

# Comparison of ship-based CTD measurement of Circumpolar Deep Water in the Amundsen Sea based on World Ocean Database

HE Hailun\* & WU Shouchang

State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou 310012, China

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**Abstract** We compare the characteristics of Circumpolar Deep Water (CDW) in the Amundsen Sea based on Conductivity-Temperature-Depth (CTD) records in the World Ocean Database. There are considerable numbers of ship-based CTD casts in the year 1994, 2000, 2007 and 2009. After confining temporal- and spatial- windows, several stations are emerged as having at-least two casts in different years. The comparisons show that the CDWs turn warmer and saltier on shelf and near ice shelf. The results therefore describe the geographic differences of CDW changes, and exhibit rareness of ship-based CTD survey in the Amundsen Sea.

**Keywords** Circumpolar Deep Water, Amundsen Sea, Conductivity-Temperature-Depth

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## 1 Introduction

Amundsen Sea (AS) is a marginal sea in the Southern Ocean, where the ice shelf suffers rapidly basal melting (Rignot et al., 2019). Satellite images support the ice coverage trend is obviously negative in the satellite era (Parkinson, 2019). Ice melting in the AS exerts global impact on the sea level change (Mercer, 1978). Compared with atmospheric forcing, the ice melting is most likely to be forced by underlying warm water (Shepherd et al., 2004; Jacobs et al., 2011).

Considering the Amundsen Sea Shelf (ASS) as a sole unit, the boundary thermal forcing is mainly provided by the warm Circumpolar Deep water (CDW). The input and output of CDW into the ASS and the related net heat exchange supply energy to ice melting. The intrusion of the

CDW to the ASS is partly caused by surface wind forcing near the shelf break (Kim et al., 2021). The thermohaline definition of CDW is  $T > 1^{\circ}\text{C}$  ( $T$  is the *in-situ* temperature), and  $S > 34.6$  psu ( $S$  is practical salinity; Klinck et al., 2004). Similarly, the thermohaline definition can be also presented by potential temperature ( $\theta$ ) and absolute salinity (SA; Assmann et al., 2019), as  $\theta > 1^{\circ}\text{C}$  and  $SA > 34.85 \text{ g}\cdot\text{kg}^{-1}$ . The upper CDW (UCDW) is characterized by a temperature maximum where the potential density is nearly  $27.72 \text{ kg}\cdot\text{m}^{-3}$ . Lower CDW (LCDW) is related to a salinity maximum (roughly 34.74 psu) at the potential density layer of  $27.8 \text{ kg}\cdot\text{m}^{-3}$ .

On the seasonal scale, the seal-borne tag CTD reveals that the seasonal variation of CDW in Eastern Trough (ET) is significant (Mallett et al., 2018). Winter CDW in ET is thicker than summer CDW. Heat content of CDW layer in winter is higher than that in summer. The season variation shows geographic difference. For instance, the seasonal variation of CDW in Pine Island Bay (PIB) is not

\* Corresponding author, ORCID: 0000-0003-0690-6252, E-mail: behailun@sio.org.cn

significant.

On the lower frequency, the comparison of ship-based CTD between the year 1994 and 2009 indicates the temperature of CDW turns warmer in the PIB, and the heat content also increases (Jacobs et al., 2011). Using the machine learning technique (Boehme and Rosso, 2021), the variability of CDW is relatively high in the off-shelf, ET and Central Trough (CT).

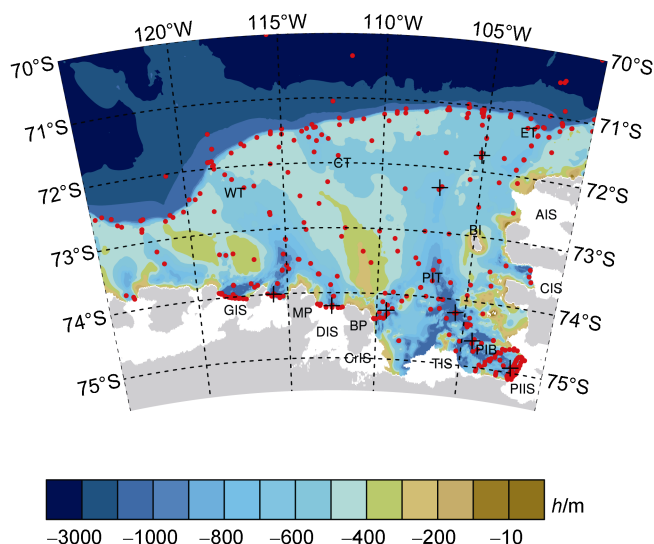
Obtaining the CTD profiles in ASS mainly depends on two platforms, i.e. seal-tag CTD and ship-based CTD. The precision and vertical resolution of seal-tag CTD are considerably lower than ship-based CTD (Mallett et al., 2018). The reported precision of seal-tag CTD is roughly  $0.03^{\circ}\text{C}$  for temperature and  $0.05$  psu for practical salinity. Besides, due to date compression of seal-tag CTD, the vertical resolution is 18 depth levels per cast, which implies the vertical resolution is coarser than  $20$  m if the column thickness of cast measurement exceeds  $360$  m. In contrast, the ship-based CTD typically has  $10$  Hz higher frequency (typically less than  $0.1$  m in vertical resolution), and the precision is roughly  $0.0001^{\circ}\text{C}$  for temperature and  $0.002$  psu for practical salinity, respectively. Therefore, data quality of ship-based CTD is more reliable than seal-tag CTD on describing CDW.

Due to the limited ship-based CTD observation, the variance of CDW leaves a large room to be understood. The problems of previous studies are exposed as the definitions of CDW are not same. The variables can depend on isothermal line, vertical temperature maximum, isopycnal layer or neutral density layer. For instance, the isotherm is defined as upper boundary of CDW (Mallett et al., 2018). Neutral density also defines the column of CDW (Whitworth et al., 1998; Assmann et al., 2019). Meanwhile, systematic study of updated public datasets on AS CDW has not yet reported. Therefore, we investigate the spatial and temporal distributions of ship-based CTD casts in the AS, and compare the profiles of CDW at possible stations.

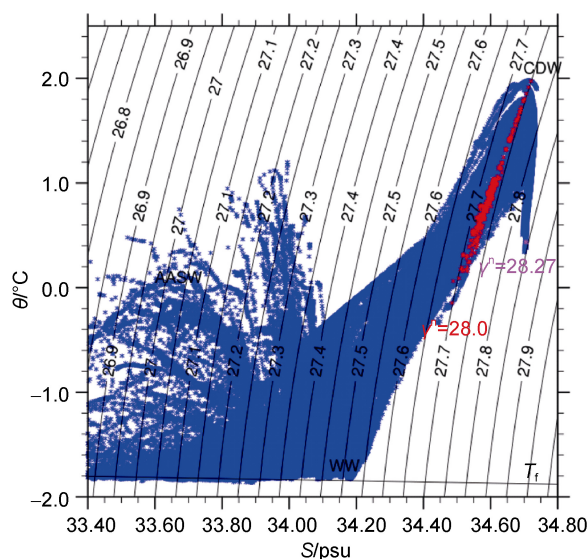
## 2 Material

World Ocean Database (WOD) is a global ocean dataset, which is provided by National Oceanic and Atmospheric Administration (<https://www.ncei.noaa.gov/products/world-ocean-database>). Figure 1 shows the spatial distribution of ship-based CTD in the WOD, where the RTOPO-2 topography (Schaffer et al., 2016) is used. In general, the ship-based CTD mainly locates at the front of ice shelf, on the shelf and slope.

The temperature-salinity diagram shows that there are at-least three water masses as CDW, Winter Water (WW) and Antarctic Surface Water (AASW; Figure 2). The maximum temperature approaches  $2.0^{\circ}\text{C}$ , which suggests CDW contains considerable heat content. The curve around CDW also shows the maximum temperature point in the temperature-salinity diagram, which indicates the core of CDW.



**Figure 1** Topography of Amundsen Sea (RTOPO2;  $h$ ) and locations of ship-based CTD casts from World Ocean Database (2018). PIIS=Pine Island Ice Shelf, PIB=Pine Island Bay, PIT=Pine Island Trough, TIS=Thwaites Ice Shelf, AIS=Abbot Ice Shelf, CIS=Cosgrove Ice Shelf, CrIS=Crosson Ice Shelf, DIS=Dotson Ice Shelf, GIS=Getz Ice Shelf, ET=Eastern Trough, CT=Central Trough, WT=Western Trough, BP=Bear Peninsula, MP=Martin Peninsula, and BI=Burke Island.



**Figure 2** Temperature-salinity diagram for all CTD stations in the Amundsen Sea.  $\gamma^b$  is the neutral density.

In present study, we use two surfaces of CDW as  $\gamma^b=28.0$  and  $28.27$ . The upper surface roughly overlay with isopycnal layers in the range of  $\sigma_0=27.7$  to  $27.75$  ( $\sigma_0$  is the potential density), while the lower surface is close to the isopycnal layer  $\sigma_0=27.85$ . The temperature of upper surface is mainly larger than  $0.5^{\circ}\text{C}$ , which shows the upper surface captures the warm characteristic of CDW. Overall, the upper surface is above the core of CDW (temperature maximum), although the upper surface approaches the core

of CDW in some stations. It is worthy to mention that some casts, which show significantly biased salinity for CDW, are not used. Meanwhile, for the lower surface of CDW, because the neutral density at the maximum depth of cast is always lower than the definition ( $\sigma^{\theta}=28.27$ ), we use the maximum depth of cast as lower surface of CDW in computing the CDW column averaged variables (temperature and salinity, Table 1).

We further plot the spatial distributions of yearly samples in Figure 3. The intensified CTD measurements were implemented in 1994, 2000, 2007 and 2009. The yearly ship-based CTD samples are reported as followings:

(1) In 1994, samples located sparsely in Getz Ice Shelf (GIS), Pine Island Ice Shelf (PIIS), ET, CT and Western Trough (WT). According to the information of CTD records, most of these casts (40 out 43) were conducted by Lamont-Doherty Geological Observatory, United States, and the cruise was *Nathaniel B. Palmer*. The other three casts were carried out by Germany, and the ship name was

*Polarstern*.

(2) In 2000, the survey was mainly conducted in PIIS, Bear Peninsula (BP), Dotson Ice Shelf (DIS), GIS, ET, CT and slope. All 82 casts were observed by Lamont-Doherty Geological Observatory, United States, and cruise was *Nathaniel B. Palmer*.

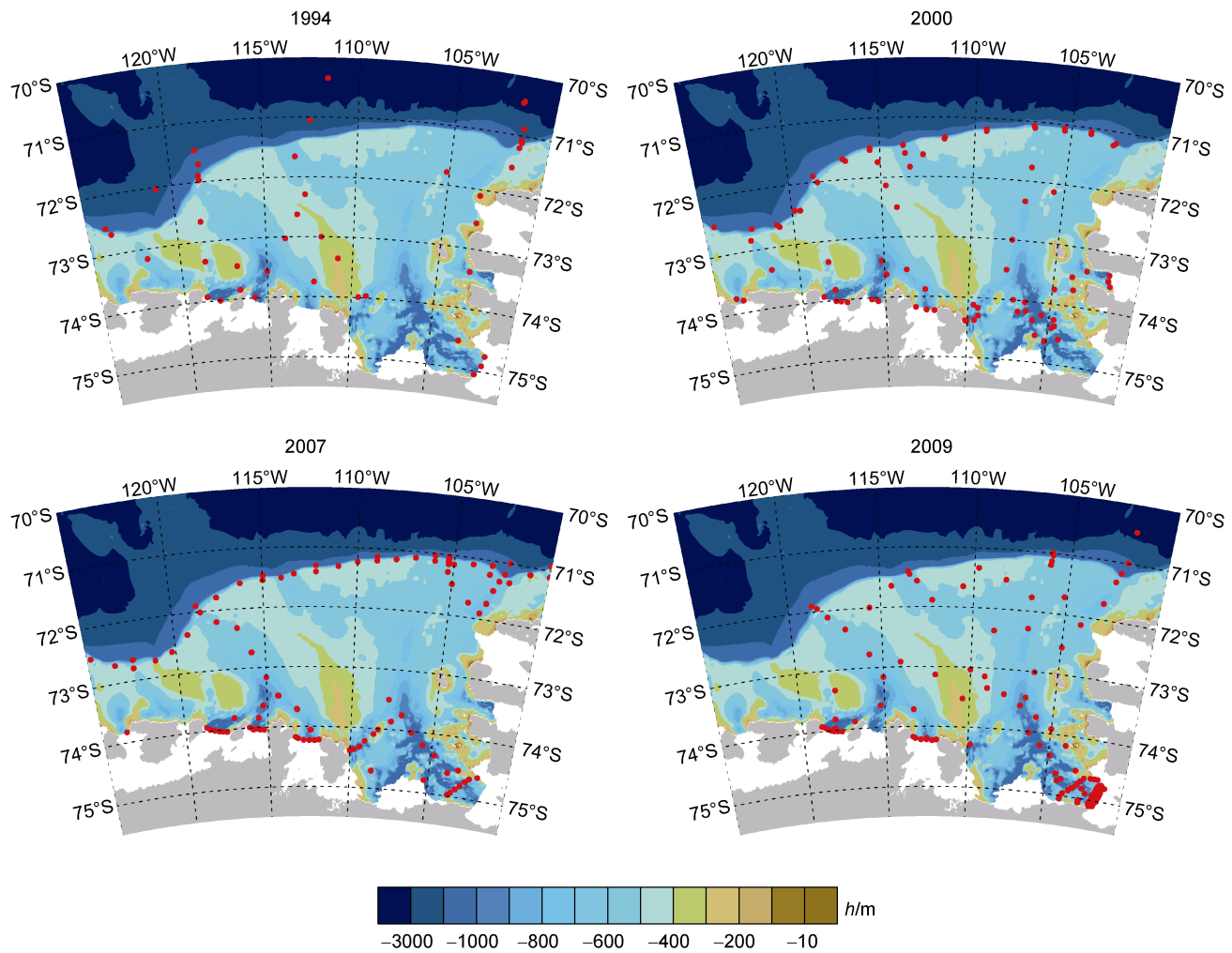
(3) In 2007, the distribution of stations is similar to year 2000, although the activity is intensified. The samples were conducted by United States, and the institute is Lamont-Doherty Geological Observatory. These records were based on *Nathaniel B. Palmer*.

(4) In 2009, the stations looked like those in 2000 and 2007, however the number of samples was relatively larger in the PIIS, but decreased in the BP. All 156 casts were implemented by Lamont-Doherty Geological Observatory, United States, and cruise was *Nathaniel B. Palmer*.

When compared the locations of all stations, several valuable stations are selected as shown in Figure 1 and Table 1. We will later discuss the records respectively (Section 3).

**Table 1** Characteristics of CDW for different years.  $h$  is the water depth.  $z^u$  is the depth of upper surface of CDW, and  $\theta$  and  $S$  are the corresponding potential temperature and practical salinity.  $\Delta z$  is the thickness of CDW,  $\bar{\theta}$  and  $\bar{S}$  are the mean potential temperature and practical salinity of CDW respectively. The water depth  $h$  is adopted from RTOPO2.  $\Delta$  in the ID column indicates the difference between two casts.

Station	ID	Date (YYYY-MM-DD)	Longitude	Latitude	$h/m$	$z^u/m$	$\theta/^{\circ}C$	$S/psu$	$\Delta z/m$	$\bar{\theta}/^{\circ}C$	$\bar{S}/psu$
PIIS	7867973	1994-03-14	101.848°W	75.061°S	941	605	0.867	34.595	355	1.053	34.666
	15269829	2009-01-04	101.846°W	75.067°S	931	635	1.029	34.611	295	1.194	34.670
	$\Delta$					30	0.162	0.016	-60	0.141	0.004
BP	9928317	2000-03-05	109.362°W	74.299°S	1000	650	0.580	34.561	345	0.928	34.644
	15269591	2007-02-28	109.435°W	74.318°S	982	585	0.925	34.600	400	1.156	34.689
	$\Delta$					-65	0.345	0.039	55	0.228	0.045
DIS	9928310	2000-03-04	112.527°W	74.221°S	945	1135	0.062	34.489			
	15269543	2007-02-23	112.529°W	74.229°S	934	920	0.538	34.546	270	0.598	34.561
	$\Delta$					-215	0.476	0.057			
GIS	7867930	1994-03-01	115.794°W	73.992°S	1152	825	-0.146	34.485	410	0.036	34.513
	15269529	2007-02-22	115.906°W	74.030°S	1023	845	0.448	34.542	405	0.570	34.566
	$\Delta$					20	0.594	0.057	-5	0.534	0.053
PIT	9928363	2000-03-18	104.277°W	74.574°S	949	640	0.675	34.575			
	15269917	2009-01-31	104.395°W	74.640°S	1380	665	0.990	34.605	825	1.233	34.692
	$\Delta$					25	0.315	0.030			
PIT	9928361	2000-03-17	105.486°W	74.206°S	1563	565	0.583	34.570	920	1.025	34.684
	15269555	2007-02-24	105.579°W	74.209°S	1620	490	0.998	34.610	1130	1.221	34.714
	$\Delta$					-75	0.415	0.040	210	0.196	0.030
ET	15122929	1994-02-22	105.150°W	71.783°S	549	360	0.842	34.597	150	1.119	34.684
	15269946	2009-02-09	105.158°W	71.707°S	543	365	0.944	34.602	160	1.150	34.702
	$\Delta$					5	0.102	0.005	10	0.031	0.018
ET	9928352	2000-03-14	107.086°W	72.341°S	677	560	0.567	34.558	105	0.926	34.670
	15269945	2009-02-08	106.941°W	72.293°S	691	480	1.025	34.609	190	1.169	34.699
	$\Delta$					-80	0.458	0.051	85	0.243	0.029



**Figure 3** Spatial distribution of yearly CTD casts in the Amundsen Sea. Color shading shows the topography ( $h$ ).

## 3 Results

### 3.1 Water mass near ice shelf

#### 3.1.1 PIIS

In PIIS, one station as  $74.93^{\circ}\text{S}$ ,  $101.95^{\circ}\text{W}$  is selected (Figure 4 and Table 1). The water depths are in the range of 600 to 1000 m. The first survey time was March 1994, while the later time was 15 years later (January 2009). For the spatial distribution, the cast in 1994 was on the front of PIIS. A sample in January 2009 located closely with initial cast in 1994. Comparing these two closely-distributed casts, pair profiles show the upper neutral density surface deepens from 605 to 635 m. Correspondingly, the temperature has increased by  $0.162^{\circ}\text{C}$ . For the vertical mean of CDW layer, the temperature has increased by  $0.14^{\circ}\text{C}$ . The corresponding salinity changes are relatively weak (less than 0.02 psu). Meanwhile, the samples in January 2009 show consistent temperature-salinity diagram.

#### 3.1.2 BP

For the station at northeast of BP ( $74.25^{\circ}\text{S}$ ,  $109.45^{\circ}\text{W}$ ; Figure 5), there are five historic casts. The earlier three casts were in March 2000, the latter two casts were in February 2007. The water depths of these casts are in the range of 600 to 1000 m. The casts in February 2007 show warmer and saltier CDW than earlier casts in March 2000. The increment of temperature (salinity) at upper layer of CDW attains  $0.345^{\circ}\text{C}$  (0.039 psu; Table 1).

#### 3.1.3 DIS

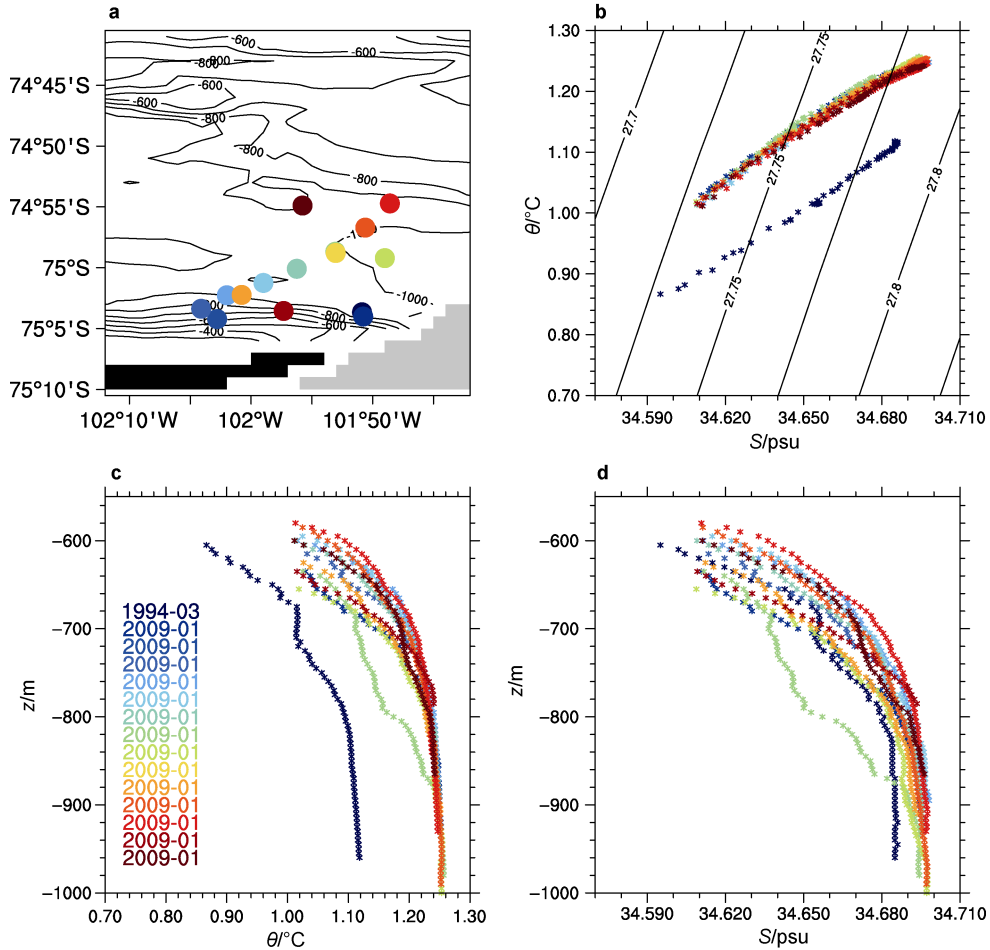
For the station close to the DIS ( $74.20^{\circ}\text{S}$ ,  $112.55^{\circ}\text{W}$ ), eight casts are recorded in the WOD (Figure 6). The earlier one cast was in March 2000, the later four casts were in February 2007, the following one cast was in December 2007, and the last two casts were in February 2009. The casts in March 2000 locate on front of DIS. On the TS diagram (Figure 6b), the casts in year 2007 show warmer and saltier CDW than initial cast in year 2000. On the profiles, the significant changes of temperature and salinity

of CDW are observed as compared with initial March 2000 cast. The temperature of upper layer of CDW increases  $0.476^{\circ}\text{C}$ . The salinity of upper layer turns saltier from 34.489 (March 2000) to 34.546 psu (February 2007), and the increment attains 0.057 psu. It is also worth noting that between the February 2007 and 2009, the temperature difference is not negligible as well (Figure 6), which

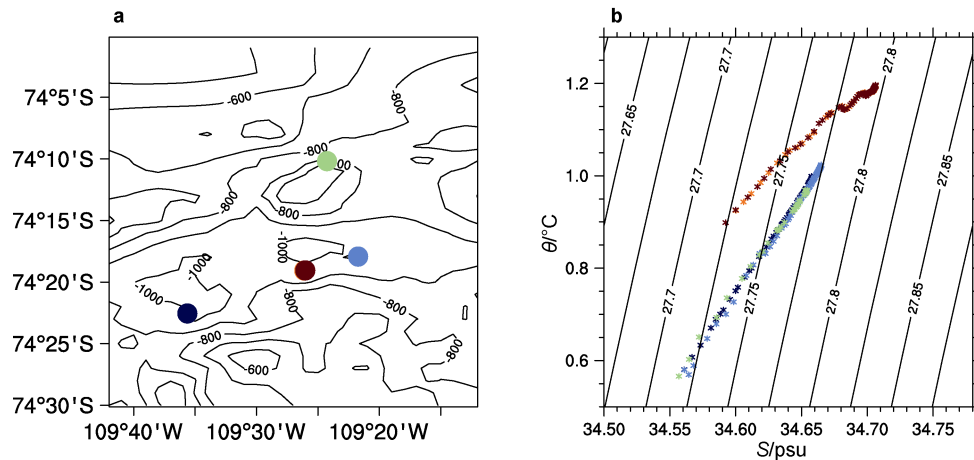
implies the inter-annual variation is probably not negligible.

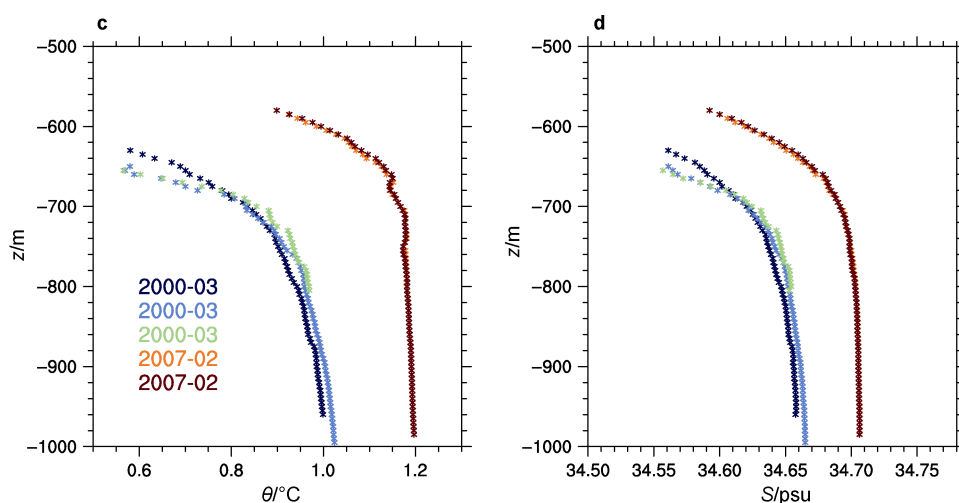
### 3.1.4 GIS

For the station close to the GIS (74.00°S, 115.80°W), there are six historic casts (Figure 7). The earlier one cast was obtained in March 1994, the following cast was in March 2000, the later four cast were in February 2007. The

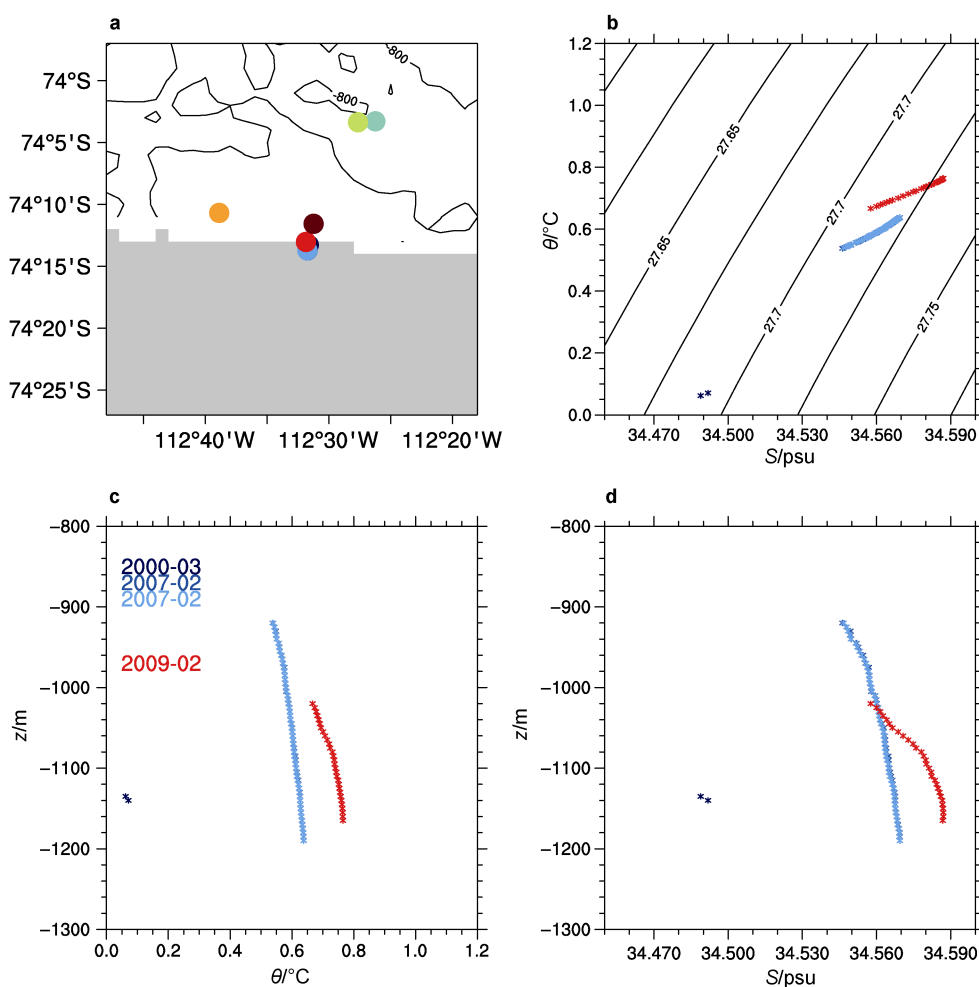


**Figure 4** CTD records at PIIS station (74.93°S, 101.95°W) in the Amundsen Sea. **a**, Topography. Black fill represents land, grey fill shows ice shelf; **b**, Temperature-salinity diagram; **c-d**, Profiles of temperature and salinity.





**Figure 5** CTD records at BP station (74.25°S, 109.45°W) in the Amundsen Sea. **a**, Topography; **b**, Temperature-salinity diagram; **c–d**, Profiles of temperature and salinity.



**Figure 6** CTD records at DIS station (74.20°S, 112.55°W) in the Amundsen Sea. **a**, Topography. Grey fill shows ice shelf; **b**, Temperature-salinity diagram; **c–d**, Profiles of temperature and salinity.

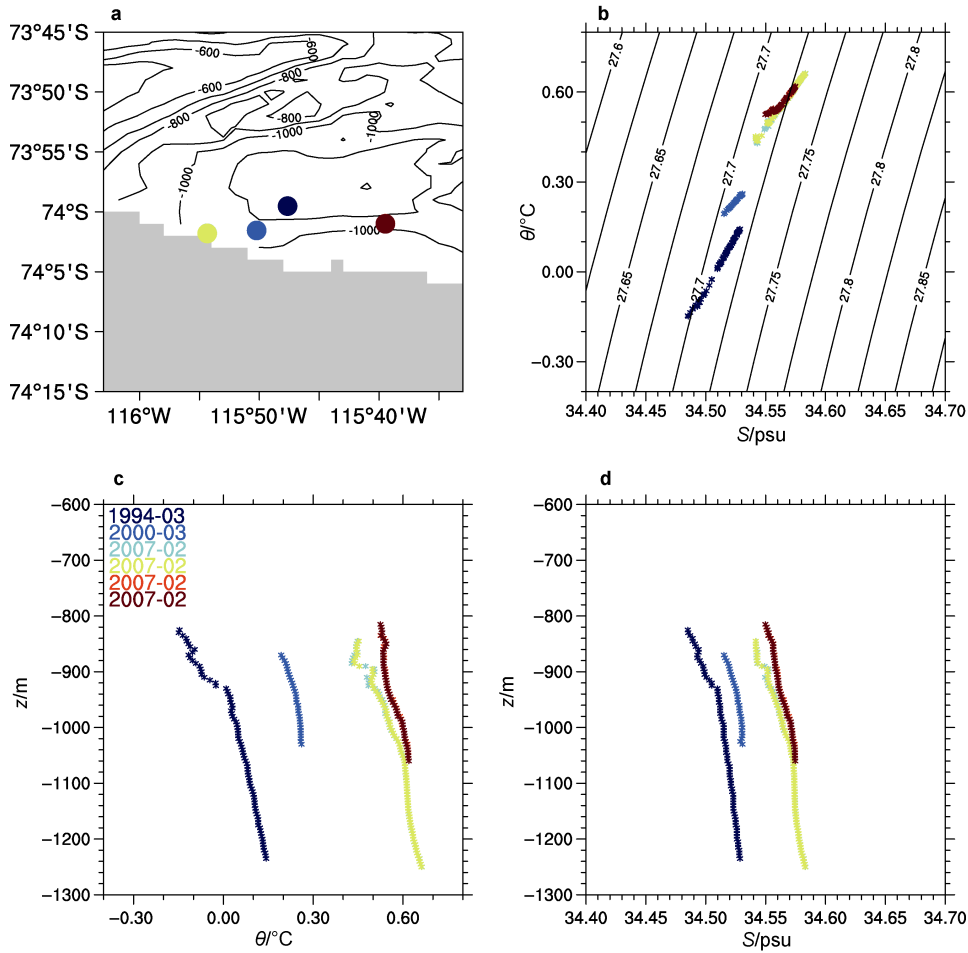
primary characteristics of initial cast (March 1994) is cooler and fresher. The depth of upper layer is 825 m in March 1994. The temperature of upper layer of CDW is  $-0.146^{\circ}\text{C}$  in March 1994,

and the salinity is 34.485 psu. Later in March 2000, the depth of upper layer move downward to 870 m. Compared with initial cast, the temperature of upper layer of CDW increases from



−0.146 to 0.193°C (Figure 7c), and the salinity slightly increases from 34.485 to 34.525 psu (Figure 7d). The CDW in February 2007 turns warmer and saltier than that in March 2000. The

differences of temperature and salinity of upper layer of CDW are 0.594°C and 0.057 psu between February 2007 and March 1994.



**Figure 7** CTD records at GIS station (74.00°S, 115.80°W) in the Amundsen Sea. **a**, Topography. Grey fill shows ice shelf; **b**, Temperature-salinity diagram; **c–d**, Profiles of temperature and salinity.

## 3.2 Water mass on shelf

### 3.2.1 PIT

For the station 74.60°S, 104.40°W (Figure 8), which is located in southeast of PIT, two casts on March 2003 and January 2009 were recorded. The later cast shows warmer CDW than earlier cast. On the profiles, on the upper layer of CDW, the salinity of later cast is saltier than that of earlier cast.

Similarly, the station 74.20°S, 105.55°W exists four historic records (Figure 9). The earlier cast was in March 2000, the latter two cast were in February 2007, and the last cast was in January 2009. The casts in years 2007 and 2009 show warmer and saltier CDWs than the former cast in year 2000.

### 3.2.2 ET

For the station around the outer shelf of ET (71.75°S, 105.12°W), two historic records exist. The earlier cast was in February 1994, and the later cast was in February 2009. The casts were in the same month, but exhibited long time gap as 15 years. The year

2009 cast shows slightly warmer CDW (increasing 0.031°C), and the water turns a little saltier follows the time evolution (increasing 0.018 psu; Table 1 and Figure 10).

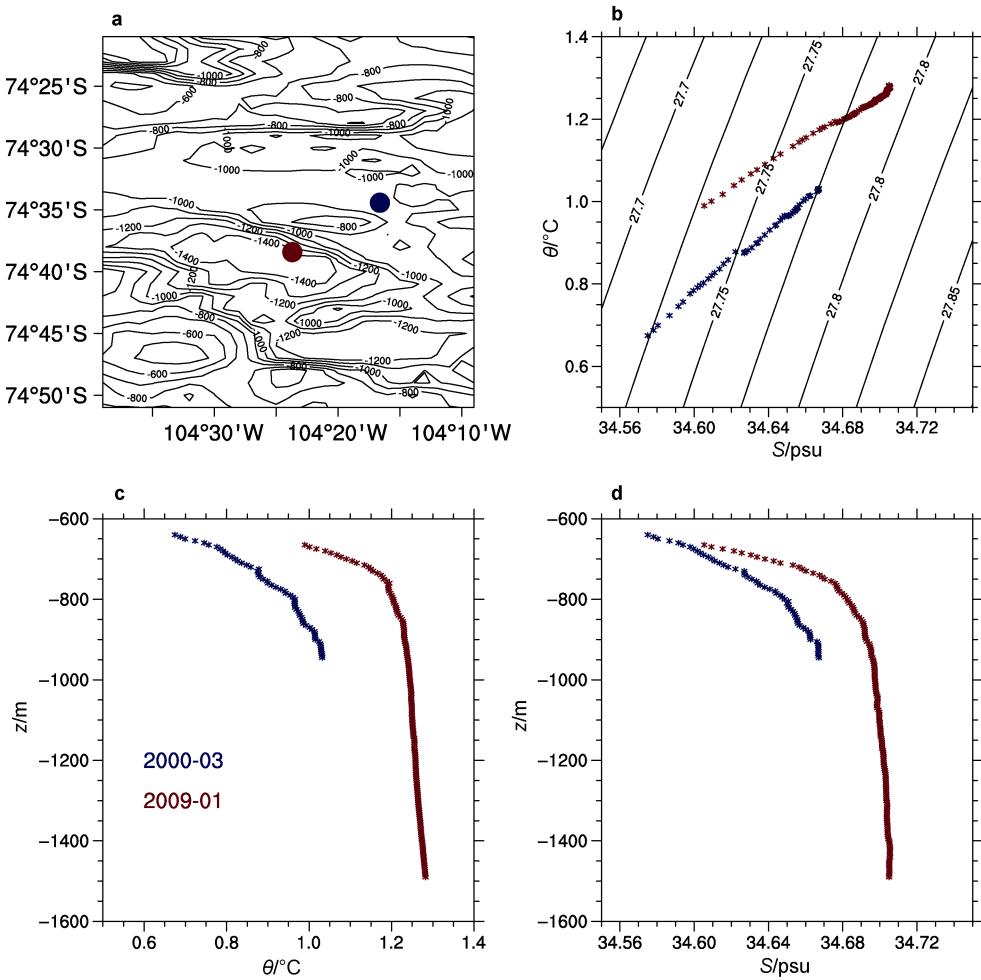
For the station close to the ET (72.31°S, 107.05°W), there are two historic casts (Figure 11). The earlier cast was in March 2000, and the later cast was in February 2009. The cast in year 2009 shows warmer and saltier CDW than earlier cast in year 2000. The depth of upper layer of CDW is lifted shallower in 2009 (480 m) than 2000 (560 m). The water temperature and salinity of upper layer increase 0.458°C and 0.051 psu from 2000 to 2009, respectively. However, the temperature and salinity changes of mean CDW column are relatively weak (0.243°C for temperature and 0.029 psu for salinity; Table 1).

## 4 Discussion

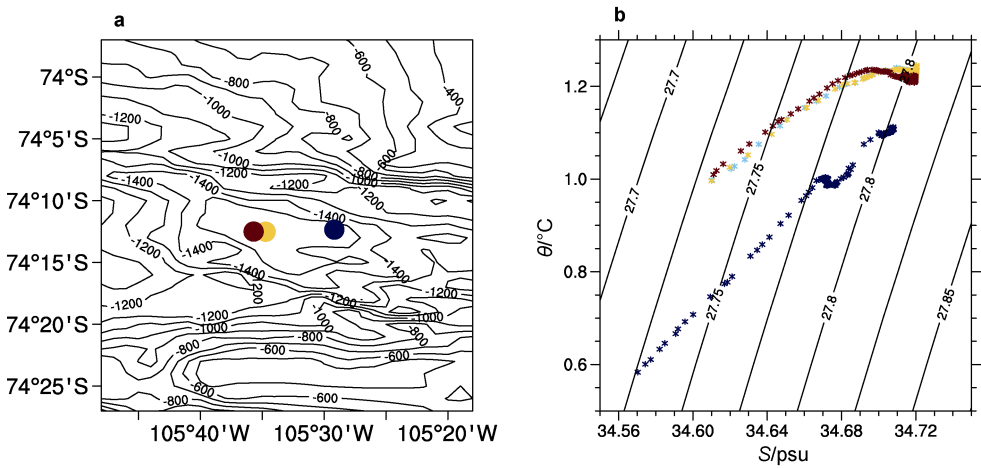
The results near the ice shelf are physical sounding, as the near-bottom water at the front of ice shelf changes warmer

and saltier continuously. However, the thermal forcing of CDW on ice melting depends on the difference between inflow and outflow of CDW, which is not involved in present study. The fresh water due to ice melting does not

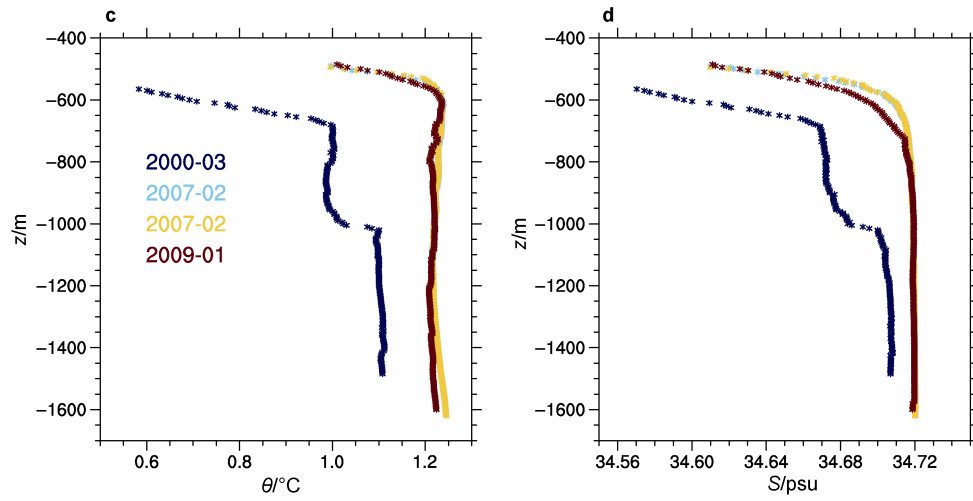
decrease the salinity of underlying CDW, and the results suggest the ice-melting water is confined in upper layer, and the ocean circulation related to CDW probably impose steady forcing on the basal ice shelf.



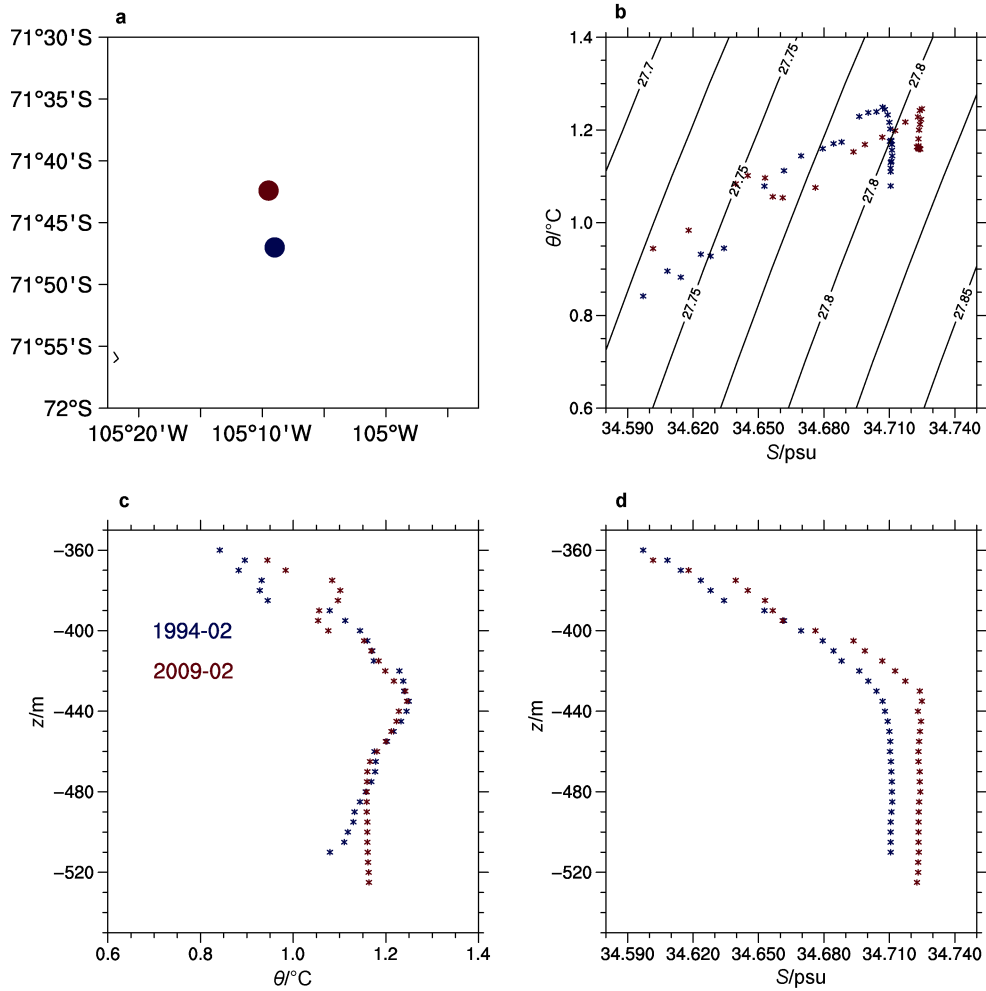
**Figure 8** CTD records at PIT station (74.60°S, 104.40°W) in the Amundsen Sea. **a**, Topography; **b**, Temperature-salinity diagram; **c-d**, Profiles of temperature and salinity.



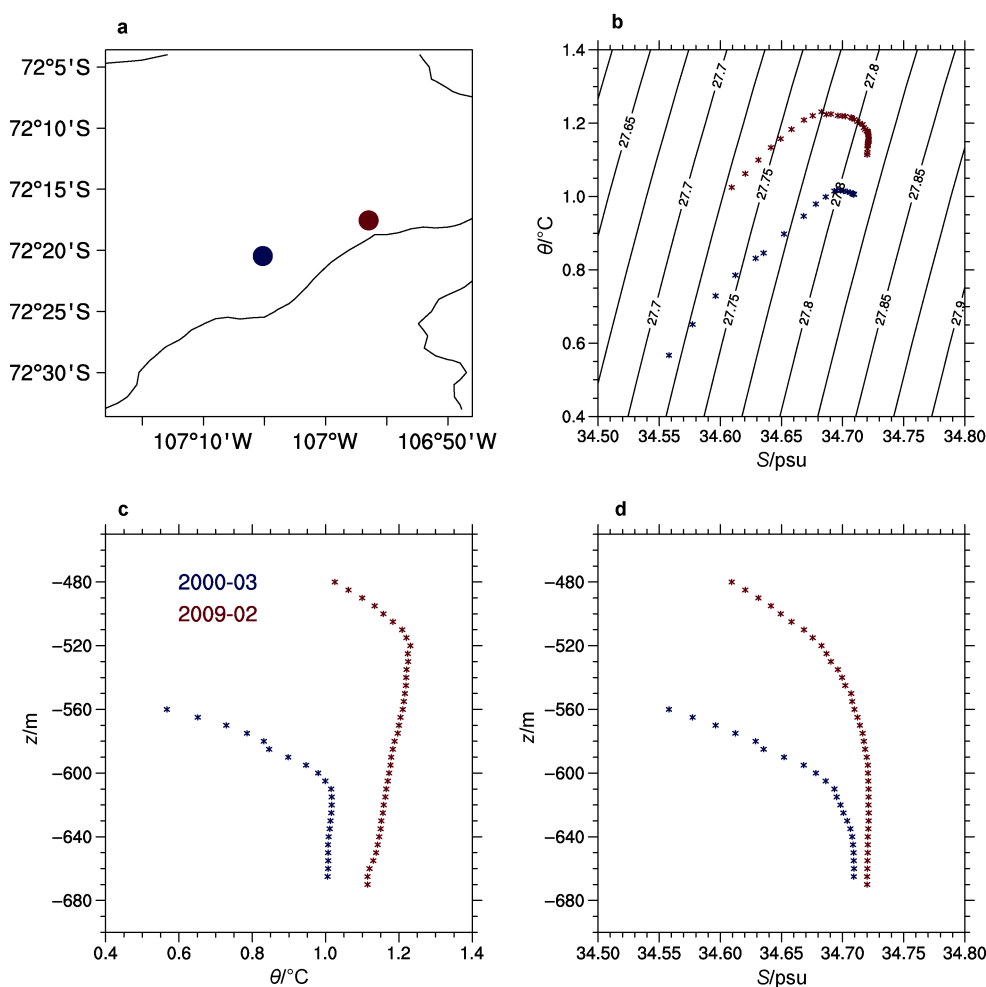




**Figure 9** CTD records at PIT station (74.20°S, 105.55°W) in the Amundsen Sea. **a**, Topography; **b**, Temperature-salinity diagram; **c-d**, Profiles of temperature and salinity.



**Figure 10** CTD records at ET station (71.75°S, 105.12°W) in the Amundsen Sea. **a**, Topography. The topography is as flat as -500 m; **b**, Temperature-salinity diagram; **c-d**, Profiles of temperature and salinity.



**Figure 11** CTD records at ET station (72.31°S, 107.05°W) in the Amundsen Sea. **a**, Topography; **b**, Temperature-salinity diagram; **c-d**, Profiles of temperature and salinity.

## 5 Conclusions

CDW is a water mass which directly supplies thermal energy to ice shelf basal. This paper focuses on the change of CDW based on reliable CTD profiles. The data are provided by WOD, and the prominent number of records were operated in year 1994, 2000, 2007 and 2009. After imposing a suitable spatial window, CTD profiles are comparable in some nearly-same locations.

In the Ice Shelf region, there are considerable number of records in the GIS. The initial cast (March 1994) exhibited cooler and fresher water. Later in March 2000, the temperature of upper layer of CDW increased from initial  $-0.146^{\circ}\text{C}$  to  $0.193^{\circ}\text{C}$ . The CDW in February 2007 further turns warmer and saltier than those in March 2000. As a result, the temperature (salinity) increases  $0.594^{\circ}\text{C}$  ( $0.057$  psu) from 1994 to 2007. The waters also turn warmer and saltier in the PIIS, BP and DIS around Ice Shelf region.

On the shelf, the CDW is also found warmer and saltier on PIT and ET. The most significant change is found on ET

(72.31°S, 107.05°W), where the temperature of upper layer of CDW increased  $0.46^{\circ}\text{C}$  from 2000 to 2009, the corresponding salinity increased  $0.05$  psu. Furthermore, the depth of upper layer of CDW is also lifted up from 560 to 480 m, and the thickness of CDW also varies.

Although the stations look sparse, the results highlight the impact of climate change, as the waters both near Ice Shelf and on shelf are most likely turn warmer and saltier. Considering the data quality of ship-based CTD casts are more reliable than that of seal-tag CTD, these results provide essential information for the regional ocean study.

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