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Supercooled water in austral summer in Prydz Bay, Antarctica*

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Abstract Supercooled water with temperatures below freezing point, was identified from hydrographic data obtained by Chinese and Australian expeditions to Prydz Bay, Antarctica, during the austral summer. The study shows that most supercooled waters occurred at depths of 63–271 m in the region north of the Amery Ice Shelf (AIS) front. The maximum supercooling was 0.16°C below the in-situ freezing point. In temperature and salinity ranges of -2.14 – -1.96°C and 34.39–34.46, respectively, the water was colder and fresher than peripheral shelf water. The supercooled water had less variability in the vertical profiles compared to shelf water. Based on analysis of their thermohaline features and spatial distribution, as well as the circulation pattern in Prydz Bay, we conclude that these supercooled waters originated from a cavity beneath the AIS and resulted from upwelling just outside of the AIS front. Water emerging from the ice shelf cools to an extremely low temperature (about -2.0°C) by additional cooling from the ice shelf, and becomes buoyant with the addition of melt water from the ice shelf base. When this water flows out of the ice shelf front, its upper boundary is removed, and thus it rises abruptly. Once the temperature of this water reaches below the freezing point, supercooling takes place. In summer, the seasonal pycnocline at ~100 m water depth acts as a barrier to upwelling and supercooling. The upwelling of ice shelf outflow water illuminates a unique mid-depth convection of the polar ocean.

Keyword: supercooled water; convection; ice shelf; Prydz Bay; Antarctica

1 INTRODUCTION

The temperature of seawater usually is above its freezing point. However, water with temperatures below the in-situ freezing point has been observed in polar oceans (e.g. Untersteiner et al., 1964). This water has been called supercooled water (SCW). The existence of in-situ supercooling has been questioned because its measured supercooling of ~0.01°C is almost the same as the accuracy of the instruments used to measure its temperature (Lewis et al., 1971). Some previous supercooling temperature measurements are confounded by methodological problems (Countryman, 1970). Recent in-situ supercooling temperature data collected with advanced instruments of high accuracy (e.g. Lewis et al., 1983; Skogseth et al., 2009) and laboratory experiments (Smedsrud, 2001) have clearly demonstrated the existence of supercooled water.

Supercooled waters have been reported both in the Arctic Ocean and the Southern Ocean. In the Arctic Ocean, supercooled waters have been found mostly in winter and near the surface of openings (i.e. polynyas and leads). With exceedingly large heat losses to the atmosphere, the water in polynyas may be cooled to ~0.01°C below the surface freezing point (Drucker et al., 2003; Skogseth et al., 2009). Another type of supercooling was found in a series of observations on a floating ice island in the Canada Basin in the 1960s (Untersteiner et al., 1964). This supercooled water was caused by the variation of freezing point with pressure (Foldvik et al., 1974). Melting may occur at the keel of ice

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islands where the freezing point is very low due to high pressure. Thus, the corresponding upwelling of melting water may become supercooled at shallower depths where the freezing point is higher. Additional ice at the bottom of ice islands and in the surrounding water may form as a result of frazil in supercooled waters. This process has been named ‘ice pump’ by Lewis et al. (1986). The process is a self-started heat engine driven by change in the freezing point with pressure. Most supercooled waters found in the Southern Ocean are related to the ice pump under ice shelves (Foldvik et al., 1974). In addition, part of Antarctic coast is occupied by ice shelves that float at the sea surface and form cavities filled with seawater beneath them. The depth difference between the grounding line and the front of the ice shelf is usually thousands of meters, which drives a very efficient ice pump under the ice shelf. Most reports of supercooled water are related to the two largest ice shelves in Antarctica, the Filchner-Ronne Ice Shelf in the Weddell Sea and the Ross Ice Shelf in the Ross Sea. Because of difficulties in observing the ocean under ice shelves, most previous studies have focused on the ocean in front of the ice shelves (i.e. in the downstream region of the outflow from the cavities under ice shelves) (Countryman, 1970; Leonard et al., 2006). Recently, supercooled water beneath the Ross Ice Shelf was identified from data recorded with a CTD in a drilled hole through the ice shelf (Nicholls et al., 2004). It should be noted that the supercooled water reported by previous researchers (e.g. Countryman, 1970) were analyzed before the modified formula for freezing point was developed by Millero (1978), and may not have been accurately reported. In fact, only few studies of supercooling in the Southern Ocean have used the new freezing point formula and modern sampling instruments.

Supercooled water in the Southern Ocean is related to the melting and freezing of the ice shelves. Water in cavities under the ice shelves could be cooled to temperatures below freezing point at the sea surface. This process produces a unique water mass, Ice Shelf Water (ISW), which is an important component for the formation of Antarctic Bottom Water (Jacobs et al., 1979). The supercooled water is the coldest part of the ISW. Thus, investigation of supercooled water near the ice shelves in Antarctica will helpful to further understanding of the modifications of water masses and interactions between ocean and ice shelves.

Prydz Bay is the third largest embayment in Antarctica. Lambert Glacier, the largest glacier in the world, drains a large portion of the East Antarctic Ice Sheet into Prydz Bay and forms the Amery Ice Shelf (AIS). The AIS is the largest ice shelf in East Antarctica. Although water masses and circulation in Prydz Bay have been studied through analysis of observed data (e.g. Smith et al., 1984; Vaz et al., 1996), and the ice pump under the AIS has been simulated with 2-D and 3-D numerical models (Hellmer et al., 1992; Williams et al., 1998; 2001), the supercooled water in this region has not been discussed in the literature. We found some evidence for supercooled water in our XCTD data obtained in a polynya at the front of the AIS. Then, we confirmed the presence of supercooled water and investigated its features by analyzing all CTD data collected in the region of Prydz Bay by the Chinese National Antarctic Research Expedition (CHINARE) and the Australian Antarctic Research Expedition (ANARE). In this study, we discuss the mechanism and processes for the formation of supercooled water.

2 DATA ANALYSIS

In order to identify supercooled water from observed hydrographic data, we first calculated the in-situ freezing point temperature, T_{f}, with salinity, S, and pressure, P, following the algorithm

$$T_{\mathrm{f}}=(-0.057\,5+1.710523\times10^{-3}\sqrt{S}\ -2.154996\times10^{-4}S)S-7.53\times10^{-4}P \tag{1}$$

given by Millero (1978). Then, we educed the supercooled temperature T_{SC}

$$T_{\mathrm{SC}}=T-T_{\mathrm{f}} \tag{2}$$

where, T is the in-situ temperature. Thus, the water with $T_{\mathrm{SC}}<0$°C was identified as supercooled water and the absolute value of T_{SC} represented the supercooling level. Considering the accuracy of the observed data, we identified supercooled water only when a water layer (at least 10 m thick) with $T_{\mathrm{SC}}<-0.02$°C was found in a hydrographic profile. For the XCTD data, P was calculated from depth, D.

Skogseth et al. (2009) named the potential supercooled water at temperatures below surface freezing point, T_{f0}, and it is possible that this water gains its extremely cold temperature through supercooling at the sea surface. We believe that this definition is at most suitable for the Arctic Ocean. In the Antarctic continental shelves, sea water with $T<T_{f0}$ usually is the ISW. The cold ISW is believed to represent the production of additional cooling in the cavities beneath ice shelves. In these deep cavities, seawater with $T<T_{f0}$ could be in a liquid state, since the local T_f is much lower than the T_{f0} due to the high pressure. Thus, supercooling is not necessarily a precondition for ISW to cool below the surface freezing point.

2.1 XCTD data

From visible images of MODIS (Moderate Resolution Imaging Spectroradiomete), we found a polynya that occurred every year in the west region north to the AIS front. This polynya often lasted until the early austral summer in December. The heavy sea ice surrounding the polynya obstructed research vessels from obtaining observations in the polynya. During the 24th and 25th CHINAREs, we launched XCTD probes into the polynya from a helicopter suspended ~20 m above the sea surface. Comprehensive 4 T-S profiles were acquired during the two expeditions. The information from these observations is listed in Table 1 and the locations are shown in Fig.1.

Table 1 Time and location information of XCTDs launched from helicopters

No	Date and Time	Longitude	Latitude
1	2007-12-11 15:13	72°32.024′E	68°34.079′S
2	2008-12-17 05:40	71°07.015′E	68°40.249′S
3	2008-12-17 05:52	70°58.132′E	68°37.383′S
4	2008-12-17 05:58	70°52.443′E	68°35.354′S

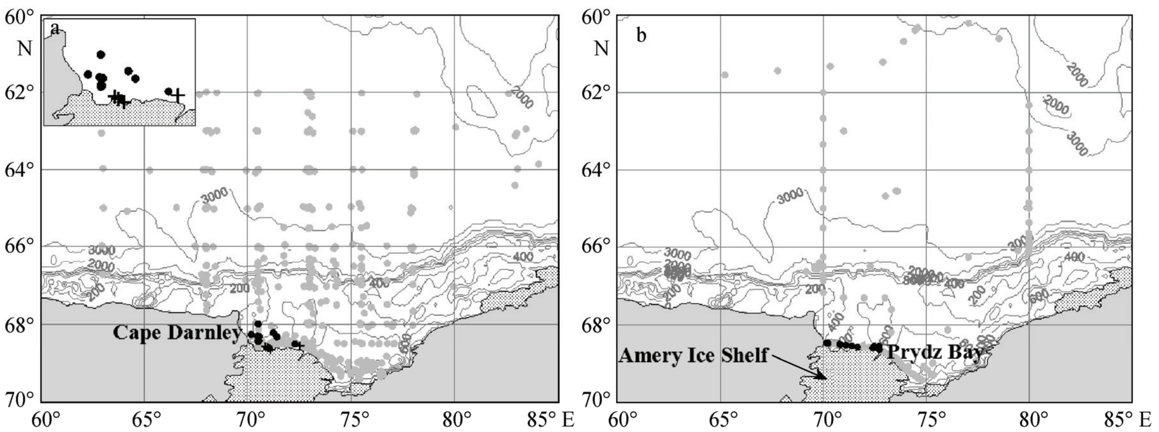

Fig.1 Map of the region near Prydz Bay with isobath curves (gray contours of depth in meters) and CTD stations (grey dots) of CHINARE (a) and ANARE (b)

CTD stations with supercooled water (black dots) and XCTD stations (black crosses) also are shown in the figures and a zoom-in figure embedded on the top-left corner of (a).

The observations in 2007 (No. 1 in Table 1) were conducted in a very small opening in the ice-covered region about 500 m away from the AIS front (denoted by the right cross embedded in Fig.1a). The observed data (red dots in Fig.2) show that temperature at almost all depths was below T_{f0} (shown by gray dots in Fig.1a, d). A vertically homogenous layer with temperatures of -2.08 to -2.09°C and salinities of 34.46 to 34.49 were found at depths of 130–300 m. Due to the homogenous salinity, the T_{f0} (shown by black dots in Fig.2a) decreased almost linearly with increasing depth. Therefore, supercooled water (denoted by large red dots in Fig.2) occurred at and above the upper part of the homogenous layer (i.e. at a depth of 100–230 m). The temperature and salinity of the supercooled water in this profile was -1.99 to -2.09°C and 34.44 to 34.46, respectively. A minimum T_{SC} of -0.09°C occurred at 128 m, which was equivalent to the bottom depth of the AIS front.

The observation locations in 2008 (No. 2–4 in Table 1, shown by 3 gathered crosses in Fig.1a) were in the region of the yearly-occurring polynya, just west of the 2007 observation location. The polynya stayed open when we launched the XCTD probes. All observed data confirmed the typical hydrographic profiles for the ice-covered ocean in early summer. That is, the entire water column was quite cold, but the near surface water was fresher due to the accumulation of water melting from the sea ice. Supercooled water was found during the two observations (No. 2 and 3 in Table 1, denoted by green dots in Fig.2) only at the surface and was not recorded at any depth at station No. 4 (Table 1, denoted by cyan dots in Fig.2). Station No. 4 was the farthest away from the AIS front of the three observations. Supercooled water observed at Station No. 2, the closest one to the AIS front, was only 34 m thick, and had a minimum T_{SC} of -0.04°C at the surface (~5 m, XCTD data within the top 5 m are unreliable due to technique limitations). In Station No. 3, the supercooled water became thicker and all the T_{SC} at D<85 m was below -0.02°C, with a minimum T_{SC} of -0.07°C at 22 m. The vertical T_{SC} profiles at these two stations (Fig.2b) imply that supercooling started at the sea surface and extended downward, which is clearly different from the data observed at Station No. 1.

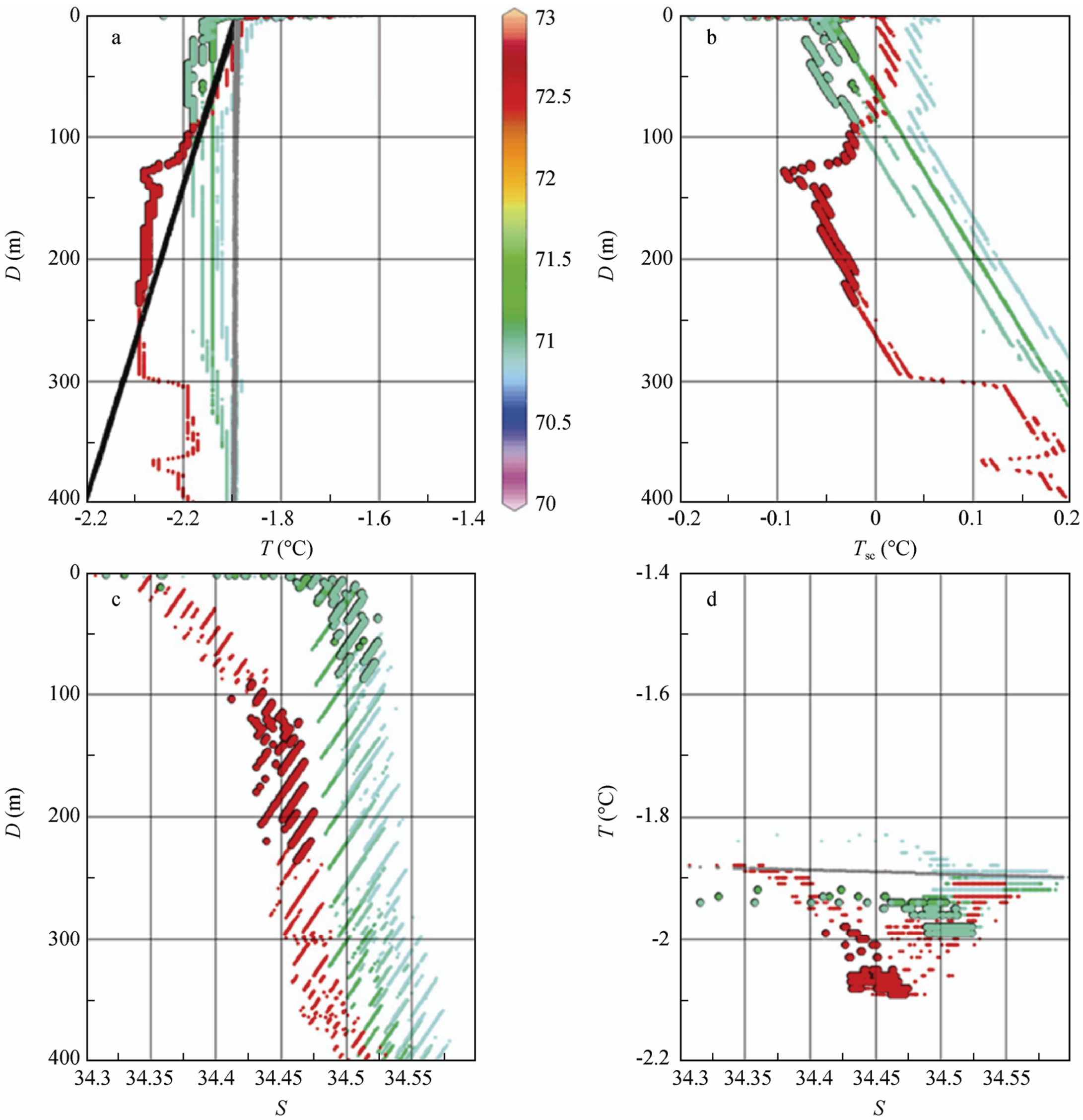

Fig.2 Vertical profiles of *T* (a), T_{SC} (b), and *S* (c), as well as *T-S* diagram (d) of the data observed by XCTDs launched from helicopters in 2007 and 2008

Supercooled waters are shown by larger dots and the other parts by smaller dots, both colored by the longitude of the observation location. The black dots in (a) denote the in-situ freezing points, and the gray dots in (a) and (c) denote the surface freezing points.

The supercooling at the sea surface only occurred as a transient phenomenon prior to ice formation (Lewis et al., 1983), which is common in polynyas in the Arctic Ocean (e.g. Skogseth et al., 2009). However, this phenomenon has never been reported in the Southern Ocean. Poor accuracy of the XCTDs (Table 2), and the circumstances of our special deployment method, introduced uncertainties in our ability to detect supercooling in the XCTD data.

2.2 CTD data

In order to verify the reliability of the presence of supercooled water observed by XCTD, we collected CTD data with better accuracy. These CTD observations were conducted by the CHINARE and ANARE in the region of Prydz Bay.

Table 2 Accuracy of CTDs and XCTDs used in Chinese expeditions

Cruise	Type	Nominal accuracy		
		T (°C)	Conductivity (S/m)	*P* or *D* (%)
13–22	Mark IIIC CTD	0.002	0.000 2	0.15
19 (Sections II and III)	SBE25 CTD	0.005	0.000 5	0.25
24	Alec ASTD687	0.01	0.002	0.3
25	SBE9 CTD	0.001	0.000 3	0.015
24, 25	XCTD-1	0.02	0.003	2

Table 3 Features of supercooled water in CTD data observed by CHINAREs

No	Cruise	Station	Date	Longitude (°E)	Latitude (°S)	Minimum of T_{SC}			
						T_{SC} (°C)	*D* (m)	*T* (°C)	*S*
1	13	I-9	1997-01-22	71.232	68.228	-0.05	114	-2.03	34.45
2	19	IS-8	2003-02-04	72.284	68.518	-0.08	106	-2.04	34.42
3	19	II-12	2003-02-05	70.508	68.000	-0.04	151	-2.04	34.41
4	19	II-13	2003-02-04	70.473	68.313	-0.07	182	-2.09	34.41
5	19	II-14	2003-02-04	70.507	68.450	-0.16	121	-2.14	34.40
6	21	II-13	2005-02-01	70.543	68.434	-0.03	184	-2.06	34.45
7	22	IS-10	2006-01-17	71.417	68.335	-0.03	130	-2.02	34.44
8	22	IS-13	2006-01-17	70.174	68.275	-0.06	78	-2.01	34.45
9	22	IS11A	2006-01-17	71.037	68.618	-0.08	101	-2.05	34.43
10	25	P215	2009-02-17	70.568	68.328	-0.08	110	-2.06	34.43
14	25	P216C	2009-02-16	70.514	68.396	-0.04	172	-2.06	34.44

2.2.1 CTD data of CHINARE

A total of 485 CTD profiles were conducted by CHINARE during 14 cruises (CHINARE 6–9, 13–16, 18, 19, 21, 22, 24 and 25) in the region of Prydz Bay (60°E–85°E, south of 60°S) during the austral summers of 1990–2009 (Fig.1a). The type and accuracy of the CTDs used for each cruise are listed in Table 2.

According to our criteria, we found supercooled waters at 11 stations in the CTD data of CHINARE. The features of these supercooled waters are listed in Table 3 and their locations are denoted with black dots in Fig.1a. It should be noted that there were a total of 6 deployments conducted during one day at Station P216 in the 25th CHINARE, and supercooled water was observed in the last 4 observations. Only the data of one observation with supercooled water were plotted in Fig.3, as a representative sample.

All the stations with observed supercooled water appeared in a small region north of the AIS front (refer to Fig.1a). Most stations were located west of 72°E, except for Station IS-8 that was close to XCTD Station No. 1. The supercooled water at Station IS-8, with a minimum T_{SC} of -0.08°C at depth of 106 m, had similar features to that of XCTD Station No.1, which confirmed the presence of supercooled water found in the XCTD data. Experiencing solar heating and sea ice melting during summer, the surface layer in February (Fig.3a, 3c) became warmer and fresher than that in late spring (Fig.2a, 2c). Conversely, shelf water below the seasonal thermocline (also halocline) was free from the influence of surface forcing.

With the criteria of T_{SC}<-0.02°C and thicker than 10 m, the depth, temperature and salinity ranges of supercooled waters at all 11 stations were 63–224 m, -2.14°C – -1.96°C and 34.39–34.46, respectively (Fig.3). The minimum T_{SC} for all stations was -0.16°C, as observed at Station II-14. This station was very close to the AIS front in February, 2003.

Among nearly 500 profiles, only about 10 profiles have evidence of supercooled water. We do not think this implies that supercooled water is rare in this region, but only rarity of observations in the area close to the AIS front. Since the oceanic section along the AIS front was conducted by CHINARE in 2003, only about 10 stations could be completed at this section in each Chinese cruise thereafter. Unfortunately, some of the stations were quite far from the AIS front due to the heavy sea ice conditions. According to our results, supercooled water was detected from almost all cruises since 2003, and mostly at more than one station, which indicates that supercooled water often occurs in the region close to the western part of the AIS front. Furthermore, it should be noted that supercooled

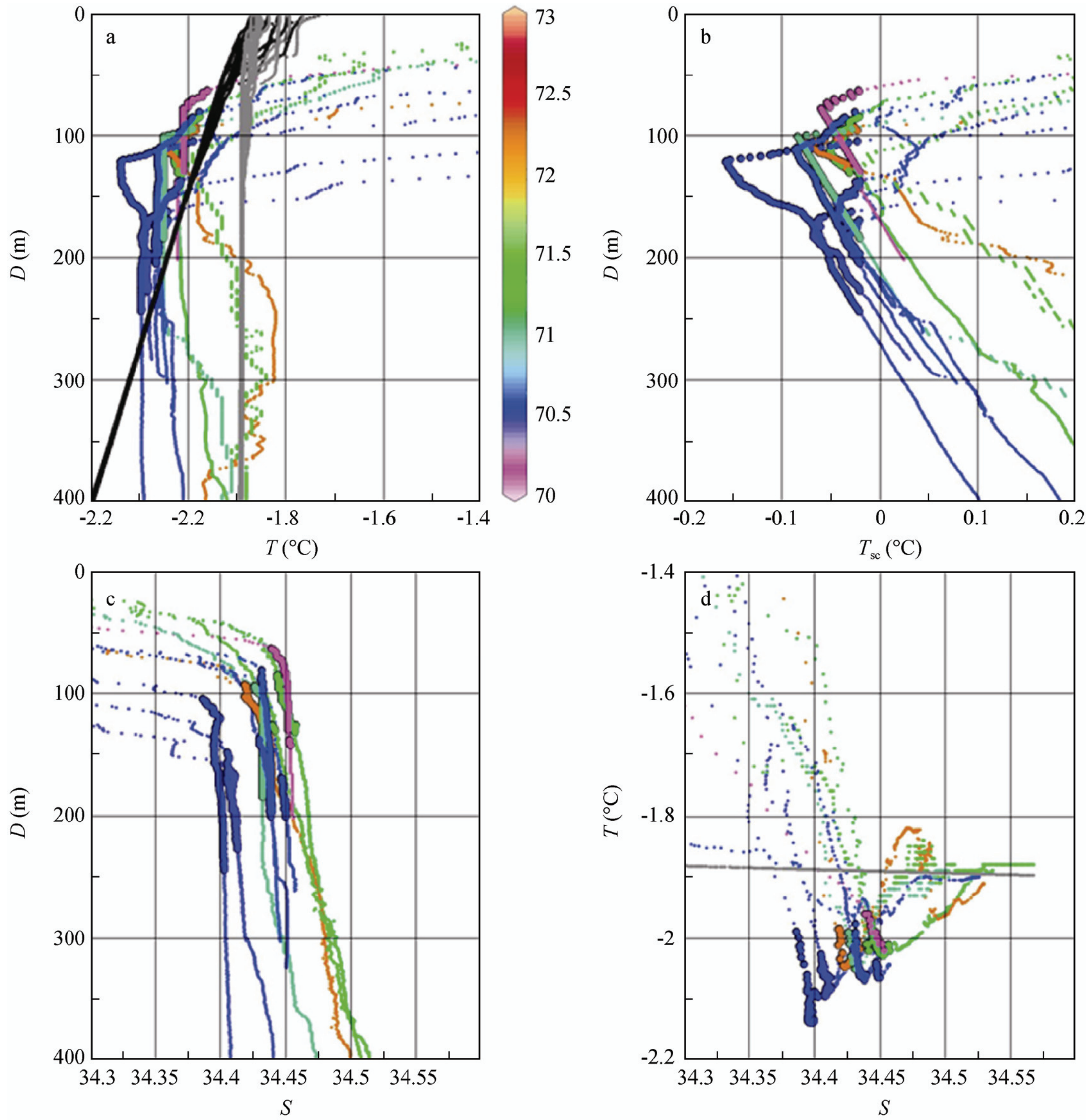

Fig.3 Vertical profiles of *T* (a), T_{SC} (b), and *S* (c), as well as the *T-S* diagram (d) of the CTD data with supercooled water collected by CHINARE

Figure notations are the same as in Fig.2.

water has never been observed west of Cape Darnley, which is quite far from the ice shelf front.

2.2.2 CTD Data of ANARE

We downloaded CTD data in the region of 65°E–80°E, 60°S–70°S from the Australian Antarctic Data Center (http://data.aad.gov.au). Among the 170 CTD profiles observed during 1993–2005, we found supercooled water at 14 profiles (Table 4, Fig.1b), and all of them located at the section along the AIS front, to the west of 73.5°E. Except for a small amount of supercooled water occurring in the top 10 m layer at Station 27 in 2002 (the quality of the surface data is questionable), all other supercooled waters existed at layers deeper than 100 m. Hence, we will focus on supercooled water at mid-depths. With the criteria of T_{SC}<-0.02°C, the depth, temperature and salinity ranges of all middle-depth supercooled waters at 14 stations were 108–271 m, -2.14°C – -1.98°C, and 34.42–34.46, respectively (Fig.4).

Two clearly different types of water separated by ~72°E (Figs.1b,4) could be recognized in supercooled waters observed by ANARE data. The western one (large purple dots in Fig.4, and marked by bold characters in Table 4) was relatively cold and saline (*S*~34.45), with a core of *D*<200 m. The eastern one (large red dots in Fig.4) was relatively fresh with a core slightly deeper than 200 m. These two types of water are clearly separated from each

Table 4 Features of supercooled water in CTD data observed by ANAREs

No	Cruise	Station	Date	Longitude (°E)	Latitude (°S)	Minimum of T_{SC}			
						T_{SC} (°C)	D (m)	T (°C)	S
1	20000106	56	2001-02-14	72.725	68.651	-0.04	231	-2.11	34.43
2	20000106	57	2001-02-14	72.703	68.562	-0.05	184	-2.08	34.44
3	20000106	58	2001-02-14	72.489	68.591	-0.06	210	-2.11	34.43
4	**20000106**	**61**	**2001-02-14**	**71.661**	**68.578**	**-0.07**	**137**	**-2.06**	**34.45**
5	**20000106**	**62**	**2001-02-14**	**71.393**	**68.557**	**-0.04**	**158**	**-2.05**	**34.45**
6	**20000106**	**63**	**2001-02-15**	**71.103**	**68.532**	**-0.04**	**170**	**-2.06**	**34.45**
7	**20000106**	**68**	**2001-02-15**	**70.171**	**68.477**	**-0.14**	**146**	**-2.14**	**34.45**
8	**20000106**	**69**	**2001-02-18**	**70.172**	**68.474**	**-0.10**	**135**	**-2.09**	**34.44**
9	**20000106**	**70**	**2001-02-18**	**70.242**	**68.475**	**-0.13**	**140**	**-2.13**	**34.45**
10	**20000106**	**73**	**2001-02-18**	**70.801**	**68.505**	**-0.06**	**140**	**-2.06**	**34.45**
11	**20000106**	**74**	**2001-02-19**	**71.130**	**68.536**	**-0.04**	**222**	**-2.10**	**34.44**
12	20010207	44	2002-02-16	72.486	68.566	-0.06	206	-2.11	34.43
13	20010207	27	2002-02-12	72.721	68.647	-0.05	214	-2.10	34.43
14	20010207	43	2002-02-15	72.442	68.586	-0.03	247	-2.10	34.44

Stations west of 72°E are denoted in bold font.

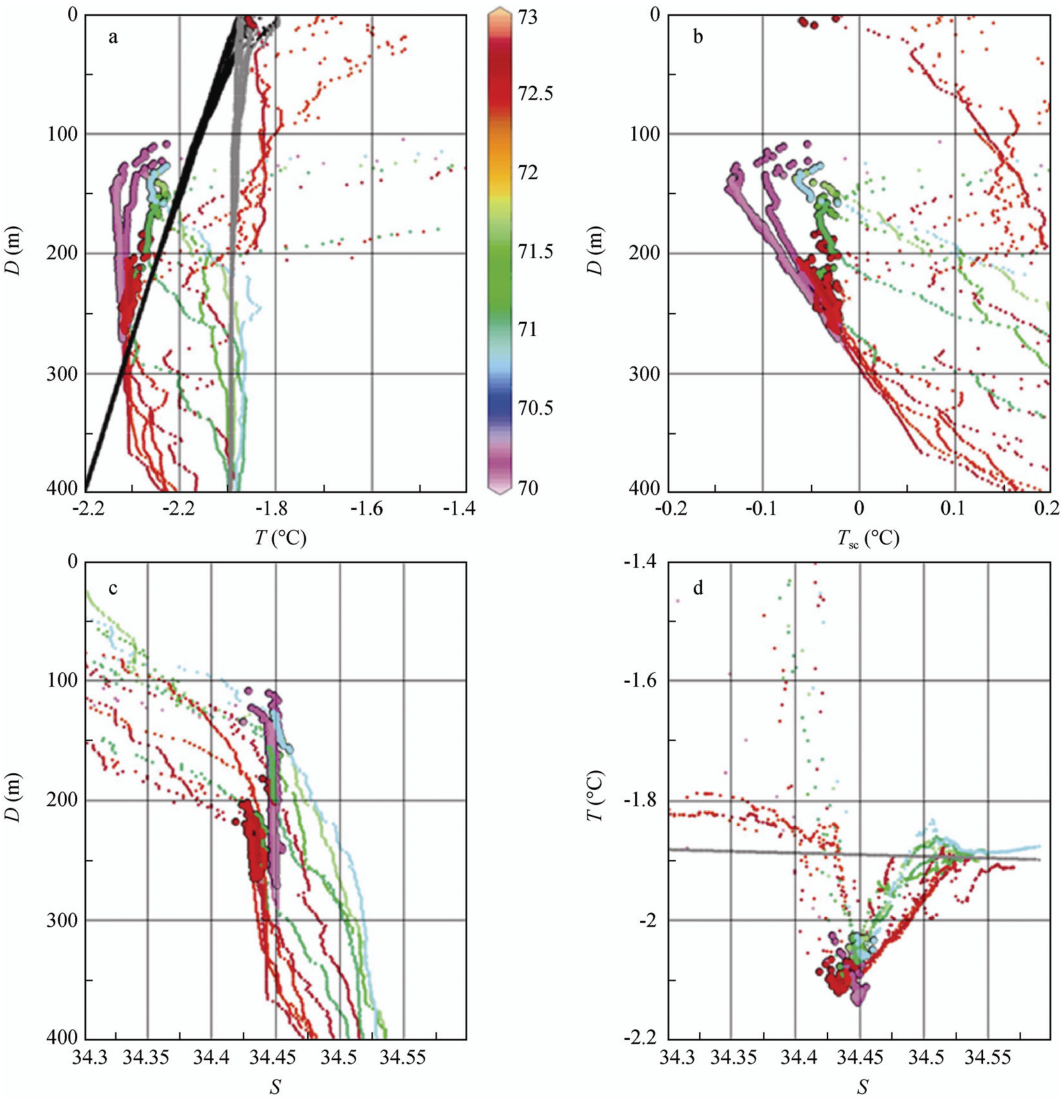

Fig.4 Vertical profiles of *T* (a), T_{SC} (b), and *S* (c), as well as the *T-S* diagram (d) of the CTD data with supercooled water collected by ANARE

Figure notations are the same as in Fig.2.

other in the *T-S* diagram (Fig.4a), which implies that they had different origins. All CTD profiles with supercooled water were obtained at the section along the AIS front in mid February 2001 and 2002. These measurements were obtained under an Australian research project AMISOR (Amery Ice Shelf - Ocean Research). Supercooled waters were found only in the region east of 72°E in 2002, but were located at both sides of 72°E in 2001.

In 2001, CTD observations were conducted at 25 stations (Stations 44–68, from east to west) on February 13–15, and then at 24 stations (Stations 69–92, from west to east) in a return survey on February 18–20. The two sections observed in about one week provided similar thermohaline structures of two layers separated by a thermocline at ~100 m to the west and ~250 m to the east (Fig.5). The upper layer was the relatively warm and fresh summer surface water (Pu et al., 2007), and the lower layer was the relatively cold and saline shelf water. All supercooled water (denoted by black dots in Fig.5) occurred below the thermocline, which is likely to be a barrier for supercooled water. The two sections, with several days delay, also show some differences. Specifically, the cold cores in the lower layer clearly had changed not only in position but also in strength. Most cold cores corresponded to the ISW with $T<T_{f0}$ (about -1.9°C for the lower layer in this region; refer to gray dots in Figs.2–4). The ISW flowed out from the cavity under the ice shelf and was colder and fresher than its peripheral water. At these two sections, most supercooled waters occurred in the upper part of the ISW. The supercooled waters at the west end of the section (Stations 68, 69 and 70) were the thickest and the most supercooled.

3 DISCUSSION

According to the above data analysis, we have not found reliable evidence to verify the existence of supercooling occurrences at the sea surface in austral summer in Prydz Bay. Thus, in the following discussion, we focus on the supercooling process that was observed at mid-depths. Most supercooled waters appeared in the western and central parts of the region, close to the AIS front. All supercooled water occurred in the upper areas of the ISW, at a

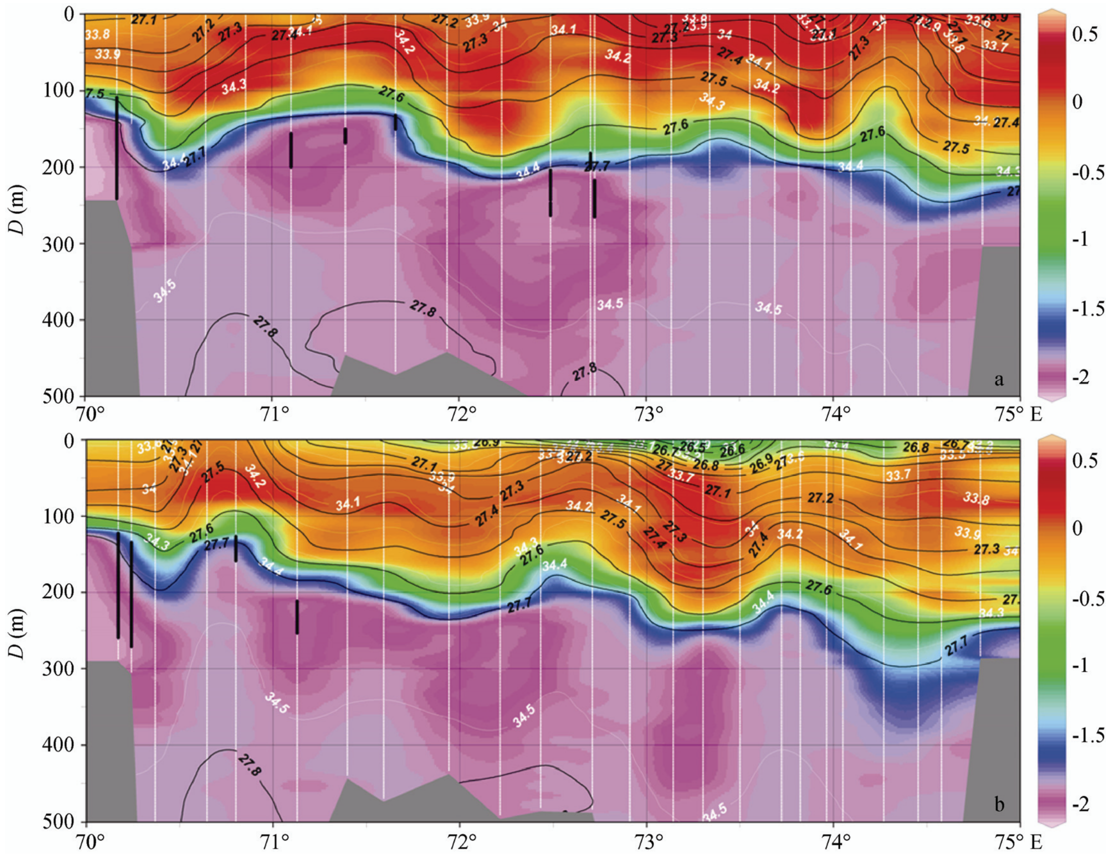

Fig.5 *T* (color bar in °C), *S* (white isohaline curves) and σ_0 (black isopycnal curves in kg/m^3) in the section in front of the Amery Ice Shelf observed by the Australian expeditions in Feb. 13–15 (a) and Feb. 18–20 (b), 2001

Lines consisting of white small dots denote data obtained at different stations (Station 44–68 from east to the west, respectively in Fig.5a; Station 69–92 from west to east in Fig.5b) and depth (1–500 m). Short lines consisting of black dots denote the areas with supercooled water.

depth corresponding to the bottom depth of the AIS front (Fricker et al., 2001). All of these findings indicate that supercooled water may come from the cavity under the AIS.

The distribution of supercooled water discussed above could be explained by the circulation pattern under the AIS. The ISW always was observed in the region north to the AIS, and in almost every austral summer (Vaz et al., 1996), which indicates that there is a stable outflow of the AIS. Both in-situ current observations (Chen et al., 2005) and numerical simulated results (Williams et al., 2001) showed a circulation pattern of inflow to the east and outflow to the west under the ice shelf. The High Salinity Shelf Water (HSSW) entering the cavity causes the melting of the ice shelf base near the grounding line. As a consequence, refreezing may take place and result in marine ice attaching on the bottom of the ice shelf when the melting water plume rises up along the bottom of ice shelf. This process forms an ice pump in the cavity beneath the AIS (Hellmer et al., 1992; Williams et al., 1998). The analysis of marine ice distribution (Fricker et al., 2001) also supports the notion that the water flowed out to the western part of the AIS front.

The observed supercooled waters show vertically homogenous thermohaline features and distinguish themselves from the layers above or beneath (Figs.3a, 3c, 4a, 4c). The vertical homogeneity indicates an extremely weak stratification for this layer, which should result from strong vertical mixing or convection. In the *T-S* diagram (Figs.3d, 4d), the observed data above and below the supercooled water are found as arrays in two lines, respectively, and the supercooled water occurred just at the intersection point of these two lines. This pattern of *T-S* dots indicates that supercooled water is not formed by mixing of the waters above and below it. Thus, the vertical homogeneity of the supercooled water could only result from convection. Based on knowledge of water masses and circulation in this region, we believe that the outflow from the cavity beneath the AIS creates an upwelling starting from mid-depth, which results in the supercooling. The process could be hypothesized as follows: The ice pump under the AIS produces a low-density plume beneath the ice shelf flowing toward the AIS front. When the plume emerges from the AIS front, and with disappearance of the upper boundary, it rises abruptly, driven by buoyancy, as shown by a dashed line arrow in Fig.6. The water in the plume could become supercooled, since its in-situ T_f rises with the decreasing pressure in the upwelling water mass. The ascent of the low-density plume does not stop until it reaches the isopycnal of the same density as that of itself. This process could explain the fact that supercooled water always occurs in the upper part of the ISW, and that the seasonal pycnocline becomes a barrier for the supercooled water. Thus, the wavy pycnocline (Fig.5), declining from east to west, represents the upper boundary of supercooled water, from ~100 m in the west to ~200 m in the east. This also could explain the observed pattern of cold cores of supercooled water in the west being deeper than those in the east, as discussed above and shown in Table 4. In addition, the bottom depth of the AIS front represents the lower boundary of the supercooled water at about 300 m (Fricker et al., 2001). The salinity of the supercooled water was just less than 34.5, which is the salinity of the shelf water in Prydz Bay (Le et al., 1996). This also was a result from the melting of the ice shelf base during the ice pump process. Due to extreme cooling of the ice shelf, the water beneath it became so cold that any ascent would have caused supercooling. The concentrated supercooled waters found to the east of Cape Darnley may be associated with the lifting of the ISW outflow and which may have been blocked off by the shallower Fram Bank east of the cape.

Usually, supercooling is just a transition state, since it results in the formation of frazil that releases latent heat to weaken and even eliminate the supercooling. Frazil could have risen to the surface and could have formed platelet ice, which has been observed in austral winter in the Ross Sea (Leonard et al., 2006). Both frazil and platelet ice (if they exist) are impossible to be observed in summer because they melt in the warm summer surface layer.

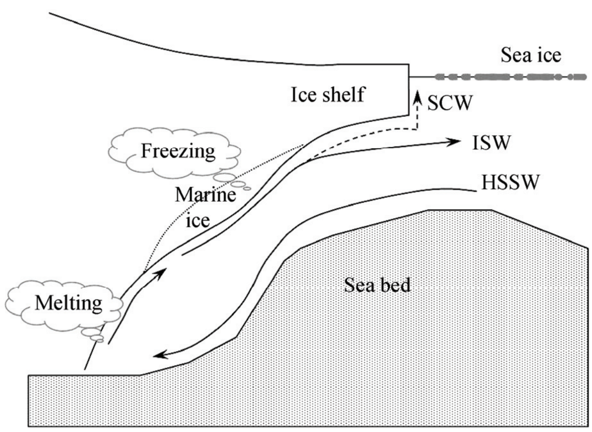

Fig.6 2-D schematic diagram showing ice pump under ice shelf, modified from Fig. 2 of Nicholls et al. (2004)

A dashed arrow is added to indicate the formation of supercooled water (SCW).

Considering the transiency of supercooling and the variability of the spatial distribution of supercooled water, we believe that the frequency of supercooled water occurrences in the observed data should be attributed to the quantity of the ISW outflow under the AIS.

Like rivers converging into a valley, low-density melting waters may converge in the concave part of the ice shelf base, such that the base topography of the ice shelf may steer the circulation pattern in the cavity. The multiple-core structure of the ISW and supercooled water observed in the section along the AIS front (Fig.5) implies that the circulation under the AIS may consist of several gyres with a strengthened outflow at the western boundary, similar to that under the Ronne Ice Shelf presented by Nicholls et al. (2004).

4 CONCLUSION

Base on analysis of observed XCTD and CTD data in the region of Prydz Bay, we identified the existence of supercooled water in the region close to the AIS front. In the austral summer, supercooled waters mostly were observed at depths of 63–271 m, just beneath the seasonal thermocline. The mid-depth supercooled waters appeared in the western part of the region north of the AIS front. With temperature and salinity ranges of -2.14°C to -1.96°C and 34.39 to 34.46, respectively, they are colder and fresher than peripheral waters. The maximum supercooling measured was 0.16°C below the in-situ freezing point. Depending on the analysis of the locations and thermohaline features, as well as considering the circulation in Prydz Bay and beneath the AIS, we conclude that supercooled waters are derived from the cavity under the AIS, and the process of ice pumping beneath the ice shelf is the precondition of formation of the mid-depth supercooled water.

All supercooled waters show vertically homogenous thermohaline features clearly distinguished from peripheral waters, which implies upwelling beneath the seasonal pycnocline, and above the depth where water flowed out of the cavity under the ice shelf. The supercooling resulted from the rising of the in-situ freezing point with decreasing pressure, due to the ascent of the extremely cold outflow water. The upwelling occurring just outside of the ice shelf front was formed by the rise of low-density outflow water that was driven by buoyancy when it loses the upper boundary of the ice shelf base. The observed thick supercooled water layer near the west end of the AIS front may be caused by the rise of concentrated ISW outflow along the shallow Fram Bank. Upwelling associated with outflow from the cavity under the ice shelf is an unusual process by which deep ocean convection may occur.

The supercooled waters and ISWs concentrated themselves in separated multiple cores at the section along the AIS front, which indicates a complex circulation pattern with a strengthened outflow at the west end of the AIS.

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