes (make: Tsurumi Seiki Company Limited, Japan; type: XCTD-3; terminal depth: 1000 m; temperature/salinity accuracy: ± 0.02 °C/ ± 0.03 mS cm⁻¹) were deployed at every degree longitude to record temperature and salinity in the upper 1 km of the ocean. A comparison of the XCTD-3 data and Sea Bird CTD profiles reveal that the former is consistent with temperature and salinity accuracy specified by the manufacturer (Mizuno and Watanabe, 1998), and that the fall rate for the XCTD probes show no systematic bias in the fall equation provided by the manufacturer (Kizu *et al.*, 2008). The temperature profiles were quality-controlled by following the standard procedures (Bailey *et al.*, 1993; Uchida *et al.*, 2011). High frequency noise in the salinity profiles was minimized by using a median filter with a 15-m (Xiaojun *et al.*, 2004). We also used ECMWF interim daily for quantifying the net heat flux at surface and surface wind speed (Berrisford *et al.*, 2011)

Results

Criteria used in this study to identify the water masses in the coastal Antarctic domain are listed in Table 1. The most important of these are Antarctic Surface water (AASW), Circumpolar Deep Water (CDW) and AABW. The Winter Water (WW) is one of the components of Antarctic Surface Water (AASW), the other being Summer Surface Water (SSW). WW, which forms a temperature minimum layer below the SSW, is characterized by temperature of -1.87 °C and salinity of 34.34. It is a remnant of the surface water formed by winter convection (Wong *et al.*, 1998), which spreads northwards by winds away from the continent. SSW has a temperature <4 °C and the salinity range of 33.5 to 34 psu. These water masses

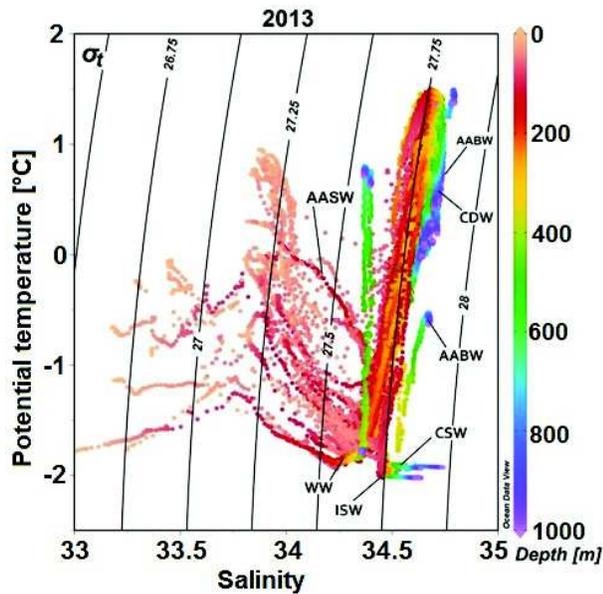


Fig. 3. θ - S diagram prepared using the XCTD data collected during period 19th-25th February, 2013

are representative of freezing and melting in the study area. Winter mixed layer are usually remnant of the previous winters. WW is usually under-saturated due to non-conservative processes of organic matter in surface layer and entrainment of warm CDW water into mixed layer during winter when sea ice cover mitigates the wind effect.

Below WW, the Continental Shelf Water (CSW) (θ : -1.85°C and salinity: 34.56 psu) was detected in the Prydz Bay. CSW is relatively salty and denser than the surface waters and is found in the subsurface region. Mixing over the shelf occurs throughout the water column unlike in the open sea. Convection supports sea ice formation and brine rejection leading to the genesis of these cold saline waters. The voluminous water mass in the study area is CDW (θ : 0.61°C and salinity: 34.68 psu). It is involved in the formation of all other water masses through vertical and lateral mixing induced by polar easterlies at the Antarctic slope and shelf regions (Whitworth *et al.*, 1998). This high saline warm water is driven from the sub-Antarctic region to the Antarctic region, where it keeps the region ice free during winter.

The CDW was detected below 75 m, between 32° and 42°E , and at a deeper depth (> 180 m) between 58° and 68°E (Fig. 4). Our profiles captured traces of AABW at deeper depths ($>900\text{m}$), which is

probably due to truncation of the profiles at 1000 m. Previous time series study carried out using portable CTD data during 24-27 February, 2006 could not detect either CDW or AABW in this region (Anilkumar *et al.*, 2010). Supercooled water having temperature and salinity ranges of -2.14 to -1.96°C and 34.39 to 34.46, respectively, have been detected in the region north of the Amery Ice Shelf (Shi *et al.*, 2011). These are caused by melting beneath the sea ice where the freezing point is very low due to high pressure (Shi *et al.*, 2010). From Fig. 4 the signatures of the supercooled water was found in the Prydz Bay at 70.9°E , between 90-167 m, at 71.8°E , between 99-139 m, and at 73.7°E , between 123-164 m.

In the Prydz Bay, up-sloping of isohalines and presence of low temperature ($<0^{\circ}\text{C}$) densest water >27.7 σ_t at surface are detected (Fig. 4). The melt water is contributed by the Amery Ice Shelf and three glaciers located nearby the Larsemann Hills, viz. Fisher ($\sim 75^{\circ}\text{S}$, 65°E), Lambert ($\sim 73^{\circ}\text{S}$, 70°E) and Polar Record glaciers ($\sim 70^{\circ}\text{S}$, 73°E) (Anilkumar *et al.*, 2010). The fresh water which is marked by low salinity (<34) in the upper 30 m pushes the high salinity dense water below 50 m (Fig. 4). The winter time observations of Middleton and Humphries (1989) indicate that the Prydz Bay shelf is occupied by water of salinity slightly higher than 34.6 psu, the minimum salinity required for the formation of AABW. Our section provides an evidence for shelf water descending down the continental slope to deeper depth (Fig. 4).

The mixed layer depth (MLD) varies from 20 m at 15.6°E to 122 m at 50°E . The deepening of the MLD is found to be unrelated to the surface wind speed or net heat flux. The deeper MLD on the eastern side of the transect can be attributed to large influx of fresh water from adjacent Amery Ice Shelf and glaciers, which forms a thick layer at the surface. On the other hand, intrusion of cold and fresh water from the Weddell Sea is evident in the temperature and salinity structure on the western side of the transect. The wedge structure in the temperature isotherms up to 40°E , where it forms a strong thermal front, is interrupted by the upwelling CDW; it is a clear indication of the confluence of Weddell Sea circulation with the study area. Likewise, three stations in the Prydz Bay capture a front at 70°E ,

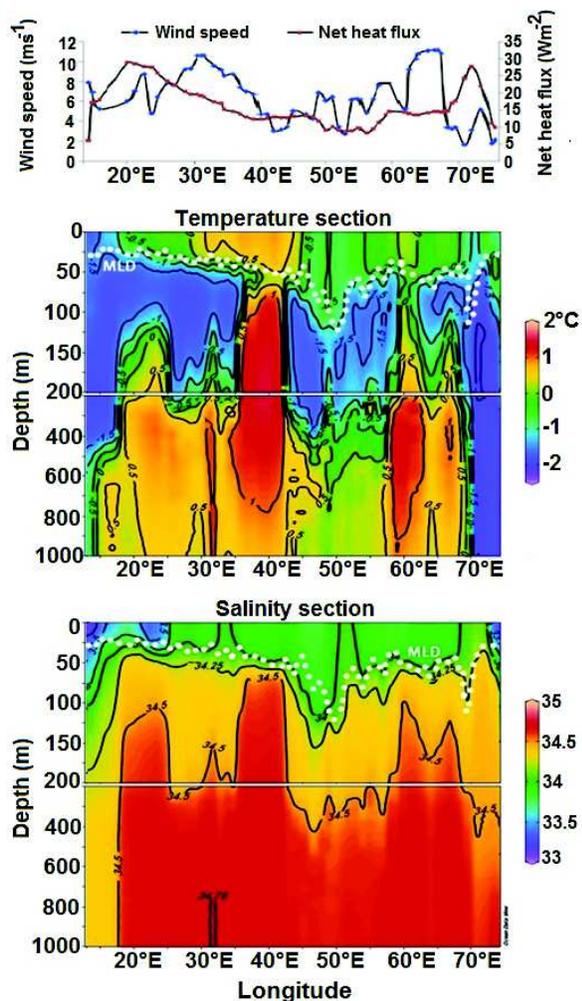


Fig. 4: Vertical temperature and salinity structures prepared from XCTD observations recorded during 19th-25th February, 2013. Mixed layer depth (represented by white dots) has been calculated as the depth where density change of 0.03 kgm^{-3} is encountered from surface value (Dong *et al.*, 2008). Surface meteorological parameters were derived from ECMWF interim forecast (Berrisford *et al.*, 2011)

which is formed due the influence of the cyclonic circulation adjacent Amery Ice Shelf.

The thermal structure indicates two upwelling zones; one centered on 38°E and the other at 60°E , which carries CDW to lower depths. India Bay and Prydz Bay experience strong downwelling whose signature is evident up to 1000 m. These characteristic features of the two domains are influenced by Weddell Sea gyre and cyclonic gyre adjacent to the Amery Ice Shelf. We note that satellite chlorophyll-a images indicate high chlorophyll-a bloom in austral summer in the Prydz Bay promoted by strong stratification

Table 1: Criteria for identification of the principal water masses (after Smith and Tréguer, 1994)

Water mass	θ ($^\circ\text{C}$)	S
WW	-1.87	34.34
CDW	0.61	34.68
CSW	-1.85	34.56
Ice Shelf Water (ISW)	-2.00	34.50
AABW	-0.51	34.66
AASW	-1 to 1	34-34.6

resulting from melt water discharged from the Amery Ice Shelf, supplemented by net heat influx ($\sim 30 \text{ Wm}^{-2}$) into the ocean (Fig. 4).

Conclusions

In this preliminary study, the results pertaining to water masses and their distribution along a coastal section between Prydz Bay and the India Bay occupied during the austral summer of 2013 are discussed. A data set consisting of temperature and salinity profiles recorded by deploying XCTD has been used to highlight the principal water masses and the vertical thermohaline structure in the study area, and to elucidate the role of the Weddell Sea and cyclonic gyre adjacent to the Amery Ice Shelf and the possible role of surface meteorological parameters on the evolution of the vertical thermohaline structure. The data indicates that the Weddell Sea circulation promote a front at 40°E in the upper 400 m, while influence of the cyclonic gyre adjacent to the Amery Ice Shelf promotes a front at 70°E which extends down to deeper depths. Deep mixed layer ($> 100 \text{ m}$) are encountered in conditions of weak wind speed. Signature of super cooled water was found in the Prydz Bay between 90-164 m. The profiles capture signatures of AABW at deeper depths ($> 900 \text{ m}$). CDW is the voluminous water mass that is detected in the study area.

Acknowledgements

The Ministry of Earth Sciences (MoES), Government of India, financed the XCTD probes deployed during the 32nd Indian Scientific Expedition to Antarctica. We are grateful to Dr. Shailesh Nayak, former Secretary, MoES, for his support and encouragement to pursue this study. Former NCAOR Directors, Shri Rasik Ravindra and Dr. S. Rajan are acknowledged for making the facilities available for the research.

We thank Shri. Mirza J. Beg, Project Director (Logistics), for extending the requisite logistics support for making the observations during the expedition. We thank two anonymous reviewers for their constructive comments on the earlier draft of this manuscript. This is NCAOR contribution 43/2016.

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