· Article ·

Advances in Polar Science

doi:10.3724/SP.J.1085.2011.00223

December 2011 Vol.22 No.4 223–234

Summer water temperature structures and their interannual variation in the upper Canada Basin

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Received September 16, 2011; accepted November 15, 2011

Abstract Conductivity, temperature and depth (CTD) data from 1993–2010 are used to study water temperature in the upper Canada Basin. There are four kinds of water temperature structures: The remains of the winter convective mixed layer, the near-surface temperature maximum (NSTM), the wind-driven mixed layer, and the advected water under sea ice. The NSTM mainly appears within the conductive mixed layer that forms in winter. Solar heating and surface cooling are two basic factors in the formation of the NSTM. The NSTM can also appear in undisturbed open water, as long as there is surface cooling. Water in open water areas may advect beneath the sea ice. The overlying sea ice cools the surface of the advected water, and a temperature maximum could appear similar to the NSTM. The NSTM mostly occurred at depths 10–30 m because of its deepening and strengthening during summer, with highest frequency at 20 m. Two clear stages of interannual variation are identified. Before 2003, most NSTMs were observed in marginal ice zones and open waters, so temperature maxima were usually warmer than 0°C. After 2004, most NSTMs occurred in ice-covered areas, with much colder temperature maxima. Average depths of the temperature maxima in most years were about 20 m, except for about 16 m in 2007, which was related to the extreme minimum of ice cover. Average temperatures were around –0.8°C to –1.1°C, but increased to around –0.5°C in 2004, 2007 and 2009, corresponding to reduced sea ice. As a no-ice summer in the Arctic is expected, the NSTM will be warmer with sea ice decline. Most energy absorbed by seawater has been transported to sea ice and the atmosphere. The heat near the NSTM is only the remains of total absorption, and the energy stored in the NSTM is not considerable. However, the NSTM is an important sign of the increasing absorption of solar energy in seawater.

Keywords **Canada Basin, upper ocean, near-surface temperature maximum, halocline, warming**

Citation: Zhao J P, Cao Y. Summer water temperature structures and their interannual variation in the upper Canada Basin. Adv Polar Sci, 2011, 22: 223–234, doi: 10.3724/SP.J.1085.2011.00223

0 Introduction

Sea ice is one of the important factors influencing the Arctic climate; it influences strongly the heat flux at the air-sea interface. Another key factor is the thermal structure of seawater under the ice cover, which absorbs solar radiation penetrating through the sea ice and provides heat to influence the melting and freezing of sea ice above.

Based on the criterion of Swift and Aagaard[1] and Aagaard et al.[2] for the water mass in the Canada Basin, there are three main water masses–Arctic Surface Water (ASW, 0–200 m) with low temperature and low salinity, Arctic Intermediate Water (AIW) or Atlantic Water (AW, 200–900 m) with higher temperature and higher salinity, and Deep Water (DW) or Bottom Water (BW, 900 m-bottom) with lower temperature and higher salinity. Usually, there are two temperature maxima in the Canada Basin. One of these is at depth 60–80 m, which originated from Pacific Water (PW), modified in

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the Chukchi Sea and embedded under the remnant of winter convection[3]. Historically, this was called Pacific Summer Water (PSW)[4], originating from either Alaskan Coastal Water (ACW) or Bering Shelf Water (BSW)[5]. Shimada et al. defined the temperature peak as the shallow temperature maximum (STM)[6]. The second temperature maximum at depth 300–600 m is the warm core of the AW, which originates from the North Atlantic and is subducted in the Eurasian Basin, transported by the Arctic Circumpolar Boundary Current, and spread to the entire Canada Basin. A temperature minimum close to the freezing point exists at depth around 150 m, between the two temperature maxima. This is formed by brine rejection during winter freezing on the Chukchi shelf and advected into the deep basin[2]; this water is sometimes called Pacific Winter Water (PWW)[4].

Most studies of the upper ocean focus on the STM, which has been observed in the Eastern Chukchi Sea[7], Canada Basin[8], and Beaufort Sea[9]. The associated water extends to most of the Canada Basin, from the Mendeleev Ridge to the Fram Strait[3], and the temperature of the STM decreases during transport[10].

Recently, another temperature maximum at depth 10–30 m has been frequently observed in the Canada Basin, especially after 2003 (Figure 1). The temperature maximum is distinct from the underlying STM, and separated from it by a temperature minimum. The temperature maximum is higher than the freezing point, but usually lower than that of the STM and the AW. This temperature maximum has been known for years. Maykut and McPhee[11] and McPhee et al.[12] reported this temperature maximum at a depth of 25 m in the Canada Basin in 1975. Shimada et al.[6] described the warm water at this level as a result of warm advection from discharge of the Mackenzie River. Solar energy penetrating through sea ice is absorbed by seawater under the ice, producing the temperature maximum[11,13]. Zhao et al.[14] examined the temperature maximum using observations from summer 1999, and named it Subsurface Warm Water. They proposed that solar heating and surface cooling are fundamental in forming the temperature maximum, and presented an analytical solution of a column model to simulate its development. Wang and Zhao[15] applied the analytical model to open water to verify the occurrence of the temperature maximum, assuming that the open water is not disturbed by strong wind and that air temperature is less than that of seawater. Using a coupled ice-sea numerical column model, Chen and Zhao[16] further simulated the warm water under various conditions, such as thin ice, thick ice, leads, and ice with ice algae, among others, indicating that solar radiation through thin ice and leads in marginal ice zones provides sufficient energy to produce the temperature maximum. Jackson et al.[17] gave the temperature maximum a better name, the near-surface temperature maximum (NSTM), and systematically studied its spatial structure and temporal variation using ice-tethered profiler (ITP) data and conductivity, temperature and depth (CTD) data. Cao and Zhao[18] studied the fine structure of the NSTM using CTD data from 2008 in the Canada Basin, and found that NSTM vertical properties are related to the nature of sea ice.

In this study, CTD data in the Canada Basin observed from 1993–2010 are used to examine the water structure in the upper ocean, and its multiyear change. Since studies of the NSTM mechanism are still limited, related physical processes are discussed in detail. Data sources include the World Ocean Database 2005

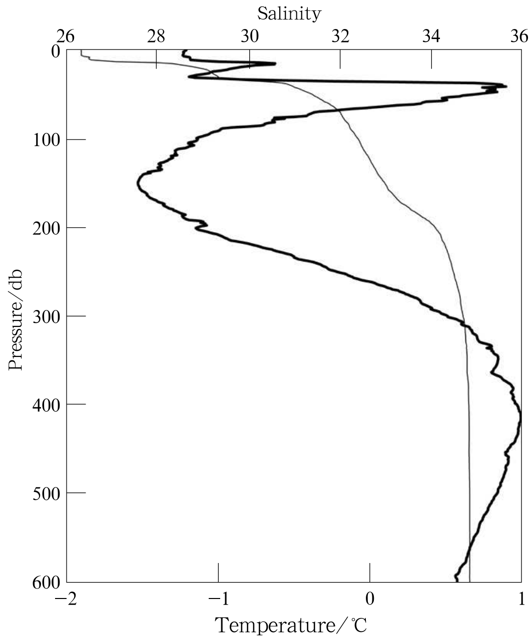

Figure 1 Typical temperature (thick line) and salinity (thin line) profiles with the NSTM in the Canada Basin. Observed at 56°44.16′W, 75°35.64′N on 19 August 2006.

(1993–2002) issued by the Ocean Climate Laboratory of the National Oceanographic Data Center, the LSSL data base (2003–2010) issued by the Joint West Arctic Climate Study (JWACS) and Beaufort Gyre Exploration Project (BGEP), the Mirrai data (1999, 2000, 2002, 2004) issued by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and Chinese National Arctic Research Expedition (CHINARE-Arctic) data from 2003, 2008 and 2010.

1 Warm waters in the upper Canada Basin

Here, the upper ocean means water from the surface down to the cold core near 150 m. Solar heating, wind mixing, vertical convection and ocean-ice-air interactions all occur in this layer. The water structure in this level is not only a result of changing sea ice and climate, but also feeding back ice melting and climate change. The upper Arctic Ocean has experienced rapid change in recent years. Interannual variation of the temperature profile has become an indicator of this change. In this section, we discuss the types of water temperature structures in the upper Canada Basin, as a foundation of the changing summer water profiles.

1.1 Winter water structure under sea ice

In the freezing season, convection occurs by brine rejection during ice freezing. This produces a uniform convective mixed layer with maximum thickness about 40–50 m[19]. The heat of the upper ocean is released to the atmosphere, and the water temperature in the convective mixed layer eventually approaches the freezing point[4].

There are two typical profiles of the winter mixed layer, as shown in Figure 2. The type appearing in most of the Canada Basin exhibits a temperature maximum at depths between 60 and 80 m (Figure 2a). The warm water called STM was advected into the Arctic Ocean from the Pacific during the previous summer. During winter, water in the top 40–50 m is cooled by convection, but the temperature maximum from 60–80 m remains. The other type appears in the shelf and slope areas, without a STM. The cold convective layer links with the cold core at 150 m, with a uniform temperature near the freezing point (Figure 2b). This type indicates that PW has not been transported into the area, or that the water there was replaced by Pacific Winter Water. A mixed layer caused by convection appears in the top 40–50 m for both profile types. These two fundamental structures provide the background for the summer water structure. In summer, the remnants of the two winter structures

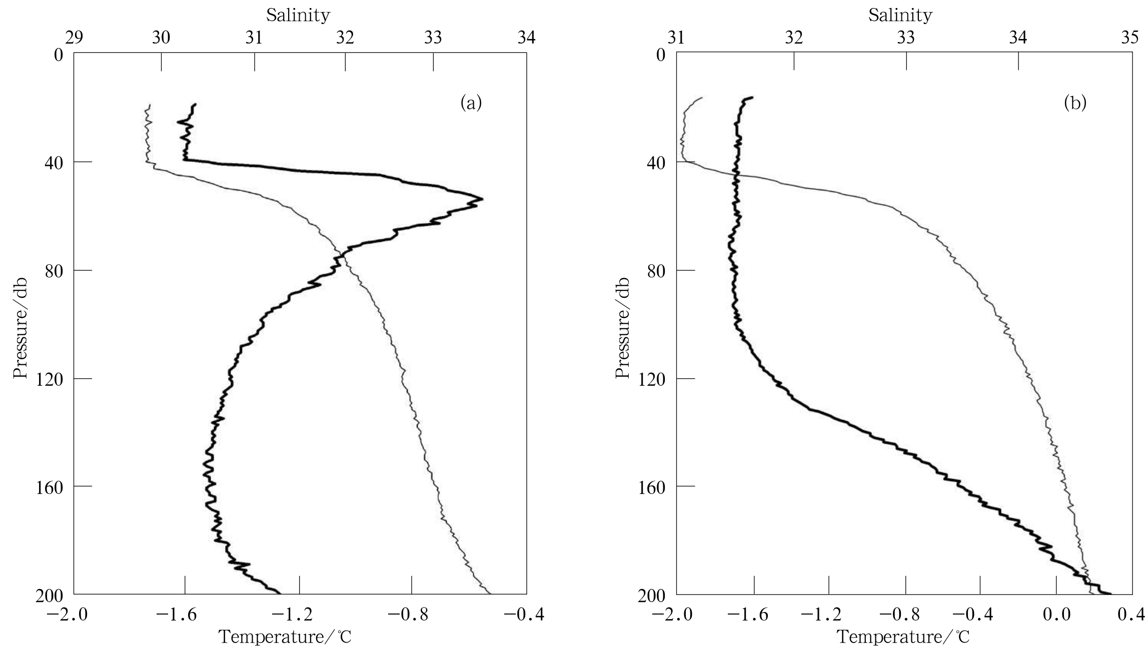

Figure 2 Two typical structures of the remnants of winter convection. (a) Convectively mixed layer with the STM, at 156°27.00′W, 75°15.40′N (on 17 April 1999); (b) convectively mixed layer without the STM, at 167°08.00′W, 85°36.50′N (on 20 April 1999). Thick and thin lines are for temperature and salinity, respectively.

still exist under the thick pack ice, as important water structures.

1.2 NSTM structure in summer

In spring, solar radiation penetrates the sea ice and enters the seawater, producing the NSTM. More solar energy enters from leads of marginal ice zones, causing higher temperature peaks. Corresponding to the two typical winter structures of the upper ocean, two kinds of typical NSTM appear, as shown in Figure 3. One embodies a NSTM+STM structure (Figure 3a), and the other has only the NSTM (Figure 3b). Therefore, the NSTM may emerge with or without the STM. The NSTM and STM are distinguishable because the NSTM is within the convective mixed layer, and its peak is always shallower than 40 m. The maximum NSTM under sea ice is usually low, but it can become much greater with decreased thickness and concentration of sea ice. Since ice melt water remains in the top of the ocean, there usually is a shallow, low salinity layer from 10–20 m, mixed by the turbulence of drifting ice. There is a strong, thin halocline under the fresher layer. The NSTM usually occurs under the halocline, because the weak turbulence of the halocline prevents the upward loss of heat content.

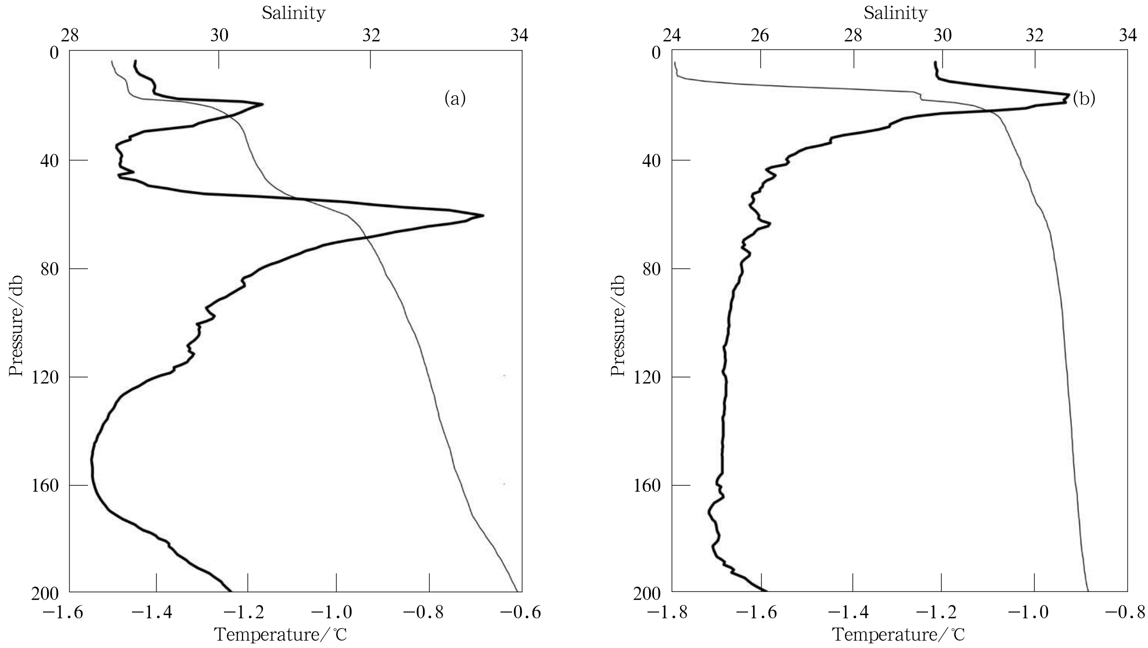

Figure 3 Two typical structures of the NSTM. (a) NSTM with the STM, at 140°00.60′W, 75°59.64′N (on 23 August 2004); (b) NSTM without the STM, at 140°11.29′W, 70°26.56′N (on 17 September 1996). Thick and thin lines are for temperature and salinity, respectively.

In undisturbed open water, more solar energy enters the ocean. As long as the air temperature is less than the water temperature, the NSTM can appear quickly, and the temperature extreme is much greater than that under sea ice (Figure 4). The observed maximum temperature extreme exceeds 5℃. It is verified that both solar heating and surface cooling are principal mechanisms for producing the NSTM.

The lifetime of the NSTM is dynamic. It emerges, strengthens, and vanishes. Jackson et al.[17] proposed three criteria for the NSTM in terms of salinity and minimum value of temperature peak, to distinguish the NSTM from the STM. These criteria apply to developed NSTMs. Emerging NSTMs have very weak temperature peaks (Figures 5a and 5b), but they represent an important stage in the NSTM annual cycle.

The NSTM under sea ice should exhibits a single temperature peak, since the cooling above is nearly constant. The NSTM in ice-free water, however, may have a multi-peak structure, such as the double peaks in Figure 6a and triple peaks in Figure 6b. We speculate that this multi-peak structure is generated by variable cooling at the surface of the ice-free water, or of ice-covered water with very low ice concentration.

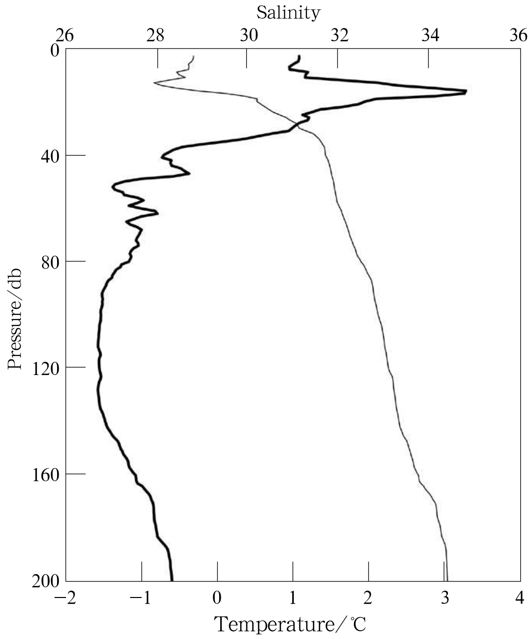

Figure 4 NSTM in open water. Observed at 158°59.28′W, 73°1.56′N (on 19 September 1999). Thick and thin lines are for temperature and salinity, respectively.

Therefore, the NSTM could appear in either ice-covered or ice-free water, when solar radiation heating and surface cooling exist simultaneously. The NSTM under sea ice is much more stable and longer lasting than in open water, where there is no wind stirring and weak turbulence. There is no NSTM under thick ice, because of insufficient solar heating. There is also no NSTM when air temperature is greater than water temperature, because of insufficient surface cooling.

Solar radiation penetrating sea ice and leads in summer is the main heat source for the upper ocean, as widely addressed by previous studies[11−13,20]. Under the influence of global warming, the Arctic is experiencing rapid changes, such as increasing air temperature, and decreasing ice extent[21−22] and thickness[23−24]. Sea ice extent particularly declined in summer 2007, by 37%[25]. These factors will greatly influence the structure of the NSTM.

Furthermore, the NSTM is not only related to solar radiation, but also to surface cooling[14]. If there is no surface cooling, the temperature maximum should appear at the surface. Therefore, heating by solar radiation and surface cooling are two basic factors in NSTM formation. Solar heating occurs when solar energy enters the ocean, whether it is ice-covered or ice-free. Surface cooling occurs when the surface temperature is less than that of seawater; whether this condition is caused by sea ice or cold air.

In previous studies, only the NSTM in the Pacific was reported. Solar radiation heating and surface cooling also occur in the Atlantic. There, however, in summer, the warm current influences the marginal ice zone, and water with higher temperature submerges the NSTM. Therefore, the NSTM should only appear in the upper

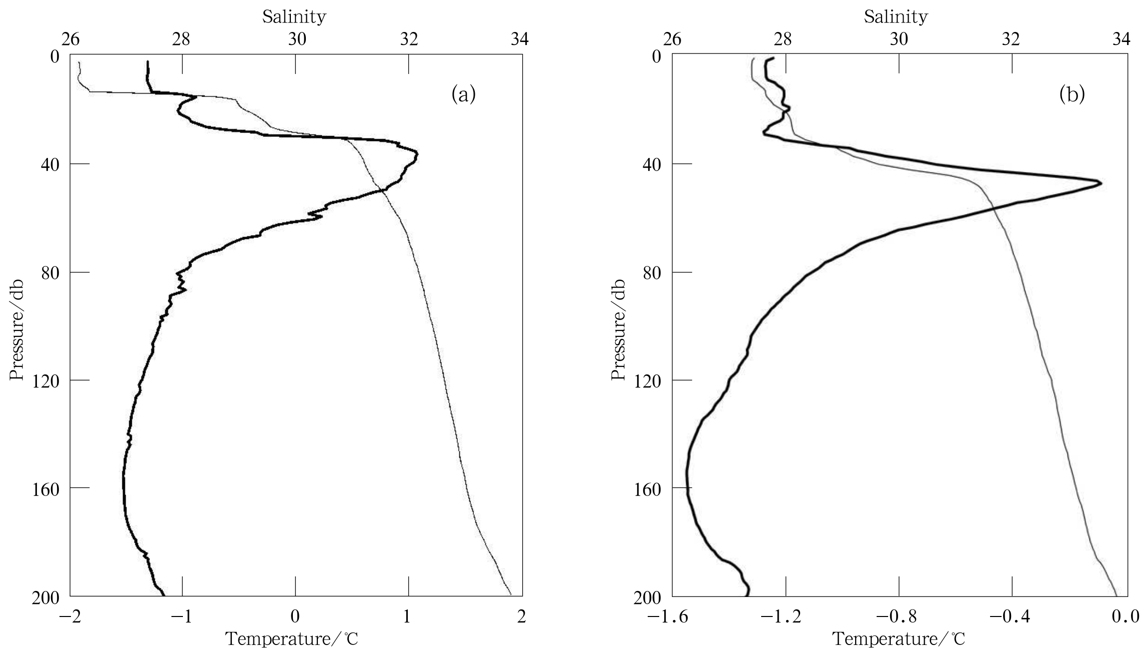

Figure 5 Developing NSTM. (a) Observed at 156°17.05′W, 75°35.26′N (on 19 August 2006); (b) observed at 139°59.34′W, 74°59.82′N (on 2 September 2003). Thick and thin lines are for temperature and salinity, respectively.

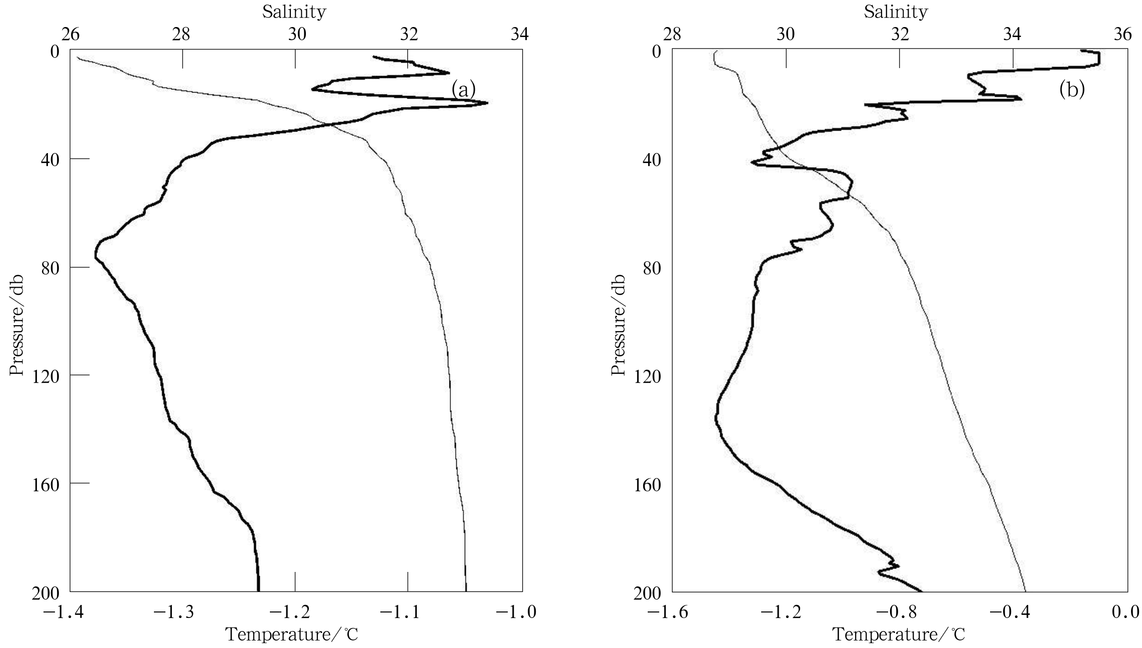

Figure 6 NSTM with multiple temperature peaks. (a) Observed at 99°19.73′W, 69°49.31′N (on 31 July 2006); (b) observed at 129°58.39′W, 73°46.61′N (29 July 2007). Thick and thin lines are for temperature and salinity, respectively.

water with low temperature.

In other regions of the world oceans, there are several kinds of water with a temperature maximum in subsurface level. They are caused by seasonal cooling or subduction of warm and salty water. The mechanism of NSTM with solar heating and surface cooling only appears in polar regions, including the Arctic and Antarctic.

1.3 Wind-mixed structure in summer

In ice-free areas, wind stirring usually produces a mixed layer of 15–20 m or more during storms. The mean temperature of the wind-driven mixed layer depends on air temperature, as shown in Figure 7. In cold conditions, a relatively cold wind-driven mixed layer (Figure 7a) will be produced as a typical upper ocean temperature profile in summer. Sometimes, a relatively warm mixed layer appears, as shown in Figure 7b. The mixed layer water comes from three possible sources.

PW as a main source in the upper ocean usually originates from the Bering Strait, with a relatively warm surface temperature. It is mixed by wind in the northern Bering Sea, before entering the Arctic with a uniform mixed layer[26]. PW always maintains a warm mixed layer during its northward journey, until its heat is exhausted. The original salinity of PW in the Bering Strait exceeds 31.2. However, the salinity becomes much less in the Arctic because of mixing with ice melt water[6].

In the Canada Basin, runoff from the Mackenzie River controls the upper ocean along the coast[27]. The river water is a source of warm water but with very low salinity. By mixing with ice melt water, the river water generates a very low salinity area. When the river water travels far from the river delta and mixes with ice melt water, it is difficult to distinguish it from PW by salinity alone.

The third source is local ice melt water in open water. After ice melt, water with low salinity and low temperature is heated by local solar radiation and mixed by wind. A mixed layer forms quickly in open water, when acted upon by strong wind.

As PW entering the Arctic follows the retreating marginal ice zone, the PW distributes widely in open water in the Canada Basin, and mixes with ice melt water. Thus, the three types of water are difficult to distinguish in open water. Isotope analysis is sometimes more effective to reveal the mixing ratio in a water sample[28].

1.4 Advected water under sea ice

Not all temperature maxima under sea ice are the NSTM.

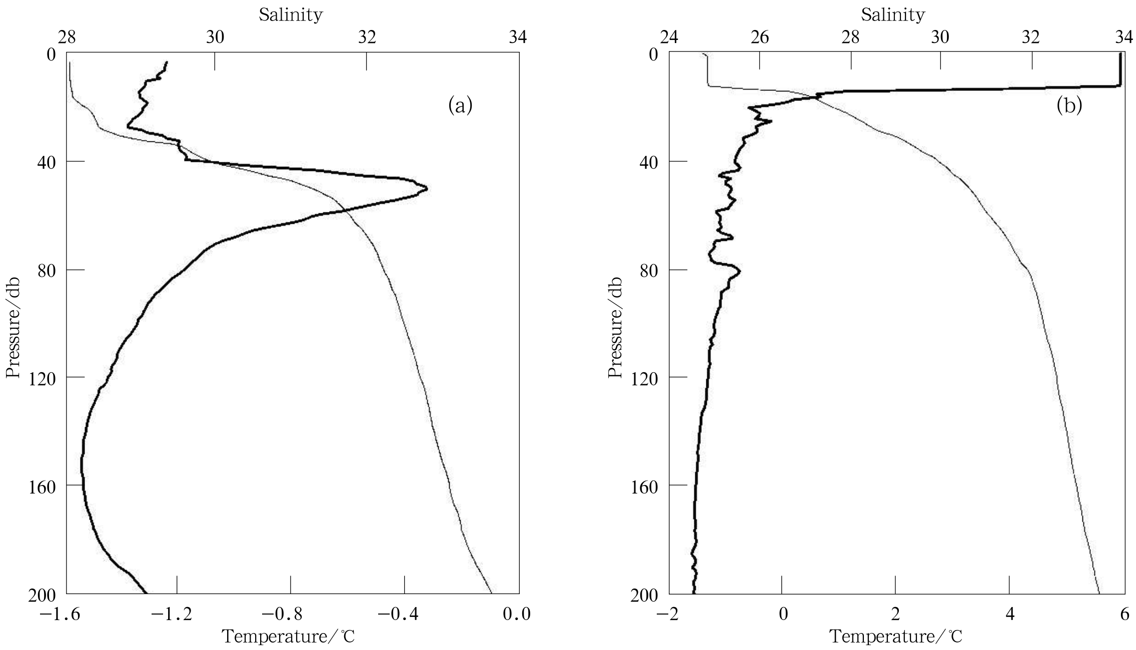

Figure 7 Colder (a), and warmer (b) wind-driven mixed layers. (a) Observed at 143°16.86′W, 75°02.70′N (on 30 August 2003); (b) observed at 150°00.01′W, 73°00.00′N (on 26 July 2008). Thick and thin lines are for temperature and salinity, respectively.

We have stressed that the NSTM is formed by solar heating and surface cooling. If the heat of a temperature maximum is produced by other mechanisms, it should be distinguished from a NSTM. A typical case is water under sea ice that is advected from open water, which we call advected water.

In a marginal ice zone, mixed water can advect beneath sea ice, or sea ice could drift above the mixed water, so it may be observed in ice-covered regions. The open water may infiltrate under sea ice, because of the barotropic pressure gradient along the marginal ice zone established by wind. The advected water, with mixed layer structure, replaces winter water when it is transported under sea ice. The original mixed layer structure is easily distinguished from the NSTM; the NSTM temperature peak is normally sharp, whereas the temperature profile of the advected water has no peaks (Figure 8a). However, since the overlying sea ice cools the advected water, the uniform temperature profile of the advected water will be sharpened, and a temperature maximum will appear similar to the NSTM (Figure 8b).

The thermal contributions of the NSTM and advected water to sea ice are very different. The heat transport of the NSTM to sea ice is from local heating, resulting in a relatively small heat flux. The advected water originates elsewhere and has a much greater heat content and upward heat flux. The heat release from this water can accelerate ice melt and retard ice freezing over a large area. Therefore, we should carefully distinguish the NSTM from the warm advected water, to accurately calculate the heat budget of the upper ocean. Nevertheless, it is difficult to distinguish the two by CTD data alone.

Sometimes, the temperature structure is more complex. When there is no strong wind, a NSTM can again develop, superposing on the wind-driven mixed layer under solar heating and surface cooling conditions. A temperature peak can arise from the advected water under sea ice (not shown).

1.5 Categories of upper temperature structures

In the Canada Basin during summer, there are four basic kinds of water structures: remnant winter convection under thick ice, the NSTM in marginal ice zones, the wind-mixed layer in open water, and advected water under sea ice (Table 1).

NSTMs are found under sea ice, in ice-free water, and superposed on mixed or advected water, all of which are related to solar heating and surface cooling. Another temperature maximum is sharpened by surface cooling

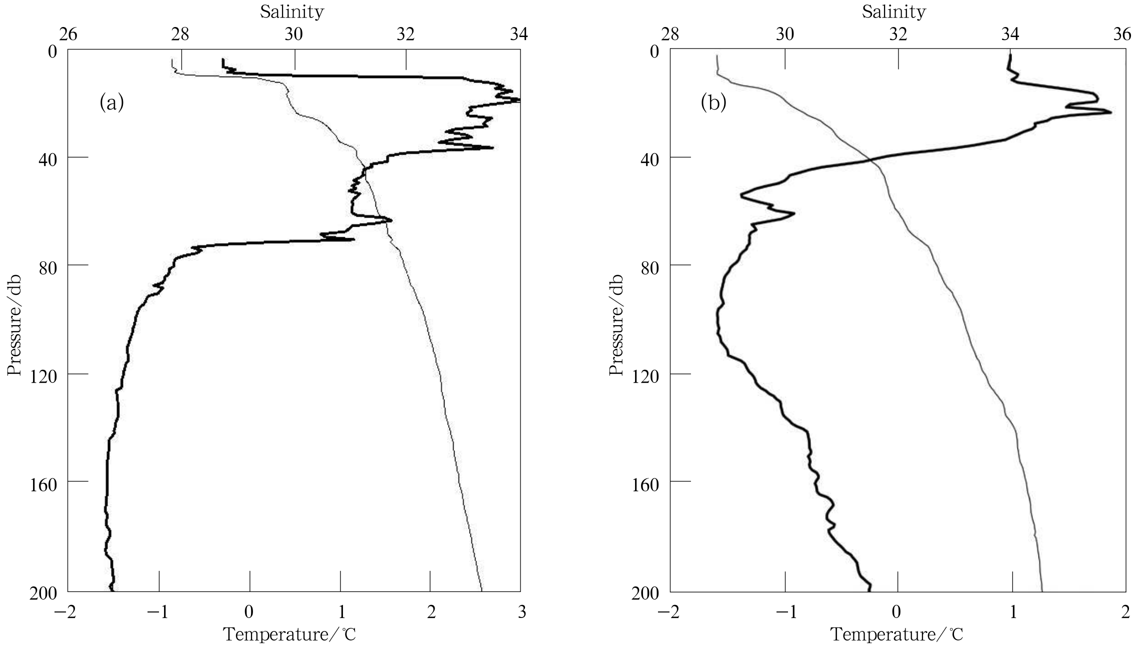

Figure 8 Advected water under ice cover. (a) Advected water observed at 158°29.91′W, 73°30.05′N (on 25 September 2000); (b) Advected water similar to the NSTM observed at 159°35.88′W, 73°12.06′N (on 19 September 1999). Thick and thin lines are for temperature and salinity, respectively.

Table 1 Structures of upper ocean water in summer

Winter	Summer	Location	Mechanism
Convective mixed layer	Convective mixed layer	Pack ice	Insufficient solar radiation
	Near surface temperature maximum	Ice covered water and undisturbed open water	Solar radiation heating and surface cooling
	Wind-driven mixed layer	Open water	Wind-driven mixing
	Advected water	Ice covered water	Surface cooling

from advected water. It is not formed by solar heating, but it is very similar to the NSTM and there is no reliable way to distinguish the two. Consequently, this temperature maximum is sometimes taken to be the NSTM.

2 Multiyear variation of the NSTM

Among the four summer water structures, the remnant winter water, wind-driven mixed layer, and advected water are less dependent on the sea ice condition. The multiyear variation of upper ocean structure is mainly expressed by the NSTM.

The NSTM furnishes an important indication of increased absorption of solar energy by seawater. Decreased ice coverage, concentration and thickness permit more solar energy transmission into the water, increasing ice melt, and producing positive feedback to the Arctic climate[29].

2.1 Occurrence of temperature maximum

The frequency of NSTM depth during 1993–2010 is shown in Figure 9. Most NSTMs were from 10–29 m, with greatest frequency at 20 m. Those NSTMs shallower than 10 m are developing; they deepen and strengthen during summer. At depths below 30 m the NSTMs are developed, or formed from advected waters. The dates of the obtained data are denoted in Table 2 by blue marks, and data with the NSTM are marked by red diamonds. Most NSTMs before 2001 appeared in September, because of heavy summer sea ice that persisted until then. From 2002 onward, the NSTM appeared earlier, and occurrences were mostly observed in August.

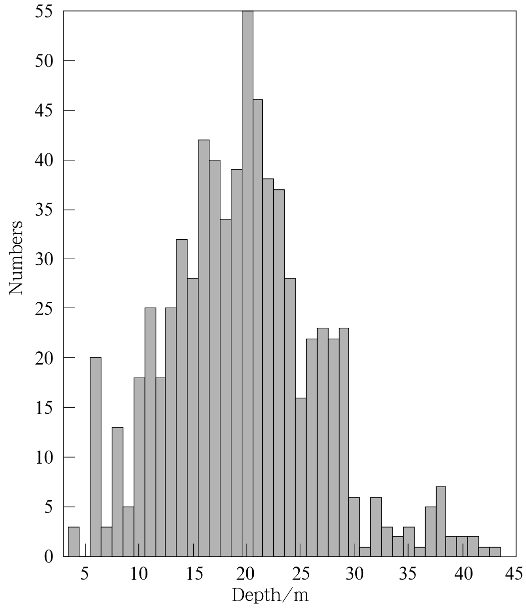

Figure 9 Frequency of depths of NSTM temperature maxima during 1993–2010.

2.2 Spatial distribution of observed NSTM from 1993 to 2010

Because of limited CTD data, it is impossible to provide a gridded spatial distribution of the NSTM. Figure 10 shows locations of CTD measurements (blue squares) and the NSTM (red dots) during 1993–2010. The NSTM showed clear regional and year-to-year differences.

From 1993 to 2003, sea ice was still heavy, and most observations were around the margin of ice cover. Therefore, most NSTMs during that period occurred around the margin of the basin, such as the slope of the Chukchi Sea, Barrow Canyon, and Beaufort Sea shelf. There are few data from the central Canada Basin over the ten years. In 1993 and 1997, there were some stations in the southwest basin, which showed the NSTM in the deep part of the basin. From 2003 to the present, Canada has carried out Arctic cruises each year, for long-term observation in the central basin. In 2003, the NSTM did not appear in central basin. During 2004–2010, the NSTM appeared in most of the basin, even at the northernmost station around 85.5°N. The NSTM has been a normal phenomenon in the central basin since then.

The large area over which the NSTM appears is related to the rapid reduction of ice concentration and thickness in summer. Since the albedo of ice is about 5–6 times that of the water, the lower ice concentration permits more solar energy to enter the ocean. Although the NSTM is correlated with ice concentration and thickness, the correlation coefficient of NSTM and ice concentration is very low, R^2=0.18[17]. The reason is that the NSTM is influenced by ice conditions over a period of time, not instantaneous ice conditions. As a result, the NSTM contains information from previous ice conditions, providing a method for understanding the heating history.

2.3 Distribution of depth and temperature extremes of NSTM

Figure 11 displays the maximum value of the NSTM vs. depth in all years. This again shows that most NSTMs occurred at depths between 10–29 m. Prior to 2003, temperature maxima (marked by black symbols) were much warmer than the freezing point at most stations, because ice was heavy and most NSTMs occurred in ice-free water. However, during 2004–2010, the NSTM in most of the Canada Basin had very low temperatures (most were less than 0°C). This was because most NSTMs appeared under sea ice, where the penetrating solar energy was much weaker.

Figure 12 shows temperature peaks colder than 0.5°C and their depths, from the period 2004–2010. This shows a quasi-linear scattering, lower temperatures corresponding to greater depth, and vice versa. The average temperature and depths of NSTMs in each year are marked by black dots. The average depths in most years were about 20 m. Only in 2007 was it about 16 m, which was related to an extreme minimum of ice cover that year. Average temperatures were around –0.8°C to –1.1°C, but increased to about –0.5°C in 2004, 2007 and 2009. This indicates that the temperature extreme of the NSTM has increased in recent years.

3 Conclusion and discussion

CTD data from 1993–2010 have been analyzed to study the spatial distribution and interannual variation of upper water in the Canada Basin during summer. There are four kinds of water temperature structures: (1) the remains of a winter convective mixed layer under pack ice; (2) water with a NSTM under sea ice or in undisturbed open water; (3) a wind-driven mixed layer formed by PW, river discharge or ice melt water in open water areas; (4) water advected under sea ice from open water.

The NSTM mainly appears within the convective

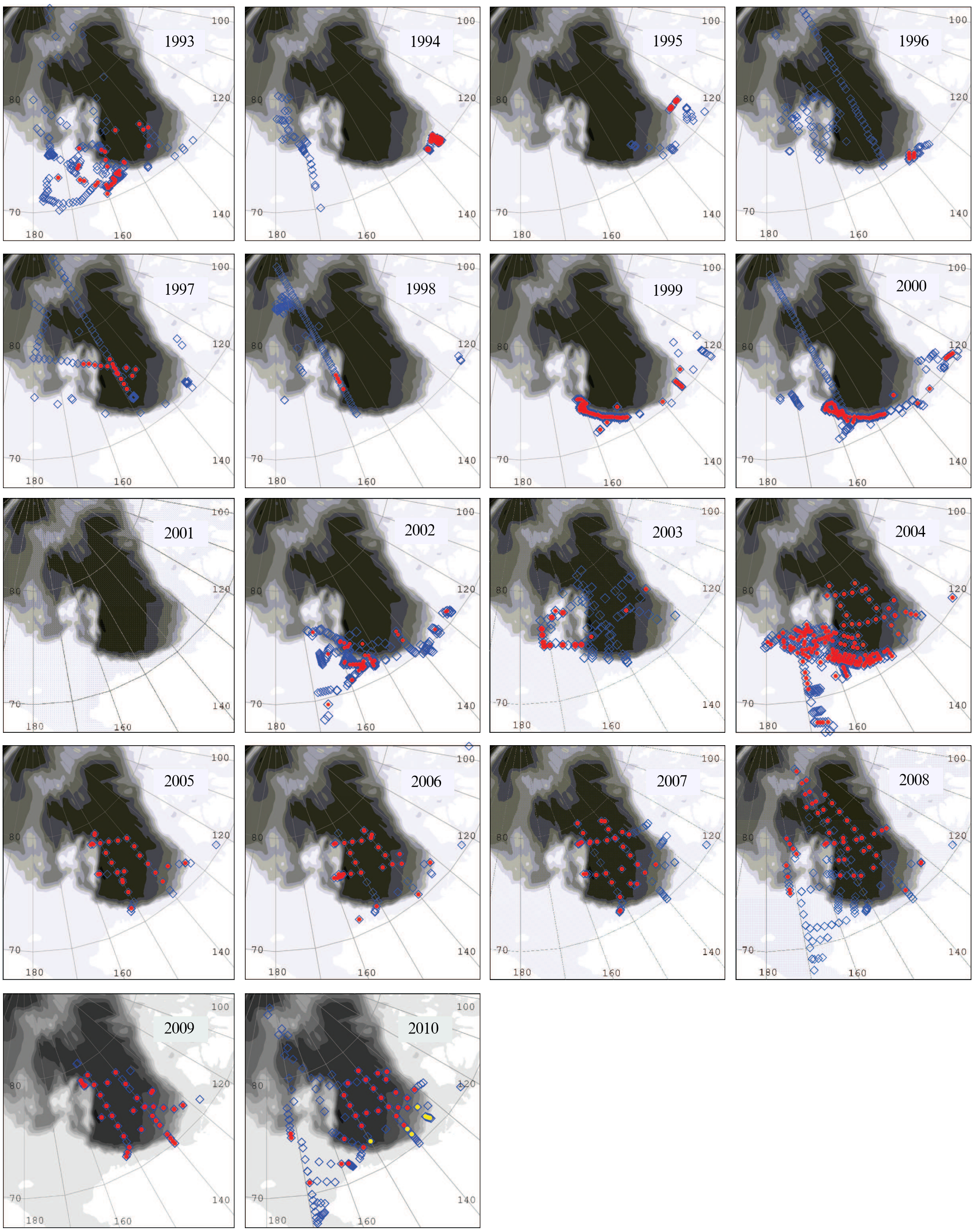

Figure 10 NSTM spatial distribution during 1993–2010. CTD locations are indicated by blue squares, and NSTM positions by red dots.

mixed layer formed in winter. Solar radiation penetrating sea ice heats seawater and increases its temperature; at the same time, sea ice on the surface cools the near-surface water. Solar heating and surface cooling are two basic factors in NSTM formation. The NSTM can also appear in undisturbed open water, as long as surface cooling persists. Under sea ice, the NSTM is simple, with only a single temperature peak. In marginal ice zones and open waters, however, the NSTM becomes complicated, with multiple temperature peaks possible.

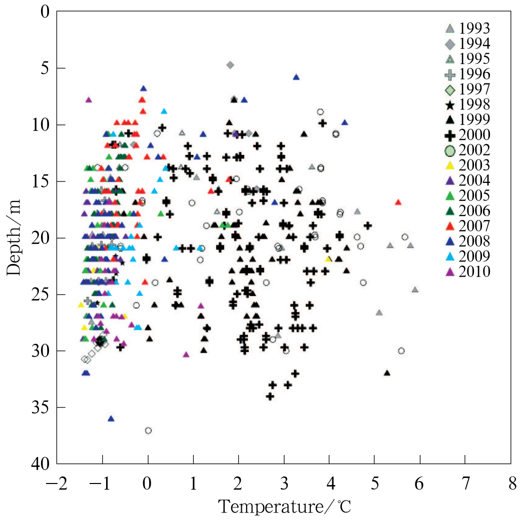

Figure 11 Temperature maximum vs. depth in different years.

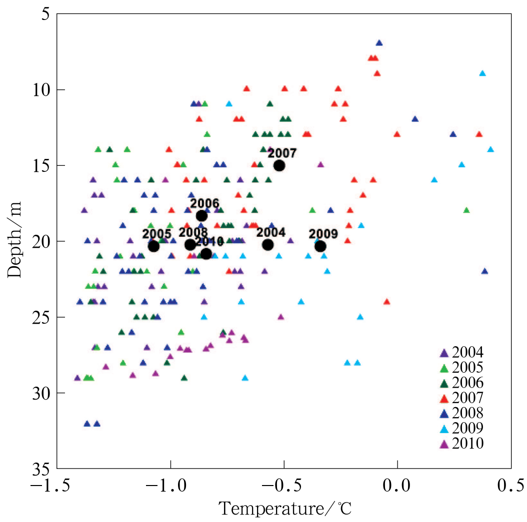

Figure 12 Temperature maximum vs. depth in 2004–2010. Black dots express average temperature maxima and average depth in each year.

Mixed and heated water in open water can be advected beneath sea ice. The overlying sea ice provides surface cooling to the advected water, and a temperature maximum appears. Sometimes, the temperature peak of the advected water is so similar to the NSTM that they are difficult to distinguish.

The NSTM occurred mainly within the depth range 10–30 m, with highest frequency at 20 m. The depth variation is the result of deepening and strengthening of the NSTM during summer.

Among the four types of water temperature profiles, only the NSTM varies interannually. Two obvious stages are identified in this study. Before 2003, based on limited data, most NSTMs were observed in marginal ice zones and open waters. Since 2004, the NSTM has been observed almost every year in the central Canada Basin. This finding is clearly related to Arctic warming and low ice concentration during that period. However, temperature maxima prior to 2003 were usually higher than those after 2004, even exceeding 0 ℃. This is because of heavy sea ice before 2003, when the NSTM only occurred in open water with higher temperature extrema. After 2004, ice concentration declined and most NSTMs occurred in ice-covered areas, where water temperature is greatly reduced because of diminished solar radiation and effective cooling by sea ice.

There was a quasi-linear clustering of the temperature maximum in temperature-depth space, with lower (higher) temperature corresponding to greater (smaller) depth. The average maximum temperature and its depth in each year show the average yearly status of the NSTM. The average depths in most years were about 20 m, excepting 2007 when it was about 16 m, related to an extreme minimum of ice cover. Average temperatures were around –0.8℃ to –1.1℃, but increased to around –0.5℃ in 2004, 2007 and 2009, corresponding to lighter sea ice. As sea ice diminishes, and a no-ice summer in the Arctic is expected, the results here suggest a warming NSTM.

The decrease in ice coverage, concentration and thickness permits more solar energy transmission into the water, enhances ice melt, and generates a positive feedback to the Arctic climate. Most energy absorbed by seawater is transmitted to the sea ice or atmosphere by turbulent diffusion, and the NSTM represents only the remains of the total absorbed heat obstructed by the halocline. By radiative transfer theory, the NSTM is proportional to the absorbed heat of seawater. Therefore, although the energy stored in the NSTM is not considerable for the ice or atmosphere, it is an important indicator of the increasing absorption of solar energy by seawater.

Acknowledgments This study was supported by the Global Change Research Program (Grant no. 2010CB951403) and the National Natural Science Foundation of China (Grant no. 40631006).

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