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Variation of upper-ocean heat content in the Canada Basin in summers of 2003 and 2008

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Abstract Conductivity, temperature, and depth data collected during the summers of 2003 and 2008 were used to study upper-ocean (top 200 m) heat content in the Canada Basin. The variation of heat content with depth, heat content differences between the summers, principal driving factors, and horizontal spatial scale differences were analyzed. A catastrophic reduction of sea ice cover in the Canada Basin was evident in 2008 by comparison with 2003, suggesting that more solar radiation was absorbed in the upper ocean during the summer of 2008. The sea ice reduction produced more freshwater in the upper ocean. Thus, seawater properties changed. The study shows that the huge reduction of sea ice would result in two changes-widespread warming of the upper ocean, and the depth of Pacific inflow water in the basin increased substantially. Near-surface temperature maximum (NSTM) water was also analyzed as an indicator of Arctic Ocean warming.

Keywords **Heat content, freshwater content, NSTM, melting sea ice, Pacific inflow water**

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0 Introduction

The ocean contains vast energy, and its heat content plays an important role in the annual variation of global heat balance[1]. The ocean warmed from 1948 to 1998, dominating the heat balance of the Earth[2].

The Arctic Ocean has experienced a tremendous change under the background of global warming. The summertime perennial sea ice extent in the Arctic decreased from 1979 to 2007, at a rate of more than 10% per decade[3–4]. The decline has accelerated in recent years, leading to very low ice concentration in the summers of 2007 and 2008. This great reduction of sea ice would alter the structure of the upper ocean in two main aspects. First, more solar radiation would be absorbed by the upper ocean. Perovich et al.[5] reported a pervasive increase in the amount of solar energy absorbed by the northern Chukchi Sea and surrounding seas, from 1979 through 2005. They estimated an increased solar heating in the upper ocean, from 200 MJ·m^{-2} during 1979–1992 to 400 MJ·m^{-2} during 1992–2005. Steele et al.[6] estimated a similar average increase in upper-ocean heat content of the summertime southern Chukchi and western Beaufort Seas, a rate of about 50 MJ·m^{-2} per decade during 1965–1995, or 150 MJ·m^{-2} over 30 years. Moreover, the melting sea ice increased the freshwater content (*FWC*) in the upper ocean, and was the dominant factor for freshwater content. There was a remarkable salinity decline in the upper 100 m during the Surface Heat Budget of the Arctic Ocean (SHEBA) project of October 1997, compared with the 1970s, equivalent to a surface input of about 2.4 m of freshwater[7]. It appeared that *FWC* had increased from 2002 to 2006[8]. This change

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*Corresponding author (Master student, polar physical oceanographic research, email: wlzhongouc@163.com) would alter seawater properties in the upper ocean[9−11].

Variation in upper-ocean heat content of the Canada Basin is closely related to inflow of Pacific water, discharge of rivers from North America and Eurasia, variation of sea ice, and other factors. The stratified structure of the upper ocean in the basin is complicated. The upper 40 m layer is characterized as a seasonal mixed layer of temperature and salinity, which is strongly affected by melting of sea ice, the extent of river discharge, and sea ice formation. From the base of the mixed layer down to about 200 m depth is Pacific inflow water; a temperature maximum marks Pacific Summer Water (PSW), whereas a temperature minimum indicates Pacific Winter Water (PWW). Atlantic Water (AW) is below the PWW[8,12−14]. A summertime temperature maximum in the upper 50 m layer was found in recent years. Zhao et al.[15] described it as a Subsurface Warm Water and pointed to heating by solar radiation and surface cooling by the sea ice as mechanisms. This summertime temperature maximum water was referred to as near-surface temperature maximum (NSTM) water by Jackson et al.[16]. Considering temperature and salinity, they posited three criteria for the definition of NSTM, to ensure that the temperature maximum water was not PSW. Zhao and Cao[17] further studied multi-year variations of NSTM water. The NSTM is an indicator of warming in the Arctic Ocean, and a high correlation between sea ice concentration and this temperature maximum has been shown[18]. The PSW and NSTM water are dominant factors in the variation of upper-ocean heat content.

One of the important goals of the SHEBA project was the study of ice-ocean heat flux mechanisms. Studies based on SHEBA have shown a positive feedback mechanism between sea ice melt, the energy of solar radiation penetrating the ocean, and seawater heat content. This indicates that thinner ice leads to increased solar radiation penetrating the ocean, resulting in greater heat content and enhanced ice bottom melting[7,19−21]. Furthermore, the heat content below the remnant of the winter Mixed Layer (rML) and above the PWW may be stored for a year, and it has a close relationship with advection and mixing[17]. The annual mean heat content of the top 1 000 m in the Canada Basin varied from –3.5 to +1.8 $\mathrm{GJ \cdot m^{-2}}$, with the greatest seasonal deviation in regions having seasonal ice cover or ice free conditions[22]. Despite these studies, very little is known about the effect of warming on the structure and properties of the upper ocean, or about the consequences of sea ice reduction on upper-ocean heat content[10].

Scientists have been paying greater attention to the crucial role of the Arctic Ocean in climate change. The most important component of this role is associated with thermodynamic processes in the upper ocean. What are the characteristics of upper-ocean heat content in the Canada Basin? How do the driving factors affect the heat content? And how did the structure of upper-ocean heat content change with the tremendous reduction of sea ice? Based on conductivity, temperature, and depth (CTD) data collected during the summers of 2003 and 2008 by the Chinese National Arctic Research Expeditions (CHINARE-Arctic) and Canadian research ship Louis S. St-Laurent, we examine vertical and horizontal variations of upper-ocean heat content and its change between those years. We quantitatively analyze the heat content and investigate the driving factors.

1 Data and method

1.1 Stations and locations

Information on station locations and CTD cast dates of the cruises by CHINARE-Arctic and the Canadian Arctic Research Project (2003 and 2008 summers) is listed in Table 1. Each row lists two geographically proximate stations in 2003 and 2008, respectively. Because of different ice conditions in the two summers, only some stations could be compared. The blue dots in Figure 1 are the stations; those with station names are used for comparison in Table 1. Most of the observation sites of the CHINARE-Arctic cruises were in the western and southwestern basin, whereas the Canadian sites were mostly in the central basin.

1.2 Data

Temperature, salinity and depth data were collected by the CHINARE-Arctic and Canadian Arctic Research cruises from July to September, 2003 and 2008. The CHINARE-Arctic data were issued by Data-sharing Network of Earth System Science–Polar Regional Center (http://www.chinare.org.cn/); The Canadian data were issued by the Joint West Arctic Climate Study (JWACS) and Beaufort Gyre Exploration Project (BGEP).

Sea ice concentration data were obtained from

Table 1 Locations of stations used for comparison, and CTD cast dates. Each row lists two comparable stations deployed in 2003 and 2008, respectively

Station	Date (DD/MM/YYYY)	Latitude (N)	Longitude (W)	Station	Date (DD/MM/YYYY)	Latitude (N)	Longitude (W)
P13	10/08/2003	74.8005°	165.8067°	B11	07/08/2008	75.0000°	165.0350°
P15	11/08/2003	74.5197°	161.8400°	B12	07/08/2008	75.0077°	162.0275°
P16	12/08/2003	74.3385°	159.9342°	B13	07/08/2008	74.5050°	158.9933°
B11	12/08/2003	73.9950°	156.3317°	B14	08/08/2008	73.9890°	155.9663°
S12	18/08/2003	72.7192°	158.6543°	S12	09/08/2008	72.7188°	158.6567°
S13	18/08/2003	72.9383°	158.2977°	S13	08/08/2008	72.9383°	158.3250°
S14	18/08/2003	73.1558°	157.9322°	S14	08/08/2008	73.1682°	157.9172°
S15	18/08/2003	73.3710°	157.5625°	S15	08/08/2008	73.3772°	157.5400°
S16	18/08/2003	73.5910°	157.1638°	S16	08/08/2008	73.5848°	157.1500°
S22	16/08/2003	71.9383°	154.5342°	S22	09/08/2008	71.9250°	154.6767°
S23	15/08/2003	72.2077°	154.1075°	S23	10/08/2008	72.2017°	154.4212°
S24	15/08/2003	72.4067°	154.1733°	S24	10/08/2008	72.4017°	154.1753°
S25	15/08/2003	72.7418°	153.4030°	S25	10/08/2008	72.7295°	153.4088°
S26	15/08/2003	73.0000°	152.6667°	S26	10/08/2008	72.9883°	152.6907°
B32	13/08/2003	75.0013°	151.5477°	B22	11/08/2008	74.9950°	151.9950°
B33	14/08/2003	74.6300°	149.2742°	B23	11/08/2008	74.6702°	149.9808°
P27	19/08/2003	75.4925°	156.0060°	P27	12/08/2008	75.4978°	155.9712°
B78	28/08/2003	78.4785°	147.0280°	B79	16/08/2008	78.9827°	147.6157°
B80	26/08/2003	80.2235°	146.7377°	B80	16/08/2008	80.0080°	147.4887°
P11A	08/09/2003	75.0005°	169.9893°	R17	06/09/2008	75.0015°	168.1455°
006	13/08/2003	73.0000°	149.9970°	021	26/07/2008	73.0000°	150.0002°
007	13/08/2003	74.0000°	149.9980°	022	26/07/2008	73.9998°	150.0023°
042	02/09/2003	75.0010°	140.0070°	063	13/08/2008	75.0003°	140.0000°
009	14/08/2003	75.0090°	150.0170°	024	27/07/2008	74.9927°	150.0567°
028	25/08/2003	76.0120°	150.0070°	030	30/07/2008	75.9965°	149.9770°
040	31/08/2003	76.2090°	139.8260°	061	12/08/2008	75.9505°	140.0822°
030	26/08/2003	76.9870°	140.1010°	055	10/08/2008	76.9922°	140.0128°
027	24/08/2003	76.9940°	150.1010°	031	30/07/2008	76.9975°	150.0408°
026	23/08/2003	78.0020°	149.9140°	034	01/08/2008	78.0027°	150.1760°
024	22/08/2003	79.0100°	149.9570°	041	03/08/2008	79.0173°	149.8920°

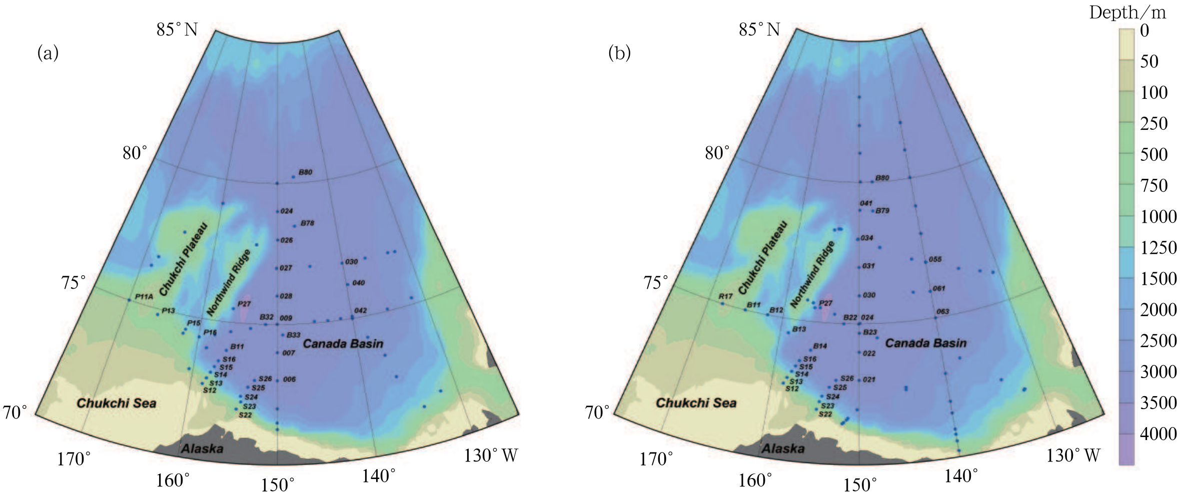

Figure 1 Locations of CTD stations for (a) summer 2003, and (b) summer 2008. Blue dots with names are stations used for comparison.

Physical Analysis of Remote Sensing (PHAROS) images of Bremen University, using AMSR-E daily sea ice concentration products with resolution 6.25 km.

1.3 Calculation of heat and freshwater contents

Heat content is superior to other variables in reflecting heat budget variation, since its change is affected by both temperature and salinity. It represents the changing energy of seawater and heat balance. We calculated the heat content using

$$\Delta H = S \cdot \int \rho C_{\mathrm{p}} \Delta T dz, \tag{1}$$

where S represents the area, ρ is water density, C_{p} is the specific heat of seawater, which is 4 096 J·(℃·kg)$^{-1}$, and $\Delta T = T - T_0$ is the temperature with respect to T_0= –2℃.

The large reduction in sea ice cover would increase freshwater content. Therefore, we also analyzed the change of FWC using

$$FWC = \int_{z_{\mathrm{lim}}}^{0} (1 - S(z)/S_{\mathrm{ref}}) dz, \tag{2}$$

where S is *in situ* salinity, S_{ref} is the reference salinity, which is set at 33.1 psu for the typical PWW salinity, and Z_{lim} is the depth of the reference salinity. The physical meaning of FWC is therefore the total thickness of freshwater in the water column above the depth of the reference salinity.

2 Results

2.1 Seawater properties of the upper ocean in the Canada Basin

To understand the distribution and properties of the upper-ocean heat content in the Canada Basin, we must have a clear understanding of the upper-ocean thermal structure, as the properties of seawater determine heat content. In the top 20 m, there is relatively fresh water with temperature near the freezing point in the surface mixed layer[13]. Below this layer is a temperature maximum that is composed of water of Pacific origin, and is called the PSW, with typical temperature exceeding –1.0℃ and salinity of ~31–33 psu[12,14]. A temperature minimum at depth ~150 m and a salinity of ~33.1 indicates the PWW[13,23], in this case establishing the complex layers in the upper ocean of the basin.

The NSTM water occurred in the top 50 m layer of the basin, after a recent drastic decline of sea ice. Past studies have shown that the NSTM phenomenon increased in dimension and strength over recent years[17–18]. Our comparison of the situations in 2003 and 2008 shows three significant changes (Figure 2). First, there were regions where NSTM appeared to increase in the basin, as a result of the tremendous reduction of sea ice cover in 2008 and more absorbed solar energy. Second, in some parts of the basin, the temperature of the PSW was lower in summer 2008 than in summer 2003. Last, the depth of the Pacific inflow water increased and its salinity decreased in the upper ocean.

2.2 Vertical and horizontal variations of heat content

The largest change of heat content in the vertical was in the top 200 m. The heat content from 200 to 1 000 m, which was constituted by AW (the core temperature of AW was at depth ~400 m) varied in space (Figure 3). In the southern stations of the basin, especially those on the slope of the continental shelf, the heat content increased at depths about 200–300 m; there were relatively small differences about 300–1 000 m. It seems that the AW was sallower in 2008 than in 2003 (Figure 3a). On the other hand, in the central and northern basin, the heat content decreased at depths about 200–300 m, while it slightly increases at about 300–1 000 m. This is very different from the southern stations. Figure 3 indicates that the AW was deeper in 2008 than in 2003 at the central and northern stations (Figures 3b and 3c). The incremental depth of AW varied between stations, mostly about 50 m. Actually, the variation of annual heat content was small below 200 m, and was determined by the changing depth of the AW. The variation of heat content in the top 200 m was more susceptible to seasonal change involving thermodynamic processes, and it also varied annually. We focused on the heat content variation of the top 200 m.

In general, the main effects on upper-ocean heat content in the Canada Basin are solar radiation, sea ice cover, freshwater input from melting of sea ice, and heat advection by Pacific and Atlantic inflows. Our results suggest that the typical characteristic of the upper ocean in the basin was warming. In most parts of the basin during summer 2003, sea ice did not completely melt, and incident solar radiation was mainly consumed by sea ice melt. In this case, the upper-ocean heat content did not significantly change. But the catastrophic reduction of sea ice in summer 2008 resulted in more open water area. Consequently, more solar radiation was absorbed by the upper ocean, and the heat content substantially

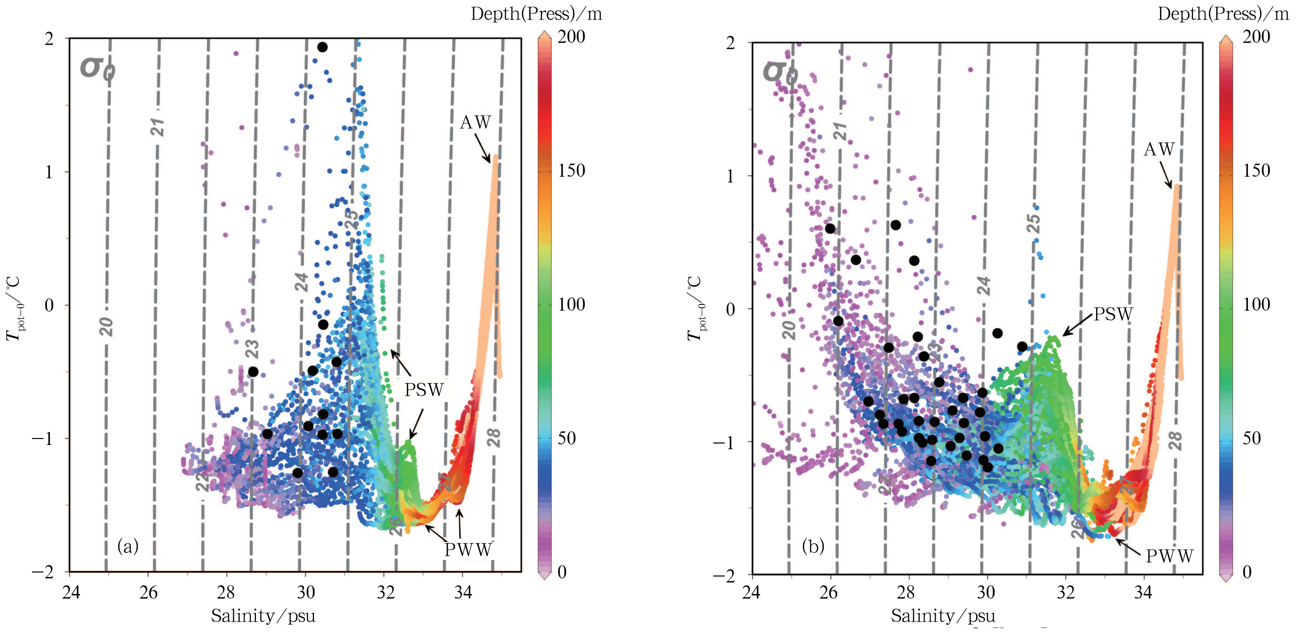

Figure 2 Vertical thermal characteristics of the upper ocean presented as T–S diagrams in (a) summer 2003, and (b) summer 2008, with depth shallower than 200 m. Black dots mark temperature maxima of NSTM. Color bars indicate depth of CTD data, while the dash line refers to the isopycnals. PSW: Pacific Summer Water, PWW: Pacific Winter Water, AW: Atlantic Water.

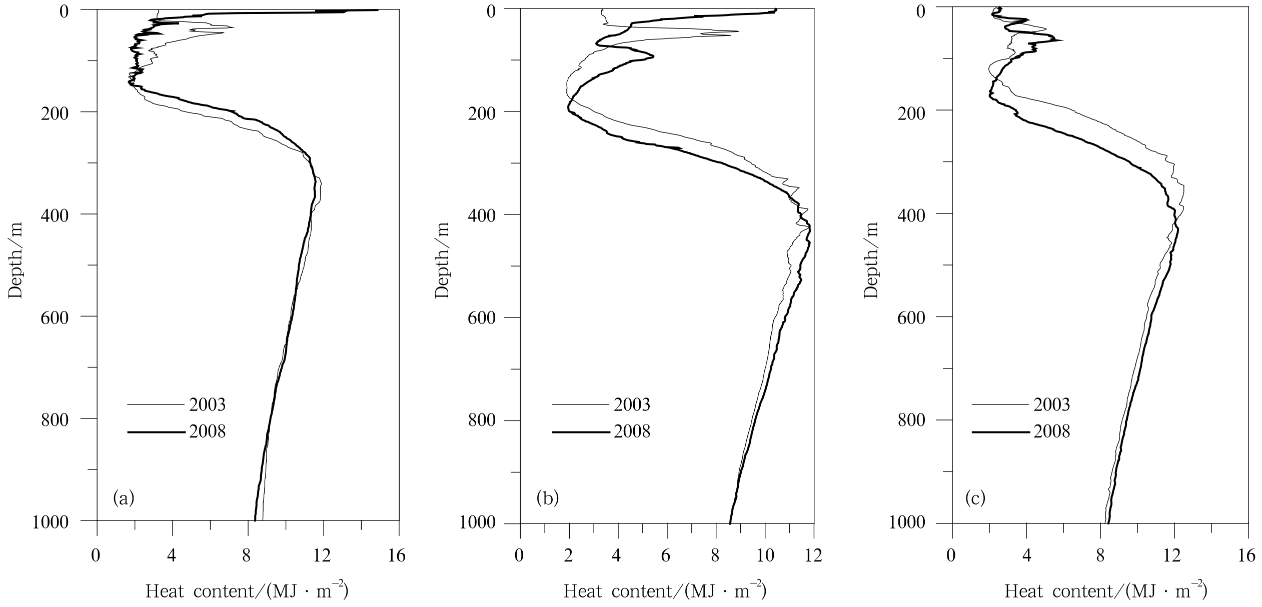

Figure 3 Heat content of the top 1 000 m for representative stations in the southern, central, and northern Canada Basin. (a) Stations S13 and S13; (b) Stations B32 and B22; (c) Stations B78 and B79.

increased in some parts of the basin. As mentioned in the previous section, our initial findings suggest three main phenomena, based on comparison of the two summers. First, the heat content decreased at the southwestern and southern stations at depths ~20–80 m. Second, the depth of Pacific inflow water (including the PSW and PWW) deepened in the central and northern basin. Third, the NSTM expanded, appearing in the northern part of the basin.

We now examine the first phenomenon, the heat content change at the southern and southwestern stations. There, we choose stations S13 (2003) and S13 (2008), and 006 (2003) and 021 (2008) (Figures 4a and 4b). The areas surrounding the stations in summer 2003 were covered by sea ice, whereas in summer 2008 the surrounding areas were ice free. In the top 20 m, there was a mixed layer of uniform low temperature in 2003 while the temperature was substantially high as the sea ice totally melted away and more solar energy was absorbed by the upper ocean in 2008. The temperature maximum water at depth ~30–50 m was affected by the NSTM and PSW in 2003, but these were absent in 2008. There were no

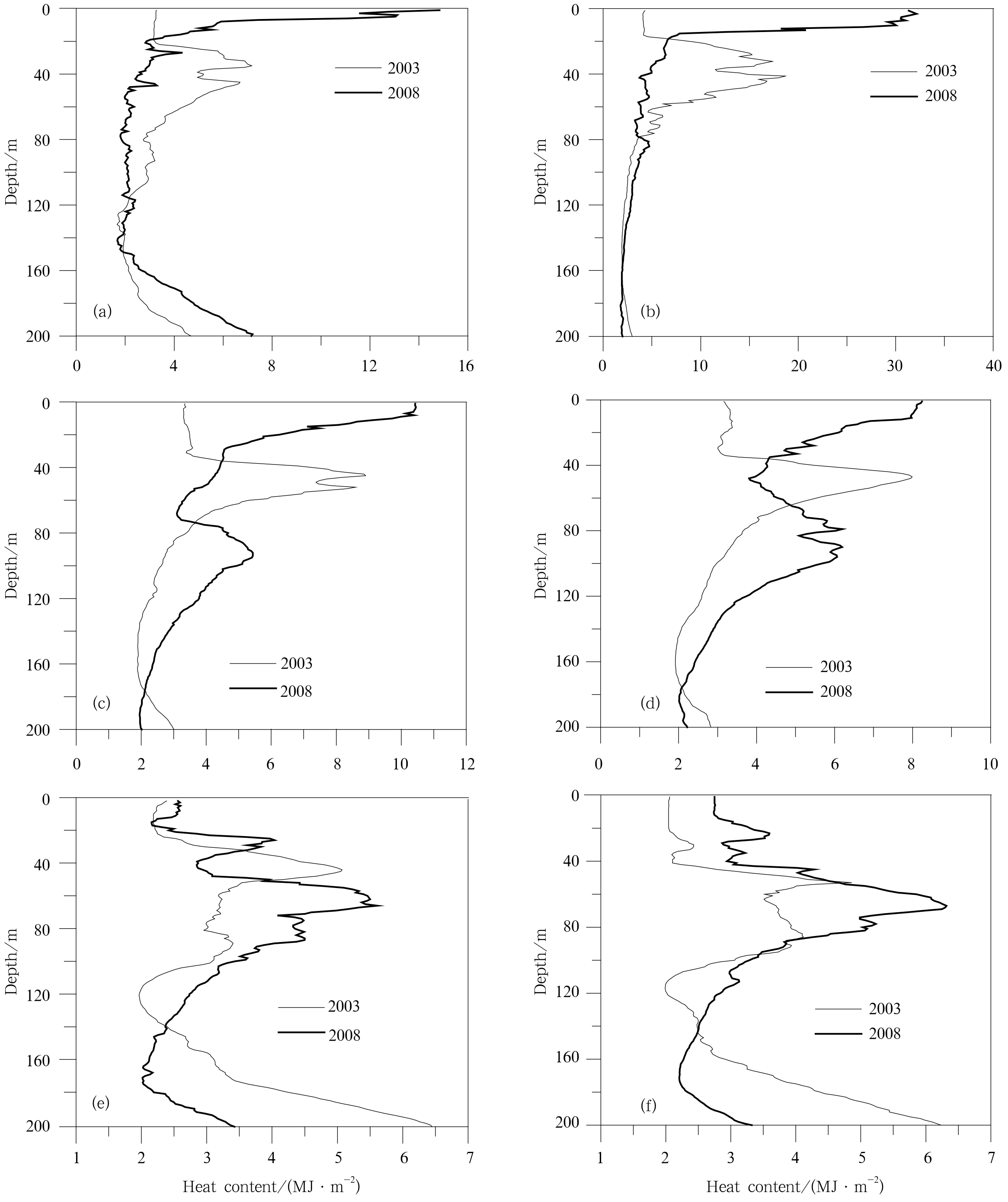

Figure 4 Heat content of the top 200 m in the southern, central, and northern Canada Basin (from top to bottom). (a) Stations S13/2003 and S13/2008; (b) Stations 006/2003 and 021/2008; (c) Stations B32/2003 and B22/2008; (d) Stations 042/2003 and 063/2008; (e) Stations B78/2003 and B79/2008; (f) Stations 024/2003 and 041/2008.

other energy sources except for AW in the depth range ~150–200 m; thus, the variation of heat content in this layer was probably affected by upwelling on the basin shelf[24].

Figures 4a and 4b show that a double-peak structure of heat content may have formed, of NSTM and PSW (from above to below), between ~20–80 m. The minimum temperature between them was the rML (with typical temperature less than −0.5℃, not shown). The reason for the lower heat content at depths ~20–80 m in 2008 may be a phytoplankton bloom following the reduction of sea ice and absorption of a large amount of energy in the top layer. This development decreased solar radiation down to subsurface layers[25], which resulted in the decreased of heat content below the near-surface mixed layer. Simultaneously, the temperature structure of the top 50 m was clearly influenced by the extension of the PSW. This PSW flowed over the shelf of the Beaufort Sea and reached the observing stations in the southern basin during summer 2003, whereas the northward PSW extension was much smaller during summer 2008 (Figure 5). This deviation may be attributable to the relationship between the Pacific inflow water and the Arctic Oscillation (AO)[12]. When the AO was in its positive phase in summer 2003, the Beaufort Gyre weakened and Alaska Coastal Water (ACW) easily flowed into the southern basin. As a result, temperature maximum water was present at depths ~20–80 m in 2003. When the AO phase was negative in summer 2008, the Beaufort Gyre strengthened, and ACW could not readily flow into the southern basin. The heat content was consequently reduced in this layer. More evidence is needed to support this speculation.

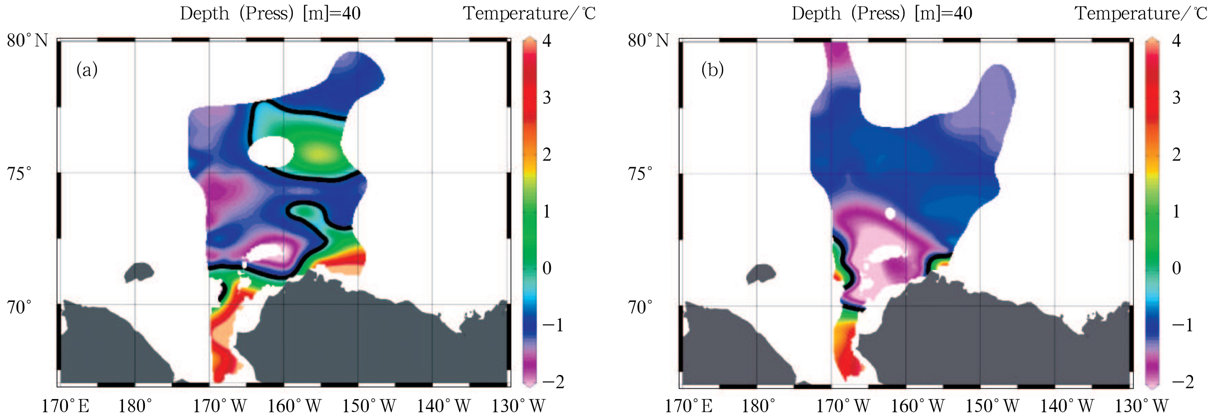

Figure 5 Spatial distribution of temperature of Pacific water. (a) 2003; (b) 2008. Black line represents −0.6℃ isotherm.

For the second phenomenon that occurred at the central stations, we selected stations B32 (2003) and B22 (2008), and stations 042 (2003) and 063 (2008). Sea ice was completely melted at these stations in summer 2008, so the temperature gradient was large in the top 30 m (Figures 4c and 4d). The vertical temperature distribution was typical, with a temperature maximum near 50 m and a minimum near 160 m. In summer 2008, while the shallow temperature maximum water was apparent near 100 m, the temperature minimum water was near 190 m. It is worth noting that the temperature in the upper ocean increased while the Pacific inflow water moved downward, and the incremental depth of Pacific inflow water ranged from 30 to 50 m in spatial scale.

There are many factors that could deepen the Pacific inflow water, such as increased Pacific water inflow, a denser upper ocean, an increase in sea surface dynamic height, and other factors. We investigated various possibilities in order to find out the deepening mechanism. First, the Beaufort Gyre was stronger in 2008, so water in the upper ocean would pile up[2], freshwater would accumulate locally as well and could not easily flow out of the region. This would increase deepening. However, we believe that the change of the gyre could not deepen the Pacific inflow water as much as about 30 m. Second, there was no evidence that showed the discharge of rivers increased. The deepening of the Pacific water could not be caused by increased inflow water. Additionally, the temperature of the upper ocean in the basin was commonly warm, which would not increase density, and it ran counter to the increase of upper ocean density.

To identify the sinking mechanism of the Pacific water, we calculated the change in the freshwater content above the PWW, finding an increased freshwater content in the central basin (Figure 6). This increase was mainly induced by the melting sea ice[7,9,11]. The change of basin freshwater content exhibited an obvious spatial difference. The greatest change was in the central basin, corresponding to the largest change of sea ice cover (Figure 7). The sinking of the Pacific water varied spatially, along with the variation in freshwater content. The maximum sinking of Pacific inflow water was in the central basin. Thus, we suggest that the dramatic reduction of sea ice in the basin increased the freshwater content of the upper ocean. Moreover, the temperature of the upper ocean increased. These two factors resulted in reduction of density in the central basin. Since the Pacific inflow water density did not change appreciably (Figure 8), when this water flowed into the less dense water area, it would sink to a deeper depth. Therefore, we suggest that the main reason for the sinking of Pacific inflow water was the increase in freshwater content in the basin, caused by the reduction of sea ice.

It is obvious that the NSTM was enhanced in the northern basin in summer 2008 (Figures 4e and 4f). The depth of the PWW deepened simultaneously. What is more, it seems that the PSW expanded. This shows a possible increase of Pacific inflow water as a result of the decreased sea ice cover prior to summer 2008. Shimada et al.[27] described a positive feedback mechanism, as follows. Warm PSW flows into the Arctic and changes the lateral boundary condition of sea ice, which would strengthen sea ice motion and upper-ocean circulation, and increase oceanic heat transport. This would warm the upper ocean, further reducing sea ice and delaying its formation near the coast. This in turn would facilitate more warm Pacific water inflow to the Arctic Ocean.

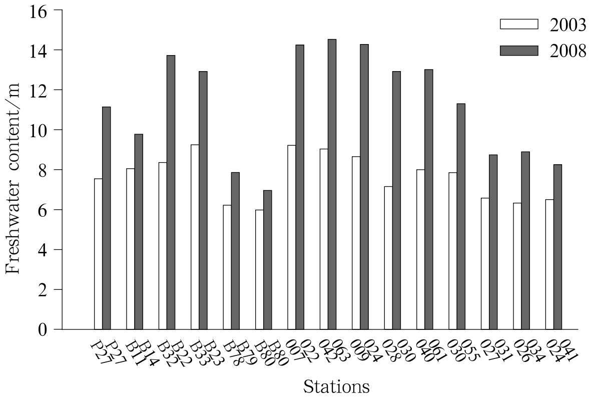

Figure 6 Freshwater content above the PWW, at stations where the depth of Pacific inflow water deepened.

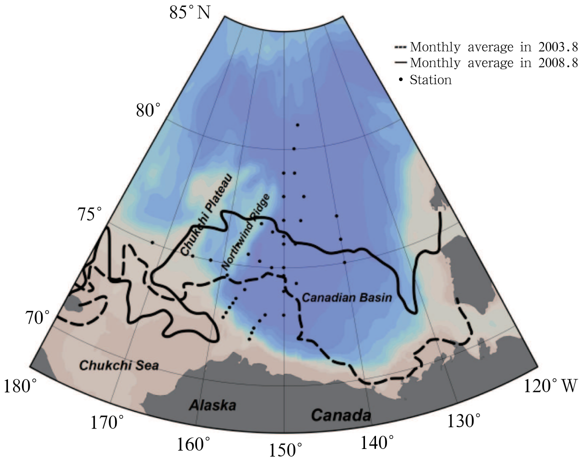

Figure 7 Monthly average ice edge in August (dashed line is ice edge in 2003; solid line is ice edge in 2008; black dots are stations for comparison).

In summer 2008, the total heat content of the top 200 m generally increased in the southern and southwestern basin. The spatial distribution of heat content did not strictly decrease from south to north; instead, there were high and low value areas (Figures 9 and 10). The locations of greatest change in upper-ocean heat content were also those with the largest change in sea ice concentration. The total heat content of the top 200 m ranged from 0.56 to 0.99 TJ·m^{-2} in 2003. The range increased to ~0.58 to 1.11 TJ·m^{-2} in 2008. At some stations, the increment of the heat content exceeded 0.35 TJ·m^{-2}, such as paired stations B33 (2003) and B23 (2008), and stations 007 (2003) and 022 (2008). The heat content at stations of the Chukchi Plateau, such as stations P13 (2003) / B11 (2008), stations P15 (2003) / B12 (2008), and stations P16 (2003) / B13 (2008) increased tremendously, since the Pacific water mainly moves into that area. In 2008, the diminished sea ice allowed more Pacific water to flow into the Chukchi Plateau area.

In the northern Canada Basin, there were some cases of slightly reduced total heat content in the top 200 m, where stations were covered by sea ice in both the 2003 and 2008 summers. Examples are stations B78 (2003) / B79 (2008) and stations 027 (2003) / 031 (2008). This can be explained by the incidence of solar energy, which was mainly consumed by melting sea ice before it

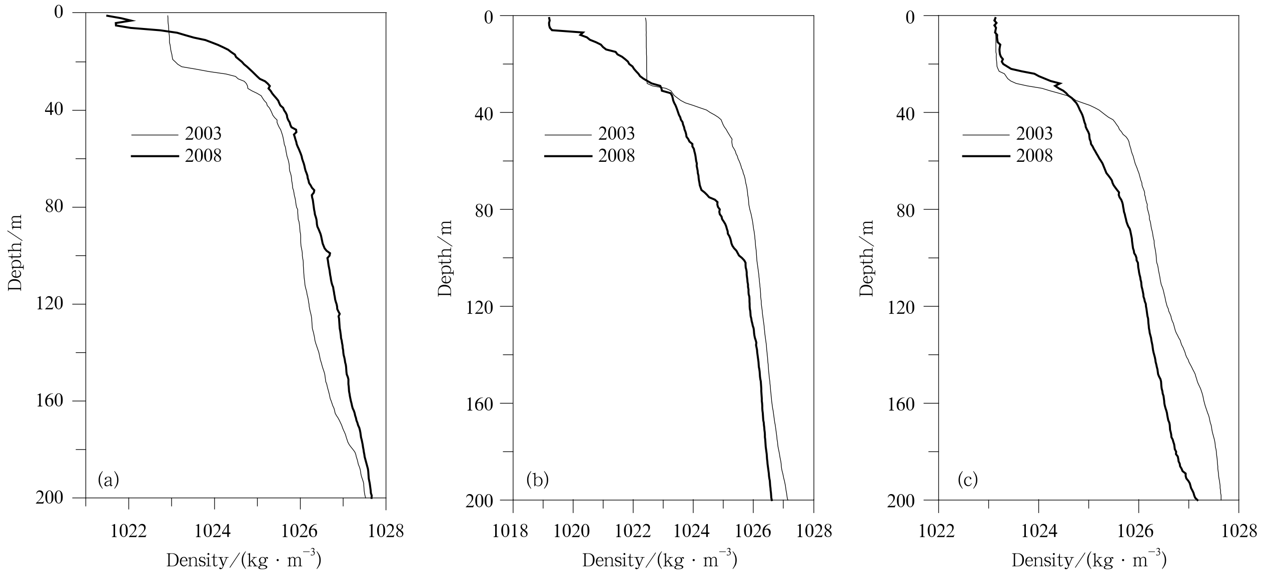

Figure 8 Comparison of density profiles. (a) to (c) represent stations from southern to northern Canada Basin.

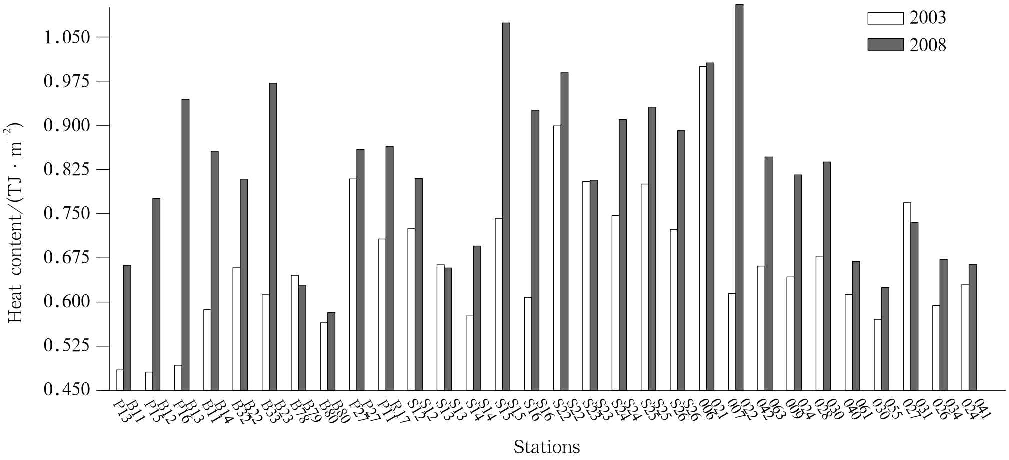

Figure 9 Heat content of the top 200 m.

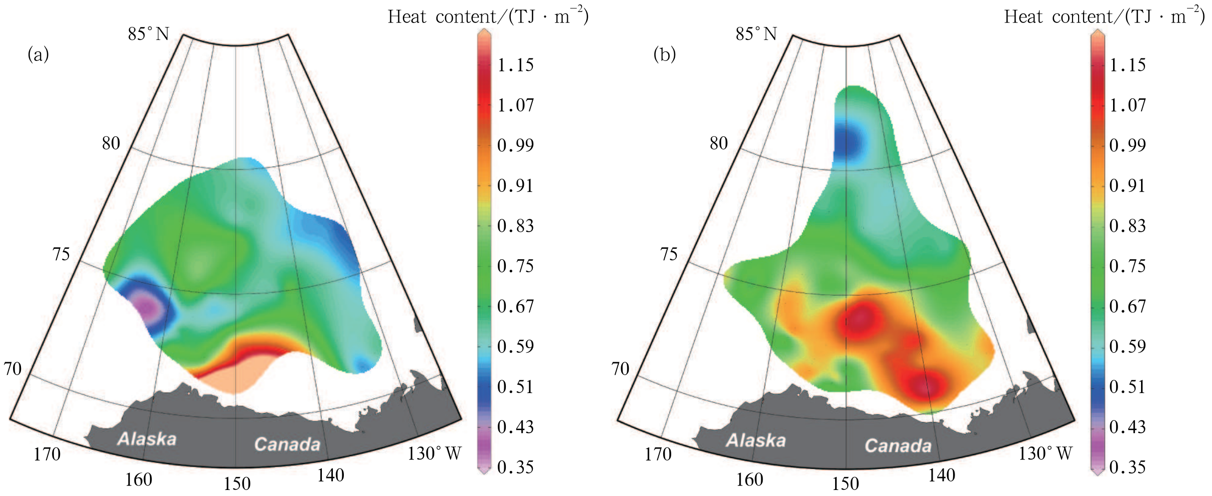

Figure 10 Spatial distribution of upper-ocean heat content in (a) 2003 and (b) 2008.

completely melted. Therefore, upper-ocean heat content did not significantly increase, and even decreased at some stations.

3 Conclusions

The upper-ocean heat content in the Canada Basin significantly changed under the background of global warming. Research into the process of this change will extend our knowledge of the rapidly changing Arctic. Based on CTD data collected in the summers of 2003 and 2008, we analyzed upper-ocean heat content and its variation. Generally speaking, the heat content of the top 200 m increased as a whole, and the depth of Pacific inflow water increased. These changes and their spatial variations were closely tied with a tremendous reduction of sea ice in summer 2008. Our results support previous studies showing not only the NSTM widespread in the Arctic Ocean in recent years, but also increase in its amplitude. What is more, the inflow of Pacific water increased slightly. Our main results are as follows.

(1) In summer 2008, upper-ocean heat content in the basin clearly increased over summer 2003, especially in the southern and southwestern basin. Because of variations in sea ice cover, the mechanisms of ocean warming and its structure differed spatially. In the southern and southwestern basin in 2008, heat content strongly increased in the top 20 m, but decreased in subsurface water. This may be explained by the phytoplankton bloom at the surface, which absorbed a great deal of energy and decreased heat transmission into the subsurface water below the near-surface mixed layer. It may also be explained by a much smaller extension of PSW in the north. In the central basin, where there was greatly reduced sea ice cover, a unique phenomenon was found. That is, the depth of Pacific summer water increased between summer 2003 and summer 2008, from ~50 m to ~90 m. The NSTM was greater in the northern basin during 2008, because of a thinner sea ice cover.

(2) The heat content was strongly related to sea ice extent. With a drastic reduction of sea ice, more solar energy is absorbed by the upper ocean. During summer 2003, the heat content of the top 200 m ranged from 0.56–0.99 TJ·m^{-2}, increasing to ~0.58–1.11 TJ·m^{-2} during summer 2008. At some stations, the increment of heat content exceeded 0.35 TJ·m^{-2}.

(3) The depth of Pacific inflow water in the basin increased substantially in 2008 over that of 2003. The CTD data showed that upper-ocean freshwater content increased as a result of the sea ice reduction. We believe that more freshwater in the upper ocean results in lower salinity and density, thus the relatively denser water from the Pacific would sink.

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