Signature of coastal upwelling in Prydz Bay, East Antarctica during austral summer 2006

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This study discusses the upwelling observed in Prydz Bay, coastal waters of East Antarctica. In February 2006, as a part of expedition to Larsemann Hills (East Antarctica) three hourly conductivity, temperature, depth (CTD) observations were carried out for three consecutive days in Prydz Bay coastal waters. This helped to understand temporal variability of hydrographic parameters in this region. An upward movement of subsurface waters was identified at around 13:30 h on 24 and 08:00 h on 26 February 2006. *In situ* micro algal concentration indicated maximum chlorophyll, diatom and green algal concentration at 13:03 h on 24 February. This study suggests that major cause for upward movement of water in the Prydz Bay area could be the influence of local wind forcing. XBT observations made outside the Prydz Bay showed temperature variations from –1.7°C to 0.4°C between 50 and 150 m. At 64°S 70°E in the north–south transect, a temperature minimum of ~ –1.68°C was observed at 97 m. This could probably be due to remnants of the previous winter water. Circum polar deep water was identified outside the Prydz Bay area whereas features of high salinity shelf water were identified inside the Bay.

Keywords: Austral summer, coastal upwelling, East Antarctica, melt water, Prydz Bay, water mass, winter water.

Introduction

COASTAL waters of Antarctic continent along the periphery of Southern Ocean play a crucial role in climatic change, especially that related to ocean–ice system response to global warming, carbon sequestration due to bottom-water formation and biological productivity[1]. The Antarctic coastal zone shares some similarities with other coastal zones, but is unique as sea-ice extends hundreds of kilometres from land in winter and melts back close to the shore in summer; thus the location of the coast changes significantly annually. Sea-ice covers ~ 22 million km^2 in winter and only ~ 8 million km^2 in summer. Studies on biological, chemical and physical aspects of coastal waters of Antarctica have been carried out by many researchers[2–10].

The Prydz Bay in East Antarctica, a triangular-shaped embayment in the Indian sector of Southern Ocean[11], is characterized by horizontal distributions of glacial meltwater and sea-ice meltwater, with the presence of circumpolar deep water (CDW), suggesting the possibility of strong upwelling in this regime[12]. The upwelling of warm water to the surface is enough to melt existing ice and/or prevent new ice forming, resulting in formation of sensible heat polynyas[13]. The physical processes associated with meltwater have varying impact on the growth of phytoplankton depending on oceanic conditions[14]. In coastal regions of the Southern Ocean, growth of phytoplankton is most likely controlled by upper ocean mixing rates which determine the amount of irradiance available for photosynthesis[15]. Here we study the relation between variations of hydrographic parameters to decipher the signature of coastal upwelling in the Prydz Bay during the austral summer 2006. In addition, the impact of physical processes on phytoplankton abundance was also carried out. All observations were made at a single location (69°19′S 76°E).

Data and analysis

During the expedition to East Antarctica (January–March 2006) onboard *Akademik Boris Petrov*, time series observations were carried out in the Prydz Bay (69°19′S 76°E) by operating portable CTD (make: SBE 9/11 plus, Sea-Bird Electronics, USA; temperature accuracy: ± 0.001°C, conductivity: ± 0.0001 sm^{-1} and depth ± 0.005% of the full scale) at ~ 3 h intervals for three consecutive days. Additional sensors for oxygen and chlorophyll attached with CTD provided data at 1 m depth resolution up to 400 m. Atlas Hydrosweep DS 2 having capability of recording bathymetry was operated with 12.5 kHz frequency. We used the centre beam of the multibeam system for depth observations. Sea surface temperature (SST) was recorded by bucket thermometer (accuracy: ± 0.1°C). A submersible fluorescence probe (Fluoro probe, bbe-Moldaenke, Kiel, Germany) was operated up to 100 m depth for *in situ* measurements of chlorophyll. Seven operations of the Fluoro probe were carried out at different time intervals between 24 and 27 February 2006 (09:19 and 13:03 h on 24, 12:22 and

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18:32 h on 26 and 09:47, 13:20 and 16:22 h on 27 February 2006). For the precision of the Fluoro probe measurements and calibration, see Buetler *et al.*[16].

Outside the Prydz Bay two CTD observations were made at 55°S 62°E and 55°S 50°E. Vertical temperature profiles were observed using XBT probes at 1° intervals (type: T-7; accuracy: ±0.15°C; depth resolution: 0.65 m) along two north–south transects (transect-1: from 59°30′S to 65°S and transect-3: from 54°S to 60°S) and one east-west transect (transect-2: from 71°E to 51°E) (Figure 1). XBT profiles were quality controlled by following the guidelines in the CSIRO Cookbook[17]. It was reported that the fall rate corrections to XBT profiles were marginal in the Southern Ocean[18,19]. Wind data was recorded from sensors fixed onboard and corrected for ship's speed and heading.

Results and discussion

Influence of local wind in the Prydz Bay

At 69°19′S 76°E in the Prydz Bay hydrographic parameters were observed at 3 hourly intervals to understand its periodic variations; in particular we examined the links between the distribution of hydrographic parameters and the local wind. We focused on East Antarctica for several reasons. Relatively little attention has been paid to this region in comparison to the Antarctic Peninsula, the Weddell and Ross Seas. East Antarctic coastal zone differs in several aspects, useful for comparisons with other regions. For example, the East Antarctic coast is largely zonal, and thus dominated by circumpolar circulation rather than large gyres which influence the Weddell and Ross Seas. Further, it lies well south of the milder climate which influences the Antarctic Peninsula.

Based on the time series data temporal variation in the vertical structure of the hydrographic parameters is presented in Figure 2. We identified short lived episodes of upward movement of subsurface waters (Figure 2 *a–d*) at around 13:30 h on 24 and 08:00 h on 26 February 2006. This was not diurnal, as it was not seen on 25 February. The time series observations of wind and SST are shown in Figure 2 *e*. Strong winds and low SST were associated with the subsurface upwelling. The wind directions (from east to southeast) were also favourable for coastal upwelling. Dissolved oxygen (DO) and chlorophyll concentrations are shown in Figure 2 *c* and *d*. The vertical structures of DO and chlorophyll also support the upwelling as reflected in the isolines of temperature and salinity. Surface chlorophyll concentration in the coastal waters of Antarctica (southward of the Antarctic Polar Front) is high during austral summer[20]. Chlorophyll concentration in the Prydz Bay during mid summer was reported[21] to be

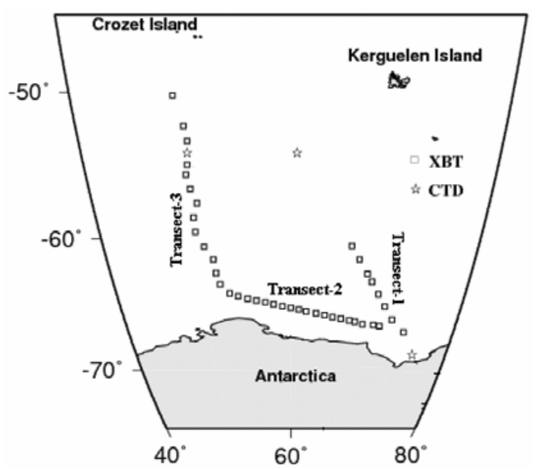

Figure 1. Station locations.

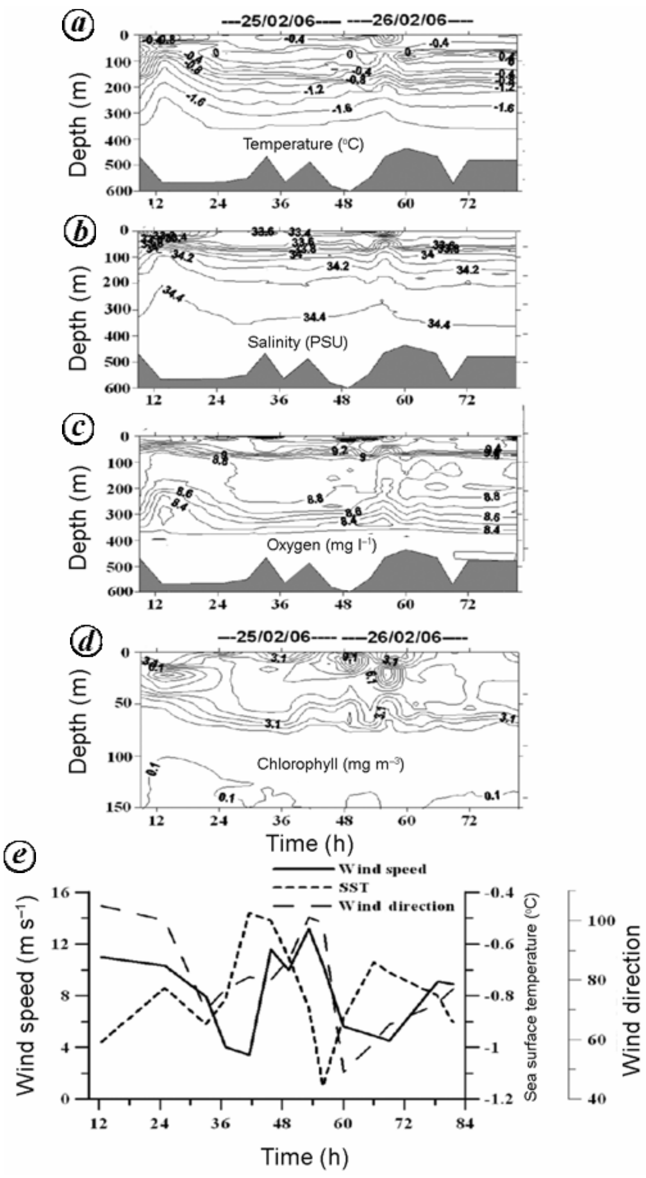

Figure 2. Vertical structure of (***a***) temperature; (***b***) salinity; (***c***) oxygen; (***d***) chlorophyll and (***e***) wind speed and SST.

> 15 mg m^{-3}. The present study was carried out during the transition period from summer to winter. The two peaks (~ 10 mg m^{-3}) for chlorophyll during 13:30 h on 24 and 08:00 h on 26 (between surface and 20 m depth) exhibited a similar trend of the periodic changes observed in other hydrographic parameters. By operating Fluoro probe, maximum chlorophyll, diatoms and green algal concentrations were observed at 13:03 h on 24 February (Figure 3 *a–c*) which matches the CTD observation. The present results perhaps suggest local wind forcing could be a probable cause for the upward movement of water in the Prydz Bay.

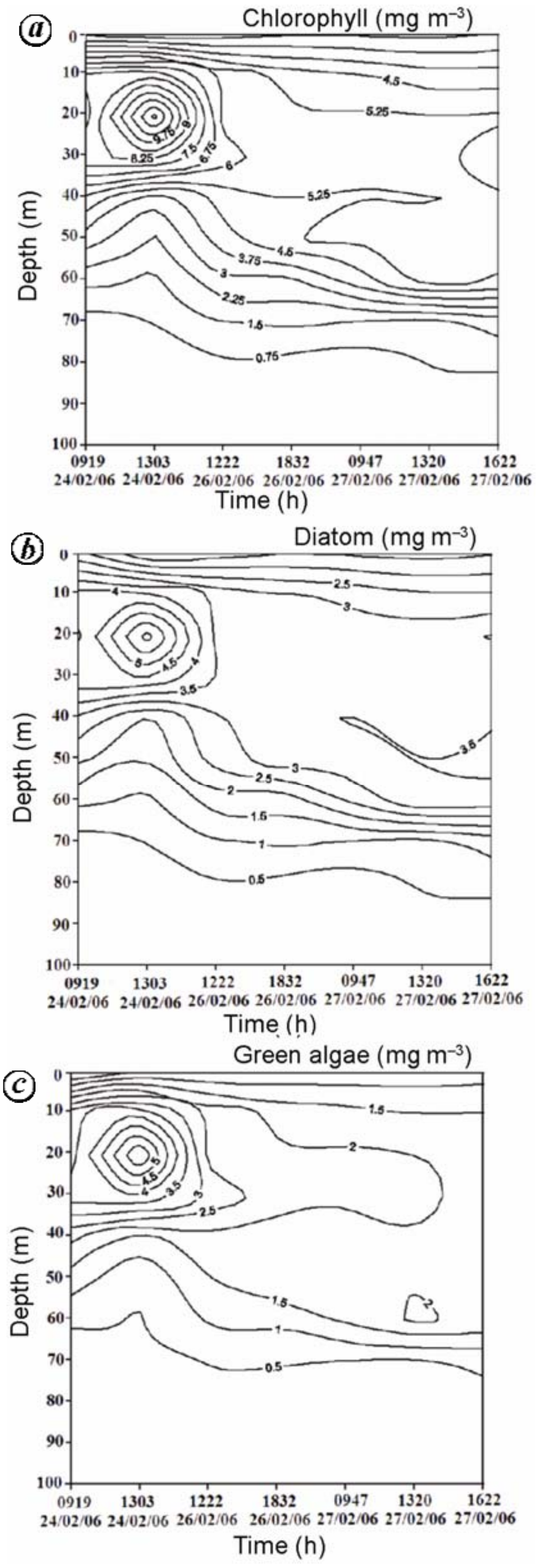

Figure 3. Concentration of (***a***) chlorophyll; (***b***) diatoms; (***c***) green algae in Prydz Bay up to 100 m depth (measured using Fluoro probe).

Freshwater influence

The vertical profiles of temperature and salinity in and out of the Prydz Bay are shown in Figure 4. Two CTD observations were taken at station far from the Prydz Bay and one station inside, near the coastal waters of East Antarctica. Outside the Prydz Bay, a strong mixed layer up to 100 m was noticed. Below this a winter water (WW) of low temperature was identified (discussed in detail below). Upper cold low saline water noticed in the Prydz Bay is attributed to the influence of Amery Ice

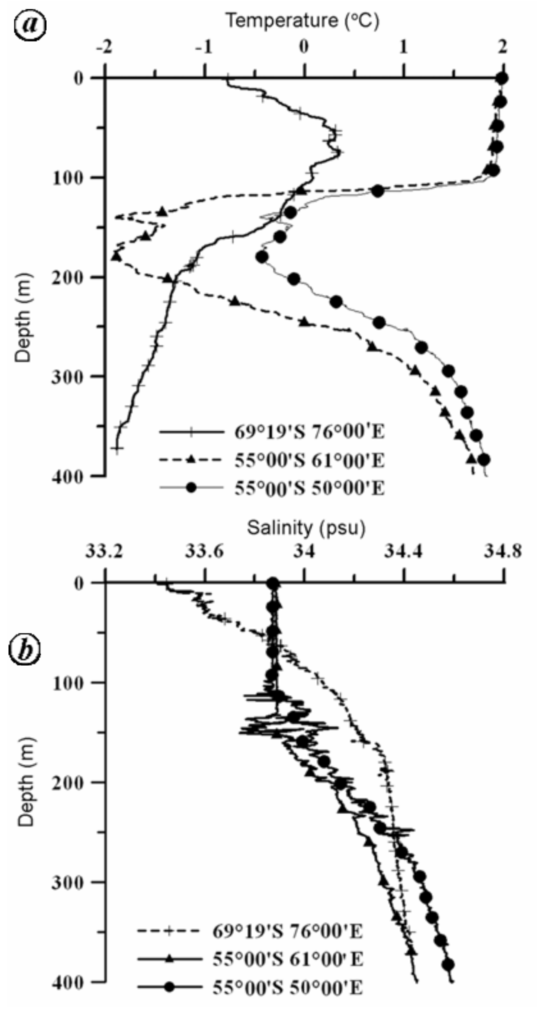

Figure 4. Vertical profile of (***a***) temperature and (***b***) salinity.

Shelf and three glaciers located nearby the Larsemann Hills, viz. Fisher (~ 75°S 65°E), Lambert (~ 73°S 70°E) and Polar Record glaciers (~ 70°S 73°E).

Water masses in Prydz Bay

Diurnal variations are strong near the shelf edge and are associated with substantial encroachment of (modified) CDW over the shelf break[22]. CDW core within the Antarctic circumpolar current (ACC) shows a clear transitional band around Antarctica, and south of this band characteristics signal of the upper CDW is no longer discernible[23]. However, no features of CDW were found in the Prydz Bay in the present study whereas its presence was noticed outside the Prydz Bay at 55°S 50°E and 55°S 62°E (Figure 5). Antarctic bottom water (AABW) observed near the foot of the continental slope at 62°E in 1974, had its origin in the Prydz Bay[22]. However this water mass was not identified in the present study. There are shelf waters (SWs), close to the freezing temperature, T_f (where $T_f = -1.89$°C at $S = 34.4$ psu), but of varying salinity, divided into low salinity shelf water (LSSW), and high salinity shelf water (HSSW), usually separated at a salinity of 34.6 psu[24]. Smith and Treguer[25] drew the boundary between these two types at salinity of 34.5 psu. In this study HSSW was observed at around 270 m depth in the Prydz Bay.

Winter water properties

The WW depth is defined as the depth where the absolute minimum in temperature is observed. The vertical variation of temperature displayed interesting features in this region. The XBT observations made outside the Prydz Bay showed a temperature variation from – 1.7°C to 0.4°C between 50 and 150 m (Figure 6 *a*–*c*). In transect-1 at 64°S 70°E, a temperature minimum (~ – 1.68°C) was observed at 97 m (Figure 6 *a*). Maximum depth of temperature minimum layer (~ 200 m) across transect-2 was seen at 66°S 71°E (Figure 6 *b*), whereas along 50°E (transect-3) temperature minimum was at ~ 100 m (Figure 6 *c*). This subsurface cold layer is attributed to WW, which is the residue of previous winter mixed layer, capped by seasonal warming and freshening[26]. Below this layer, temperature increased gradually to ~ 1.9°C.

The temperature structure up to 760 m along transect-2 exhibited cold waters in the eastern side. A gradual decrease in temperature can be observed from west to east along this transect. A decrease in temperature of ~ 0.6°C at surface, ~ 3°C at 200 m depth and ~ 0.6°C at 500 m from 64°S 53°E to 66°S 71′E was noticed (Figure 6 *b* and 7). At the western side of the transect-2 distance between station location (64°S 53°E) and coast (65°56′S 53°E) is 116 nm, whereas at the eastern side the distance between station location (66°S 71°E) and coast (68°30′S 70°E) is 150 nm. However cold water was observed at 66°S 71°E and warm water at 64°S 53°E, even though 64°S 53°E is closer to the coastline (Figure 1). But previously

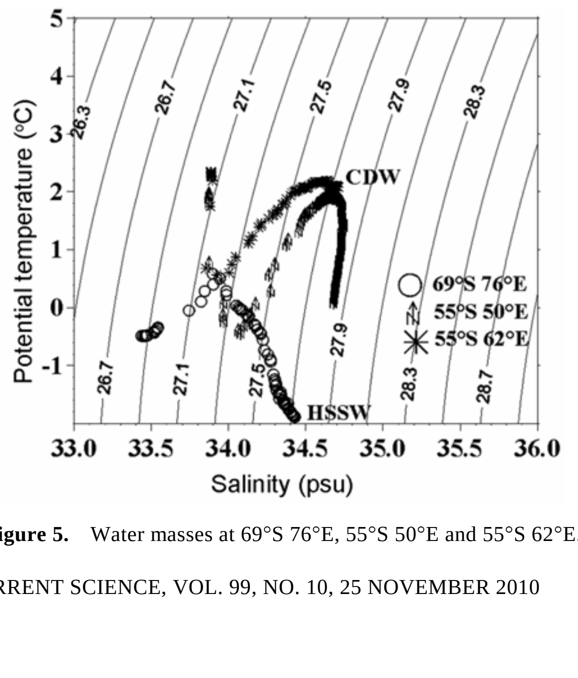

Figure 5. Water masses at 69°S 76°E, 55°S 50°E and 55°S 62°E.

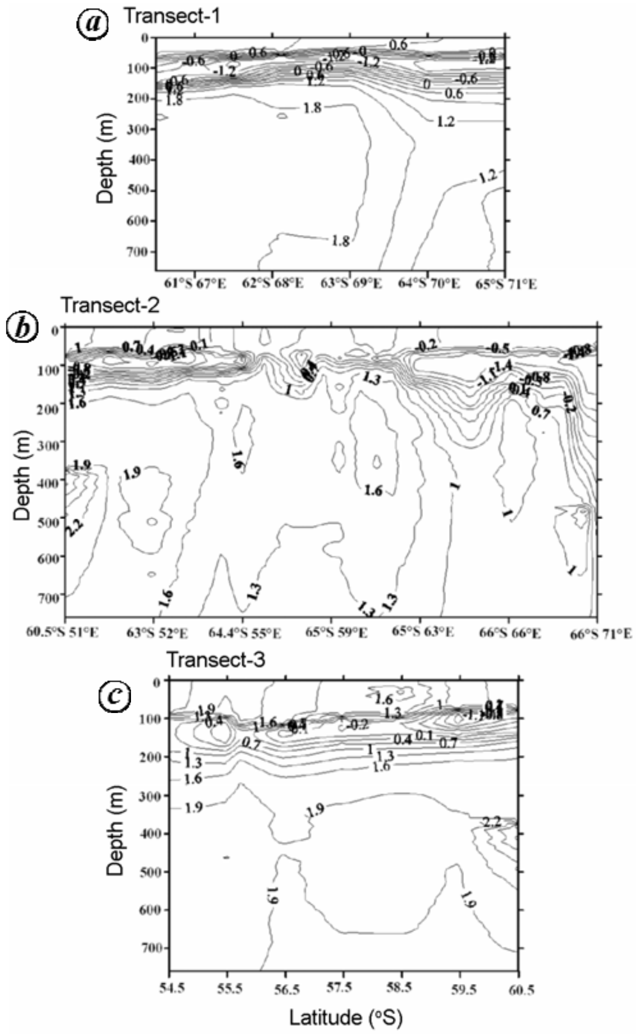

Figure 6. Thermal structures from XBT data: (***a***) 61°S 67°E to 65°S 71°E; (***b***) 60.5°S 51°E to 66°S 71°E; (***c***) 54.5°S to 60.5°S along 50°E.

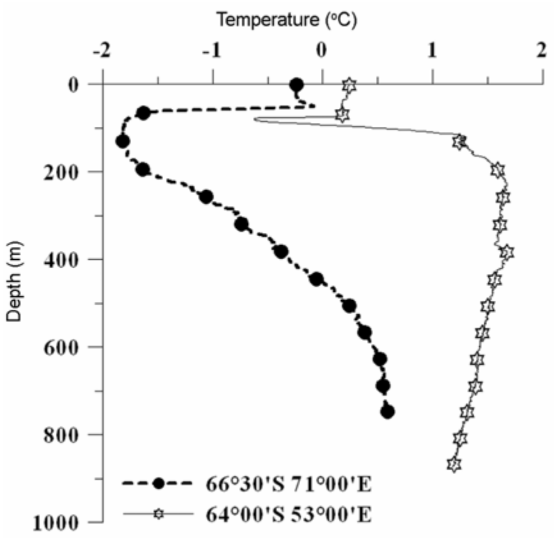

Figure 7. Vertical profile of temperature at 66°S 71′E and 64°S 53°E.

no temperature variation was reported (see figure 8 in ref. 26) up to 70 m depth between these locations. However the result obtained in the present study (drop in temperature towards the east) could be due to the cold water influence from the nearby glaciers.

Conclusions

Time series observations in the Prydz Bay coastal waters showed an upward movement of subsurface waters at around 13:30 h on 24 and 08:00 h on 26 February 2006. Strong episodic winds were favourable for coastal upwelling, supported by wind direction, dissolved oxygen and chlorophyll concentrations. In the Prydz Bay, cold low saline waters in the upper 50 m and warm saline waters from 50 to 100 m was noticed. HSSW was identified in the Prydz Bay, but features of CDW were identified outside the Bay. Between 50 and 150 m water depths a temperature minimum of ~– 1.68°C was observed at 97 m at 64°S 70°E probably due to WW. The cold water observed at 66°S 71°E, the eastern part of transect-2, could be originated from near by glaciers.

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