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The role of Pacific water in the dramatic retreat of arctic sea ice during summer 2007

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Abstract A model study is conducted to examine the role of Pacific water in the dramatic retreat of arctic sea ice during summer 2007. The model generally agrees with the observations in showing considerable seasonal and interannual variability of the Pacific water inflow at Bering Strait in response to changes in atmospheric circulation. During summer 2007 anomalously strong southerly winds over the Pacific sector of the Arctic Ocean strengthen the ocean circulation and bring more Pacific water into the Arctic than the recent (2000-2006) average. The simulated summer (3 months) 2007 mean Pacific water inflow at Bering Strait is 1.2 Sv, which is the highest in the past three decades of the simulation and is 20% higher than the recent average. Particularly, the Pacific water inflow in September 2007 is about 0.5 Sv or 50% above the 2000-2006 average. The strengthened warm Pacific water inflow carries an additional 1.0×10^{20} Joules of heat into the Arctic, enough to melt an additional 0.5 m of ice over the whole Chukchi Sea. In the model the extra summer oceanic heat brought in by the Pacific water mainly stays in the Chukchi and Beaufort region, contributing to the warming of surface waters in that region. The heat is in constant contact with the ice cover in the region in July through September. Thus the Pacific water plays a role in ice melting in the Chukchi and Beaufort region all summer long in 2007, likely contributing to up to 0.5 m per month additional ice melting in some area of that region.

Key words Pacific water, Arctic, sea ice.

1 Introduction

Significant decline of arctic sea ice has been detected in recent years[1,2]. The decline was particularly dramatic during summer 2007 when arctic sea ice extent plunged to a record low and most of the Pacific sector of the Arctic Ocean was ice free[3,4]. Models suggest that preconditioning, anomalous winds, and ice-albedo feedback are very important for the dramatic summer retreat[5,6]. Arctic sea ice in 2007 was preconditioned for radical change by years of shrinking and thinning in a warmer climate[7]. The thinning of the ice began in 1988 with the epoch of strong positive Arctic Oscillation index (1989-1993)[8,9]. The shrinking and thinning of sea ice has increased the surface absorption of solar radiation[10]. Perennial ice, particularly the oldest and thickest ice within the multiyear ice pack[11], has in recent years been replaced by thinner first-year ice that is more sensitive to changes in atmospheric and oceanic forcing[2,12,13]. Thus, the arctic sea ice in the beginning of 2007 was preconditioned for radical changes[8,9].

During summer 2007 atmospheric changes strengthened the transpolar drift of sea ice[14], causing more ice to move out of the Pacific sector where the reduction in ice thickness due to ice advection is estimated to be up to 1.5 m more than usual[15]. Some of the ice exited the Arctic via Fram Strait and some piled up in part of the Canada Basin and along the coast of northern Greenland, leaving behind an unusually large area of thin ice and open water. Thin ice and open water allow more surface solar heating because of a reduced surface albedo, leading to amplified ice melting. In summer 2007 the Arctic Ocean lost an additional 10% of its total ice mass. Of this extra ice loss 30% is due to the unusual ice advection and 70% is due to the amplified melting, mainly in the Pacific sector of the Arctic Ocean[15].

While much work has been done on the role of atmospheric circulation in the rapid summer sea ice retreat, the role of ocean circulation in the 2007 retreat is still not clear. Were there any changes in ocean circulation that may facilitate the ice retreat during summer 2007? Particularly, to what degree does the Pacific water entering the Arctic Ocean through the Bering Strait contribute to the amplified melting in the Pacific sector and hence the rapid ice retreat of 2007. To enhance our understanding of the roles of ocean circulation and especially the Pacific water in the unprecedented summer ice retreat, we conducted a retrospective model study using the Pan-arctic Ice-Ocean Modeling and Assimilation System (PIOMAS).

2 Model description

PIOMAS is a variant of the Parallel Ocean and Ice Model (POIM) of Zhang and Rothrock (2003)[16]. It consists of the multicategory thickness and enthalpy distribution (TED) sea-ice model coupled with the POP (Parallel Ocean Program) ocean model developed at the Los Alamos National Laboratory[17-19]. The TED sea ice model has 12 categories each for ice thickness, ice enthalpy, and snow depth. It employs a teardrop viscous-plastic rheology[20], a mechanical redistribution function for ice ridging[18,21], and a LSR (line successive relaxation) dynamics model to solve the ice momentum equation[22]. Although PIOMAS is capable of assimilating satellite ice concentration data following[23], no data assimilation is performed in this study.

The PIOMAS configuration is based on a generalized orthogonal curvilinear coordinate system, covering the Arctic Ocean, North Pacific, and North Atlantic (Figure 1). The northern grid pole is placed in Greenland and the mean horizontal resolution is about 22 km for the Arctic Ocean, Barents and GIN (Greenland-Iceland-Norwegian) seas, and Bafin Bay. Vertically the ocean model has 30 levels of varying thicknesses, with ten levels in the upper 60 m to resolve the surface waters of the Arctic and subarctic seas. The model bathymetry is obtained by merging the IBCAO (International Bathymetric Chart of the Arctic Ocean) dataset and the ETOPO5 (Earth Topography Five Minute Gridded Elevation Data Set) dataset[24].

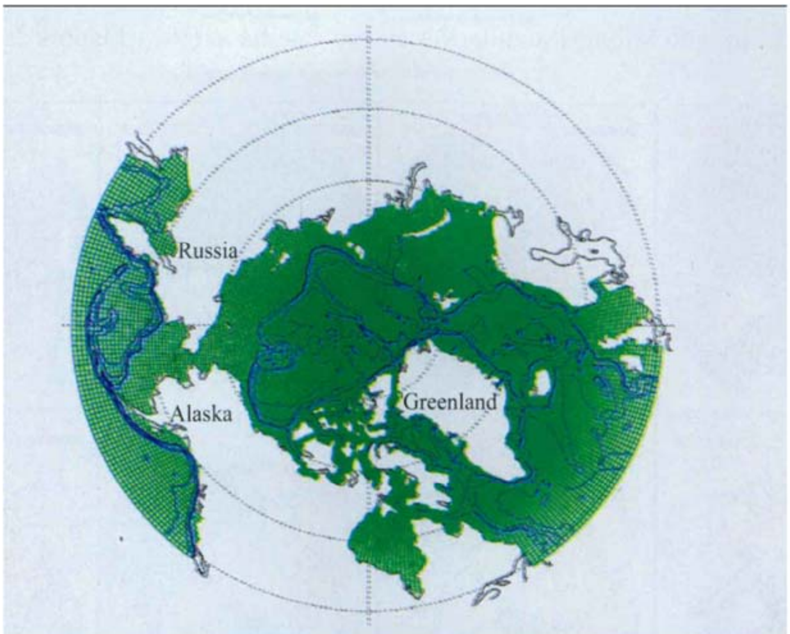

Fig. 1 Model grid configuration and bathymetry; bathymetry contours of 400, 800, 2200, and 3600 m are plotted. The model is nested to a global ice-ocean model[20]. The open boundaries are along 43°N for an easy implementation of open boundary conditions from the global model's output.

The POP ocean model is modified so that open boundary conditions can be specified along the model's southern boundaries along 43°N[15]. Open boundary conditions for sea surface height and ocean velocity, temperature, and salinity are obtained from a global POIM[25].

PIOMAS is forced by daily NCEP/NCAR reanalysis forcing[26], which consists of surface winds, surface air temperature (SAT), specific humidity, precipitation, evaporation, downwelling longwave radiation, and cloud fraction. SAT and cloud fraction are used to calculate downwelling shortwave radiation following[27].

3 Changes in atmospheric forcing during summer 2007

In order to better understand the linkages between the rapid arctic sea ice retreat and the atmospheric changes during summer (July-September) 2007, it is helpful to examine how the changes are reflected in the NCEP/NCAR surface atmospheric forcing that is used to drive the model. The changes in sea level pressure (SLP), surface winds, and SAT leading to and during summer 2007 are illustrated in Figure 2. Figure 2 compares the 2007 atmospheric conditions with those averaged over 2000-2006, a period of relatively low summer sea ice extent compared to the past 3 decades. Here, the 2000-2006 average is referred to as the "recent average" and the difference between a 2007 value and the recent average value is referred to as an "anomaly" (2007 minus the recent average).

As shown in Figure 2a, the arctic SLP and surface wind anomalies are small in the first half of 2007. In July, SLP is considerably higher in much of the Arctic Basin and lower over a large area in Russia than the recent average (Figure 2b). This is in association with stronger southerly winds in the northern Canada Basin and easterly winds along the East Siberia coast. In August and September, the area of high SLP anomaly is mostly confined to the Canada Basin with stronger southerlies in the Pacific sector (Figures 2c-2d).

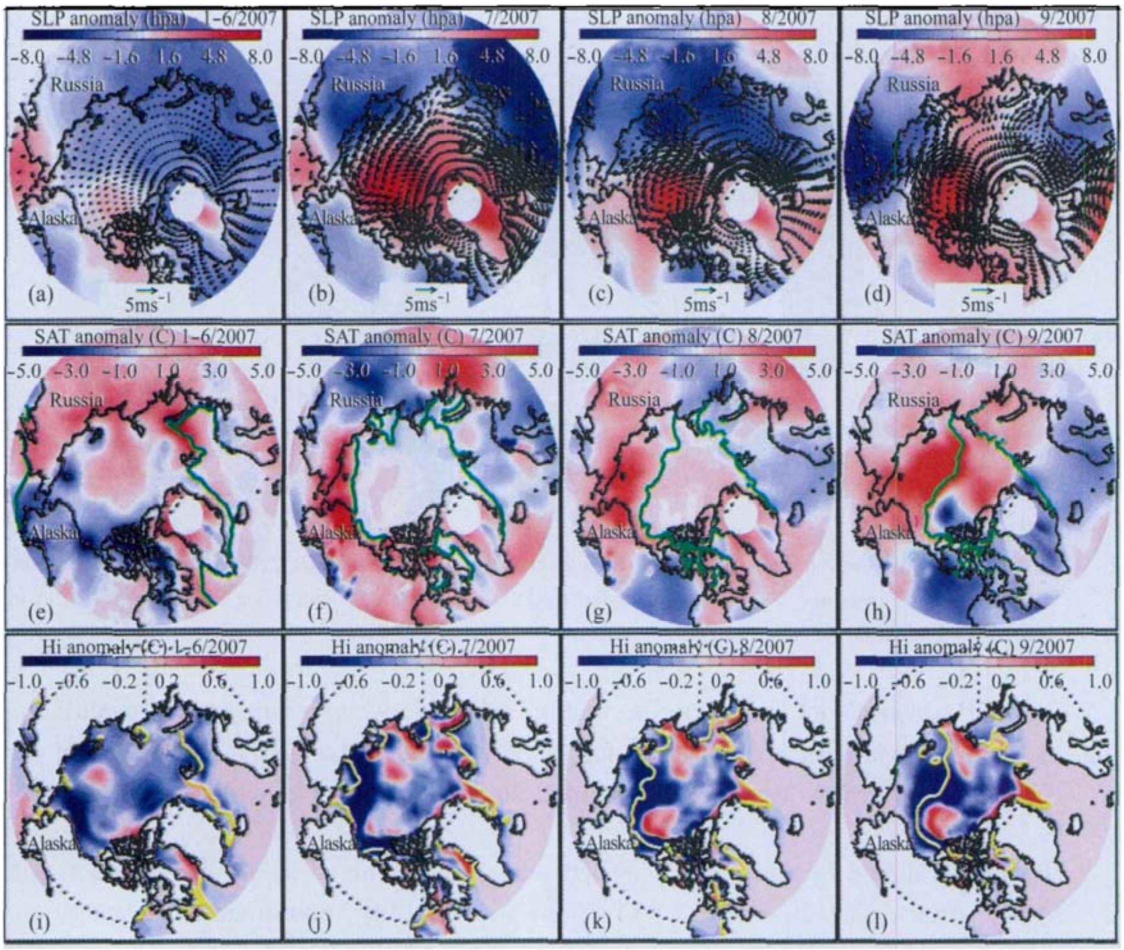

Fig. 2 Anomalies of the NCEP/NCAR reanalysis sea level pressure (SLP) and surface wind (a-d) and surface air temperature (SAT) (e-h); anomalies of simulated sea ice thickness (Hi) (i-l) Throughout the paper an anomaly is defined as the difference between the 2007 value and the 2000-2006 average. One of every 36 wind vectors is plotted in (a-d). The green line in (e-h) represents satellite observed ice edge and yellow line in (i - l) model simulated ice edge.

Similar to the SLP and wind anomalies, the arctic SAT anomaly is relatively small in the first half of 2007: SAT is slightly warmer in the central Arctic Basin and slightly cooler in the Chukchi and Beaufort seas compared to the 2000-2006 average (Figure 2e). In July, SAT anomaly increases significantly in the Chukchi Sea (Figure 2f). In August and September the increase in SAT is most striking: SAT is up to 5 ℃ warmer than the recent average over much of the Pacific sector (Figures 2g-2h). However, in an area in the Canada Basin SAT is lower than the recent average in September 2007 (Figure 2h). This SAT decrease is likely due to the air-ice interactions in that area where ice is thicker than the recent average (Figure 2l). Ice is also thicker in August in that area (Figure 2k); however, SAT is not lowered (Figure 2g).

4 Model results and observations

PIOMAS is integrated from 1948 to 2007 using the NCEP/NCAR reanalysis forcing after a 30-year spin-up. The 30-year spin-up is forced by 1948 reanalysis data repeatedly. After this spin-up the ice thickness is close to steady state and the model proceeds to retrospectively simulate the period from 1948 to 2007. Results for the period 1978 - 2007 are presented. Special attention is paid to the 2007 ice - ocean results in comparison with the 2000 - 2006 averages.

a. Changes in summer arctic sea ice and the record low ice extent during summer 2007

Figure 3 shows the simulated and observed September (summer) arctic sea ice conditions between 1978 and 2007. The simulated September ice volume has decreased steadily since 1988 (Figure 3a) and the September 2007 ice volume appears to follow the 1988-2006 downward trend line described by Lindsay *et al.* (2008)[6]. The simulated September ice extent has also decreased since 1988 (Figure 3b). However summer ice extent appears to have stronger interannual variability than summer ice volume and the record low September 2007 ice extent is considerably below the 1988-2006 downward trend line[6]. This indicates that summer ice extent may be more susceptible to changes in dynamic and thermodynamic atmospheric forcing than summer ice volume.

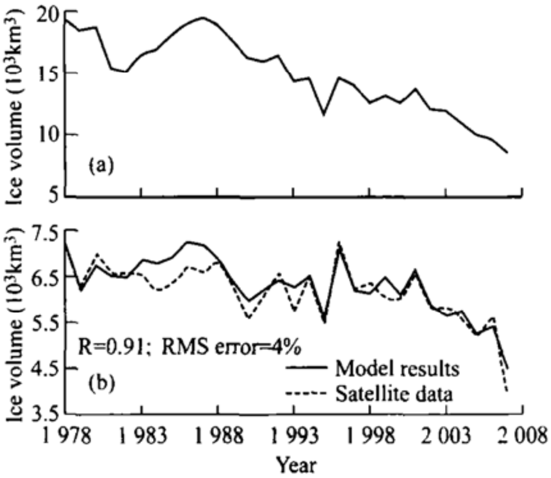

Fig. 3 Simulated September (summer) arctic sea ice volume (a) and simulated and observed September arctic sea ice extent (b); model-data correlation (R) and root-mean-square (RMS) error indicated.

The simulated September ice extents are highly correlated with satellite observations over 1978-2007 ($R = 0.91$), with a low RMS (root-mean-square) error of 4% (Figure 3b). The model overestimates September ice extents in the mid-1980s, but is in a generally good agreement with observations since 1988. The simulated spatial patterns of September ice extent are also in a reasonably good agreement with the observations since 1988 (Figure 4). Figure 4 also shows the spatial distribution of September ice thickness that has been generally decreasing since 1988 (also see Figure 3a). Moreover Figures 2i - 2l show ice thickness in the Pacific sector is lower than the recent average before and during summer 2007. The model captures the spatial pattern of the reduced ice cover in the Pacific sector of the Arctic Ocean in September 2007 (Figure 4t), although it overestimates the total ice extent to some degree (Figures 3a and 4t).

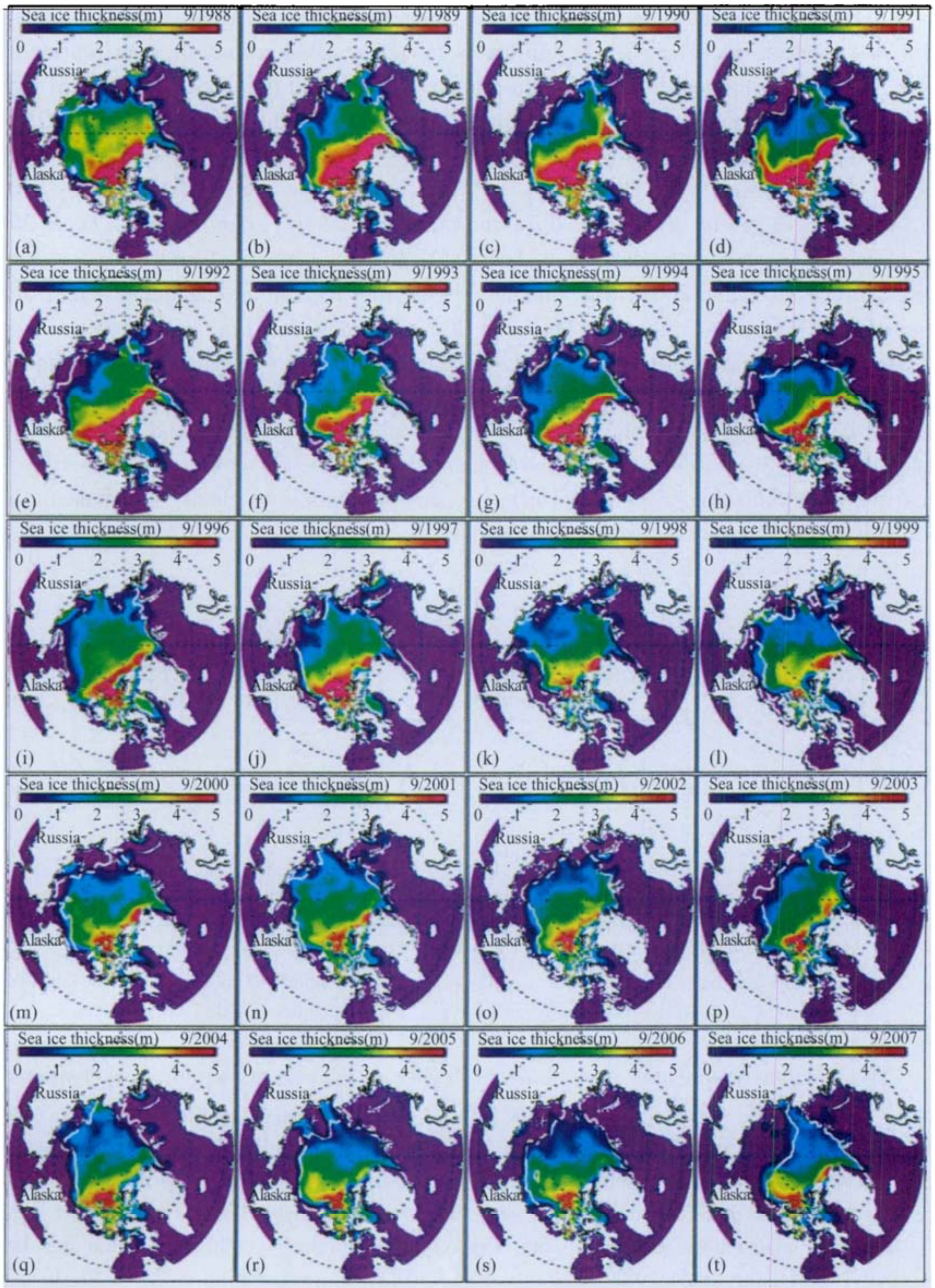

Fig. 4 Simulated September sea ice thickness since 1988. Black (white) line represents model simulated (satellite observed) ice edge.

What is the cause of the substantially reduced ice cover in the Pacific sector during summer 2007? Zhang *et al.* (2008)[5] found from model results that 30% of the anomalous reduction in ice extent mainly in the Pacific sector is due to the unusual ice motion and advection. Ice motion in the Arctic Ocean is characterized by an anticyclonic Beaufort gyre and a transpolar drift (Figures 5a-5d). In the first half of 2007, the SLP and wind anomalous are small (Figure 2a), so the changes in ice motion and changes in ice thickness due to ice advection are small in comparison to the 2000-2006 average (Figure 5e). In July, there were stronger southerly winds in the northern Canada Basin (Figure 2b). The ice motion responds to the winds with a much stronger transpolar drift so that there are considerable changes in ice thickness due to ice advection almost everywhere (Figure 5b). In a large area of the Pacific sector, the reduction in ice thickness due to ice advection is up to 0.5 m/month more than the recent average (Figure 5f). In August and September, there were even stronger southerly winds in the Pacific sector (Figures 2c-2d), which further strengthen the ice motion and transpolar drift (Figures 5g-5h). Thus, the Pacific sector continues to lose ice. Again, the reduction in ice thickness due to ice advection is up to 0.5 m/month more than usual (Figures 5g-5h). In other words, from July to September 2007 the unusual ice motion pattern drives so much ice into the Atlantic sector from the Pacific sector that the ice thickness in most of the Pacific sector is reduced by up to 1.5 m more than the recent average, leaving the Pacific sector with an unusually large area of thin ice and open water. Yet this effect is only 30%.

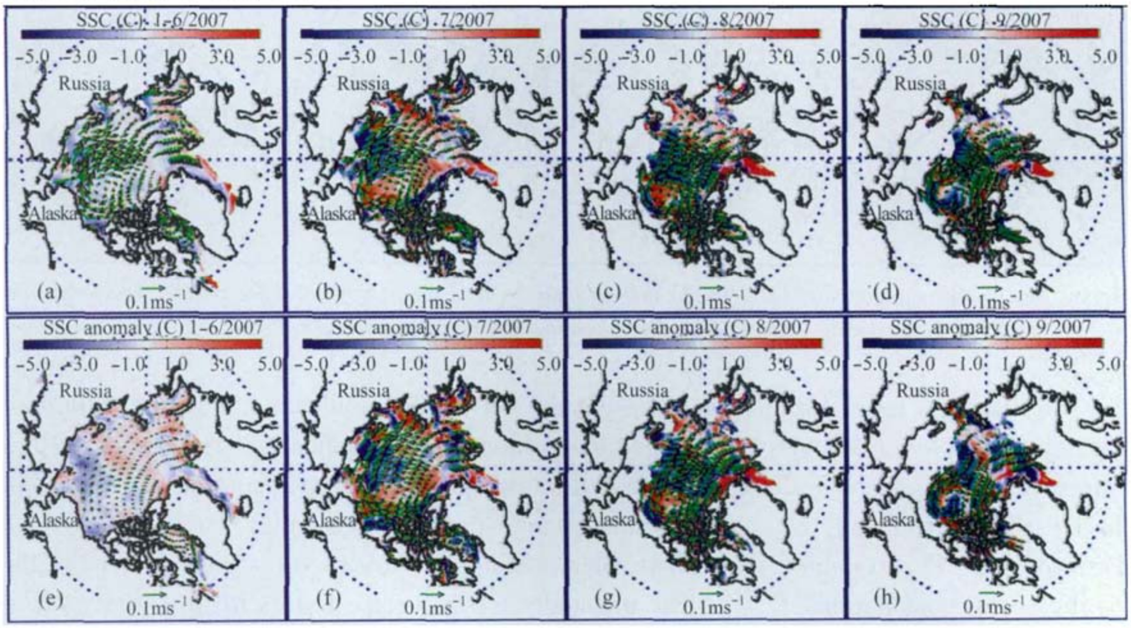

Fig. 5 Simulated ice motion (vectors) and ice advection (IA) (color contours) (a-d) and their anomalies (e-h). Note the difference between ice motion and ice advection. Ice motion isdescribed by ice velocity and ice advection by ice mass convergence$[-\nabla\cdot(uh)]$, where u is ice velocity and h is ice thickness. One of every 36 ice velocity vectors is plotted.

About 70% of the anomalous reduction in ice extent in the Pacific sector during summer 2007 is due to reduced ice production or enhanced ice melting[15]. Ice production is the net ice thermodynamic growth or decay due to surface atmospheric cooling/heating and ocean heat flux. In summer a decrease in ice production is equivalent to an increase in ice melting. Ice production is negative in July and August due to ice melting caused by atmospheric or oceanic heating (Figures 6b and 6c); it is generally positive in the January-June mean (Figure 6a) and in September (Figure 6d). In the first half of 2007, the ice production anomaly is generally small (Figure 6e). In summer 2007, however, ice production decreases considerably in most of the Pacific sector (Figures 6f-6h) where a large reduction in ice thickness due to ice advection also occurs (Figures 5b-5d and 5f-5h). This is because the large reduction in ice thickness due to ice advection is associated with a large area of thin ice and open water and thin ice and open water tend to allow more surface solar heating owing to the ice-albedo feedback, leading to reduced ice production or enhanced ice melting[6][15].

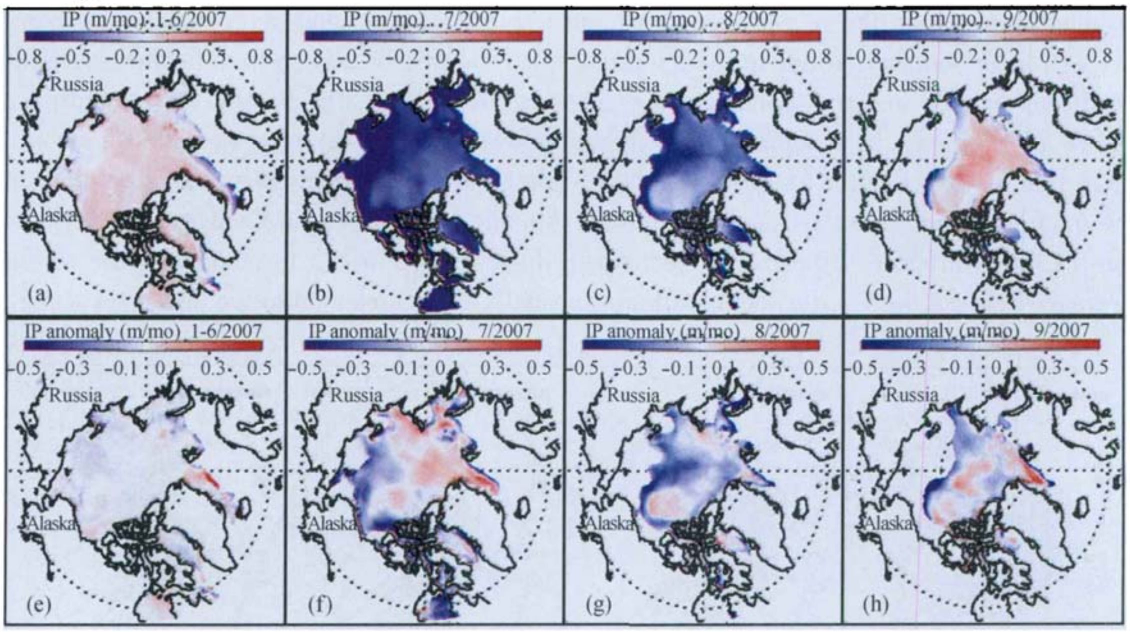

Fig. 6 Simulated ice production (IP) (a-d) and anomaly (e-h). Ice production is the net ice thermodynamic growth or decay due to surface atmospheric cooling/heating and oceanic heat flux.

The changes in ice production represent the net effects of all the air-ice-ocean thermodynamic processes. Although the reduced ice production or enhanced ice melting in the Pacific sector during summer 2007 is dominated by intensified surface solar heating because of the ice-albedo feedback[15], other thermodynamic processes also play a role, albeit to a lesser degree. For example, intensified solar heating also warms the surface waters in the Pacific sector considerably[28,29]. The unusually warm surface waters in turn warm the overlaying atmosphere, elevating summer SAT in the Pacific sector (Figures 2f-2h). The stronger southerly winds (Figures 2b-2c) may also contribute to increasing SAT by bringing warm air from the south to the Arctic. An increase in SAT leads to an increase in surface longwave radiation and turbulent heat fluxes, resulting in additional ice melting[15]. Ocean circulation and thermodynamic processes may have also played a role in the reduced ice production or enhanced ice melting in the Pacific sector during summer 2007, which is the focus of this study.

b. Changes in ocean circulation and Pacific water inflow during summer 2007

Figure 7 shows the simulated surface ocean velocity and sea surface temperature (SST) and their anomalies. Some of the key features of the surface circulation of the Arctic Ocean include an anticyclonic Beaufort gyre, a transpolar drift, and a strong Bering Strait inflow (Figures 7a-7d). In the first half of 2007, the changes in SST and surface ocean velocity are small (Figure 7e) likely because the wind anomaly is small (Figure 2a). In summer, the ocean responds to the stronger winds with stronger northward surface ocean velocities in most of the Pacific sector (Figures 7f-7h). The pattern of the surface ocean velocity anomaly resembles that of the ice velocity anomaly (Figures 5f-5h). The magnitude and direction of the anomalous surface ocean velocity at Bering Strait indicate that the Pacific water inflow into the Arctic Ocean in summer 2007 is stronger than the recent average, particularly in September 2007 (Figure 7h). It is generally accepted that the Bering Strait inflow is dominantly driven by local winds[30]. Thus the anomalously strong winds in summer 2007 not only strengthen the transpolar drift of sea ice, but also strengthen the ocean circulation and bring more warm Pacific water into the Pacific sector of the Arctic Ocean.

Fig. 7 Simulated surface ocean velocity (vectors) and sea surface temperature (SST) (color contours) (a-d) and their anomalies (e-h).

Meanwhile, there is an increase in SST by up to 5 ℃ over the recent average in a large area in the Pacific sector (Figures 7f-7h) as also found in satellite observations[28]. Although the SST increase in summer 2007 is largely due to the intensified solar heating in association with the ice-albedo feedback[15], the enhanced warm Pacific water inflow certainly contributes to the increase.

Figures 8 and 9a plot both simulated and observed Pacific water inflow at Bering Strait. Observations show significant seasonal and interannual variability in the Pacific water inflow[31,32]. The model is able to capture some of the observed variability. Most of the simulated inflow values are within the range of the error bars of the corresponding observational estimates. The simulated summer (July-September) mean Pacific water inflow for 2007 is 1.2 Sv (1 Sv = 10^6 m^3s^{-1}), which is the highest summer value in the period 1978-2007 and is about 20% higher than the 2000-2006 average at 1.0 Sv (Figure 8). Particularly, the inflow in September 2007 is about 0.5 Sv or 50% above the recent average (Figure 9a).

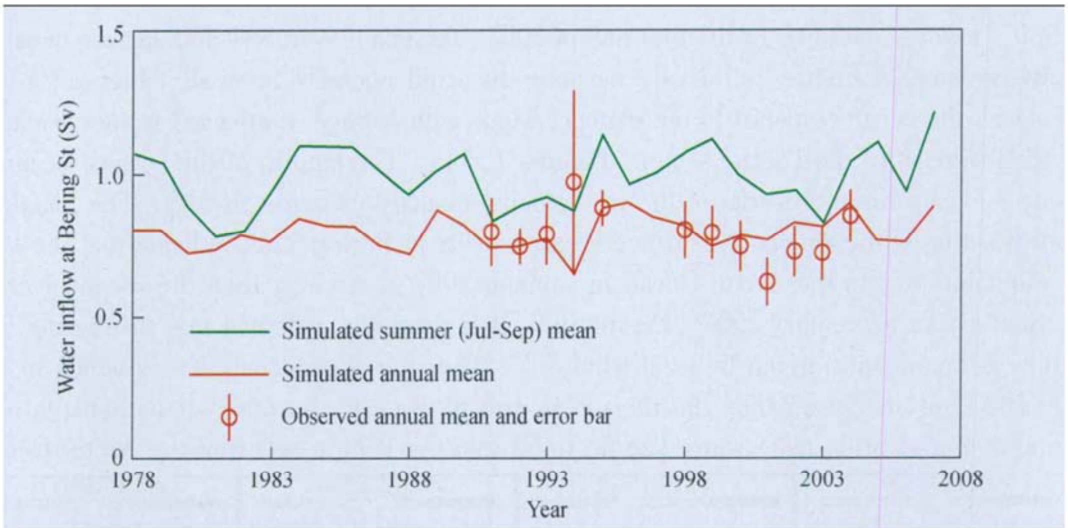

Fig. 8 Simulated annual and summer (July-September) mean volume inflow of Pacific water through Bering Strait. Also plotted are annual mean estimates and error bars based on mooring data[32]. The observational estimates are subject to up to ~20% systematic errors in addition to those indicated by error bars in the plot.

As a result, there is significantly more heat inflow at Bering Strait in summer 2007 than the recent average (Figure 9b). The heat inflow is obtained by calculating the volume inflow and heat content of the incoming Pacific water relative to the freezing temperature. The increase in heat inflow in September 2007 is particularly strong because of the particularly strong water inflow and warmer water temperature (Figure 9c). The total July to September (summer) heat gain is 1.0×10^{20} Joules more than the recent average. If this amount of extra heat is used to melt ice, it is enough to melt 3 cm of ice over the whole Arctic Ocean plus the Barents Sea or equivalently 0.5 m of ice over the whole Chukchi Sea.

c. The role of Pacific water in the retreat of arctic sea ice during summer 2007

Where does the extra heat carried with the Pacific water go after entering the Arctic? Figure 10 shows how it is distributed spatially inside the Arctic. The figure plots anomalies of ocean heat convergence in the upper 60 m. The ocean heat convergence (lateral heat transport) is defined as ed as $-\nabla \cdot [u_o(T - T_{freeze}]\Delta z \cdot \rho C_P$, where u_o is ocean velocity, T is ocean temperature, Δz is the thickness of the layer considered (here upper 60 m), ρ is water density, and C_p is the specific heat of water. From January to June there is little oceanic heat coming via Bering Strait (Figure 10a). In summer 2007, the Chukchi and Beaufort region gains significantly more heat due to the enhanced Pacific water inflow compared to the recent average (Figures 10b-10d). This is consistent with the results shown in Figure 9b. The extra heat is in constant contact with the ice cover in July through September of 2007. This suggests that the increased heat inflow contributes to additional ice melting in the Chukchi and Beaufort region all summer long. Specifically, it contributes to early summer melting in the Chukchi Sea and late summer melting in the Beaufort Sea.

The contribution of the Pacific water to ice melting is further illustrated in Figure 11 which shows the 2007 oceanic heat induced ice melting and its difference to the 2000-2006 average. Here ocean heat includes the lateral and vertical ocean heat transport and the surface atmospheric heat deposited into the ocean through leads and open water. Large ocean induced melting occurs mainly in July and August 2007 (Figures 11b and 11c), particularly in the areas near the ice edge in the Pacific sector. In these areas, ocean induced melting takes up a significant, often major, portion of the total (surface plus bottom) ice melting (Figures 6b and 6c). This is consistent with the observations of an ice mass balance

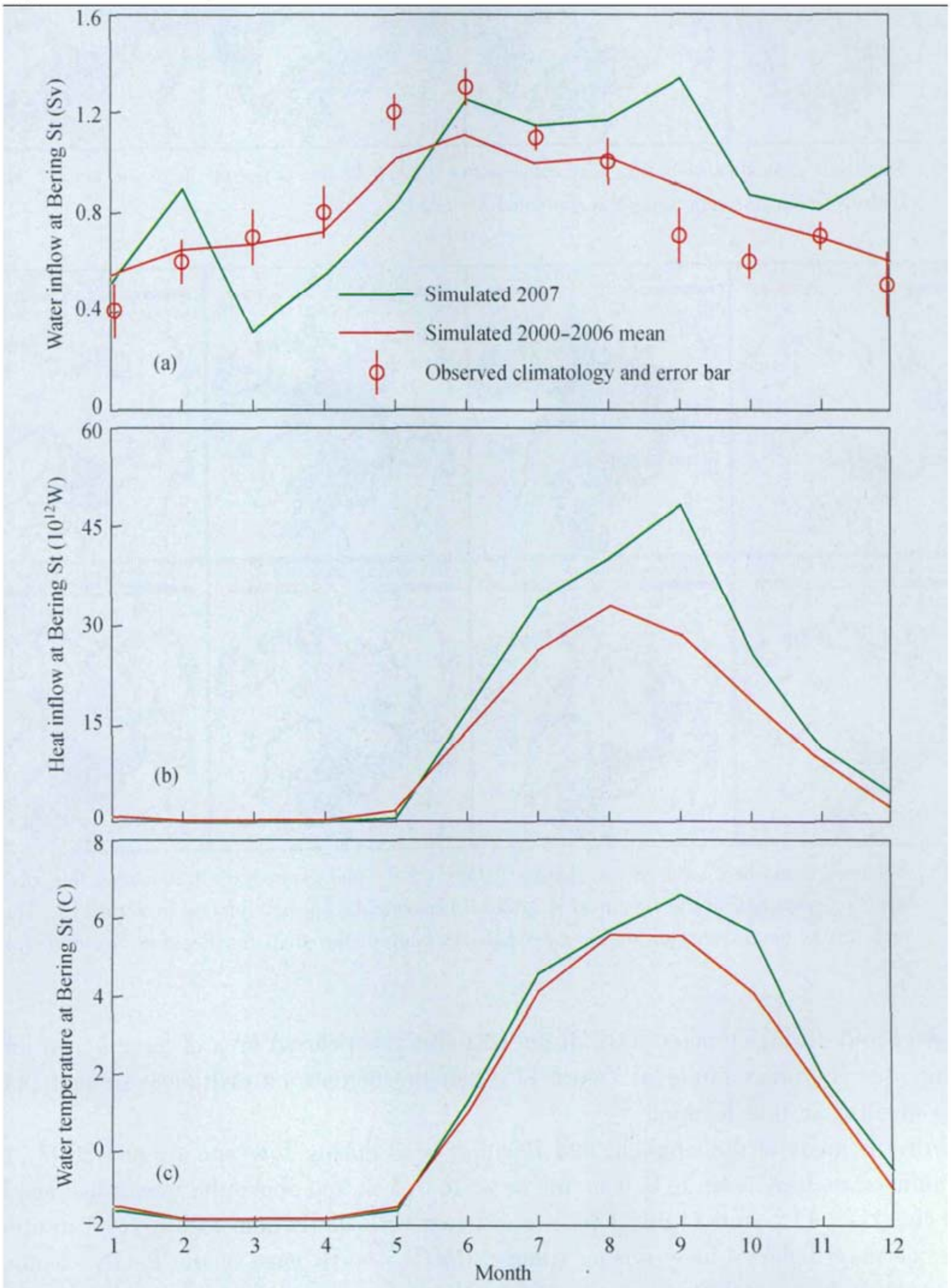

Fig. 9 (a) Simulated monthly 2007 and 2000-2006 average volume inflow of Pacific water through Bering Strait. Also plotted are observation-derived climatology values and error bars[31]. The observational estimates are subject to up to ~20% systematic errors in addition to those indicated by error bars in the plot. (b) Simulated monthly 2007 and 2000-2006 average heat inflow through Bering Strait. (c) Simulated monthly 2007 and 2000-2006 average water temperature at Bering Strait.

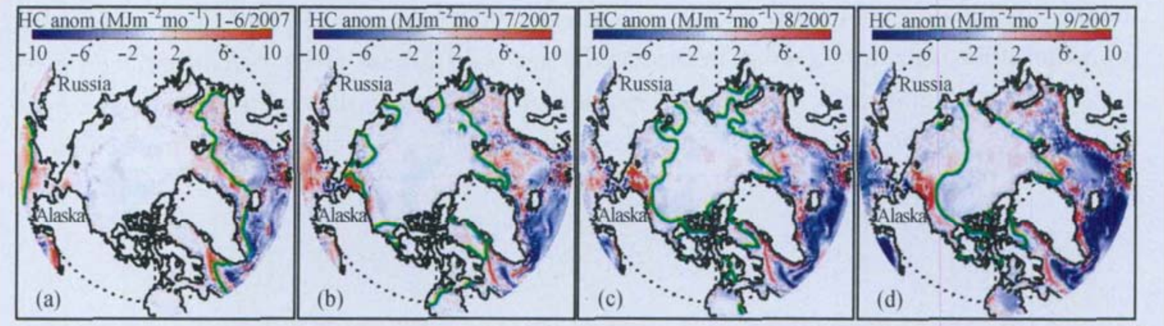

Fig. 10 Simulated anomalies of ocean heat convergence (HC) in the upper 60 m of the ocean. MJ = 10^6 Joules. Green line represents the simulated ice edge.

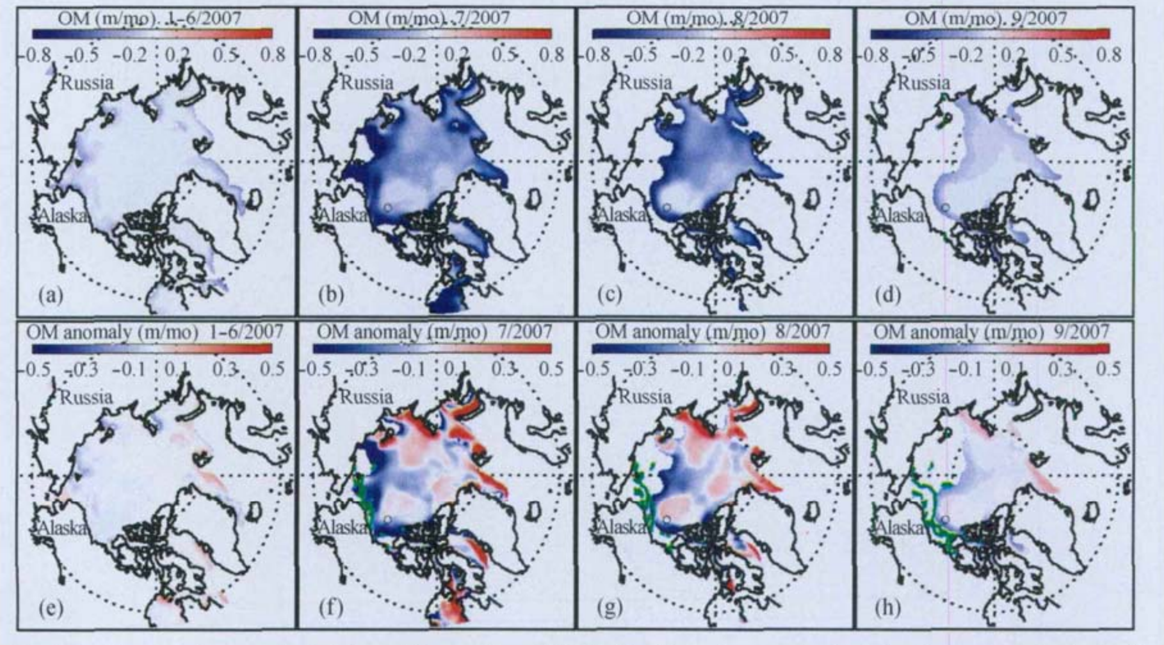

Fig. 11 Simulated ocean heat induced ice melting (OM) (a-d) and anomaly (e-h). Green line is the 2.0 $MJm^{-2}mo^{-1}$ contour of the simulated ocean heat convergence anomaly plotted in Figure 10. The black circle marks the location of an ice mass balance buoy deployed in the Beaufort Sea during summer 2007[29].

buoy deployed during summer 2007 in the Beaufort Sea near an area of large ocean induced melting (see the black circle in Figure 11) that the bottom ice melting is greater than the surface melting in that location[29].

In some areas of the Chukchi and Beaufort seas during July and August 2007, the ocean induced melting is up to 0.8 m/mo or up to 0.5 m/mo above the recent average (Figures 11b, 11c, 11f, and 11g). This is consistent with the bottom melting of 2 m observed by the ice mass balance buoy during summer 2007[29]. In most of the Pacific sector, the large ocean induced melting is dominated by the enhanced surface atmospheric heat input (due to the ice-albedo feedback and the intensified solar heating) and local lateral ocean heat transport that brings the solar heat absorbed in the upper ocean into the ice. However, some areas of large ocean induced melting are in the reach of the incoming heat from the Bering Sea as indicated by the green contours in the plot. The green contours are used to illustrate that oceanic heat due to the Pacific water inflow reaches some of the areas with large ocean induced melting. This means that the Pacific water contributes to the ice melting in these areas.

5 Concluding remarks

A model study is conducted to examine the role of Pacific water in the dramatic retreat of arctic sea ice during summer 2007. Observations indicate considerable seasonal and interannual variability in the Pacific water flowing into the Arctic through Bering Strait[32]. The model, PIOMAS, demonstrates some skill in reasonably capturing the observed variability. The variability in the Pacific water inflow at Bering Strait is closely linked to changes in local wind circulation which are found to also play a prominent role in the rapid retreat of sea ice in the Pacific sector of the Arctic Ocean during summer 2007[31,32].

During summer 2007 there were anomalous strong southerly winds over the Pacific sector. On one hand, the strong southerly winds drive an unusually large amount of ice out of the Pacific sector, leaving behind an unusually large area of thin ice and open water. The large area of thin ice and open water allows enhanced surface solar heating because of the ice-albedo feedback. The enhanced solar heating not only causes amplified ice melting[15], but also results in elevated SST that tends to warm the overlying atmosphere and increase SAT through air - sea interactions[3]. The strong southerly winds may also contribute to increasing SAT by bringing warm air from the south to the Arctic. An increase in SAT leads to an increase in surface longwave radiation and turbulent heat fluxes, resulting in additional ice melting[5].

On the other hand, the unusually strong southerly winds during summer 2007 also strengthen the ocean circulation and bring more warm Pacific water into the Pacific sector of the Arctic Ocean. The simulated summer 2007 mean Pacific water inflow through Bering Strait, with a value of 1.2 Sv, is the highest summer value in the past three decades and is 20% higher than the average over the period 2000-2006 when summer arctic sea ice is significantly lower than the past. Particularly, the Pacific water inflow in September 2007 is about 0.5 Sv or 50% above the 2000-2006 average.

The summer inflow of warm Pacific water through Bering Strait brings considerable oceanic heat into the Arctic Ocean. The heat mainly stays in the Chukchi and Beaufort region. Because of the strengthened Pacific water inflow in summer 2007, there is an increase of 1.0×10^{20} Joules in heat inflow at Bering Strait compared to the 2000-2006 average. If this amount of extra heat is fully utilized to melt ice, it can melt half meter of ice over the whole Chukchi Sea. This extra heat has a great impact on sea ice extent in 2007 because arctic sea ice at the beginning of summer 2007 was thinner than prior years. Most of the extra heat staying in the Chukchi and Beaufort region contributes to the warming of the surface waters in that region. Some of the heat is in constant contact with the ice cover in the region in July through September. Thus the Pacific water plays a role in ice melting in the Chukchi and Beaufort region all summer long in 2007, contributing to up to 0.5 m/mo additional ice melting in some area of that region.

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