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Causes for different spatial distributions of minimum Arctic sea-ice extent in 2007 and 2012

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Abstract

Satellite records show the minimum Arctic sea ice extents (SIEs) were observed in the Septembers of 2007 and 2012, but the spatial distributions of sea ice concentration reduction in these two years were quite different. Atmospheric circulation pattern and the upper-ocean state in summer were investigated to explain the difference. By employing the ice-temperature and ice-specific humidity (SH) positive feedbacks in the Arctic Ocean, this paper shows that in 2007 and 2012 the higher surface air temperature (SAT) and sea level pressure (SLP) accompanied by more surface SH and higher sea surface temperature (SST), as a consequence, the strengthened poleward wind was favorable for melting summer Arctic sea ice in different regions in these two years. SAT was the dominant factor influencing the distribution of Arctic sea ice melting. The correlation coefficient is –0.84 between SAT anomalies in summer and the Arctic SIE anomalies in autumn. The increase SAT in different regions in the summers of 2007 and 2012 corresponded to a quicker melting of sea ice in the Arctic. The SLP and related wind were promoting factors connected with SAT. Strengthening poleward winds brought warm moist air to the Arctic and accelerated the melting of sea ice in different regions in the summers of 2007 and 2012. Associated with the rising air temperature, the higher surface SH and SST also played a positive role in reducing summer Arctic sea ice in different regions in these two years, which form two positive feedbacks mechanism.

Key words: Arctic sea ice extent, atmospheric circulation, upper-ocean feedback

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1 Introduction

The monthly sea ice extent (SIE) in the Arctic has been decreasing since 1979, with the most pronounced loss in September (Comiso et al., 2008). The sea ice minimum (SIM) extents were recorded during the summers of 2007 and 2012 in the Arctic. However, the spatial distributions of sea ice reduction were quite different in these two years. Compared with the climatological sea ice concentration in September, the sea ice loss in 2007 was mainly in the East Siberian Sea of the Arctic Ocean, while that in 2012 was in the Beaufort Sea, the northern of Barents Sea and Kara Sea and Laptev Sea of the Arctic Ocean.

Some explanations have been proposed for the minimum Arctic SIE during summer 2007 (e.g., Stroeve et al., 2008; Zhang et al., 2008), which was the most palpable manifestation of accelerated climate change and the so-called “Arctic amplification” during recent decades. The warming of Atlantic intermediate water on the Russian side of the Arctic Ocean in recent decades has helped to precondition the polar ice cap for the ice loss (Polyakov et al., 2010). Rigor and Wallace (2002, 2004) and Stroeve et al. (2011) researched variation in wintertime wind patterns, such as the Arctic Oscillation (AO), which impacts the SIE in subsequent summer by changing the transport of thicker multi-year ice toward the Fram Strait (Rigor et al., 2002; Rigor and Wallace, 2004; Stroeve et al., 2011). Devasthale et al. (2013) provided three-dimensional (3-D) information on atmospheric thermodynamics by comparing the recorded minimum SIEs in 2007 and 2012 using the Atmospheric Infrared Sounder instrument onboard NASA’s Aqua satellite. It is shown that, in sharp contrast to 2007, the meteorological conditions during 2012 were not extreme but three factors in preconditioning from winter through early summer probably played an important role in accelerating sea-ice melt in central Eurasian, North Atlantic sectors, Canadian Archipelago and southeast Beaufort Sea (Devasthale et al., 2013). Kay et al. (2008) showed that the effect of warm air advection, reduced cloudiness and increased shortwave surface heat flux over the Beaufort high region, may have contributed to the observed sharp decline in SIE. These may explain the low SIE observed in summer contribute to the melting conditions for sea ice in winter and spring, but cannot explain the different spatial distributions of SIE in the Septembers of 2007 and 2012.

Summertime atmospheric conditions play an important role in controlling the variation of Arctic SIE (Ogi and Wallace, 2007; L’Heureux et al., 2008; Ogi et al., 2008, 2010). Ogi and Wallace (2012) showed that anti-cyclonic circulation anomalies over the Arctic Ocean during the summer months favor low SIE in September in 2007, 2010 and 2011. Strong summertime anti-cyclonic wind anomalies over the Arctic Ocean, with anomalous flow toward the Fram Strait, during summer months of 2007 con-

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tributed to the record-low the Arctic sea-ice extent observed in September of that year. The summer winds over the Arctic during the summers of 2010 and 2011 had been the same as those in 2007 (Ogi and Wallace, 2012). The preconditions, such as wind, thermodynamic and other surface parameters before the melt season, are also important factors (Vihma et al., 2008; Zhang et al., 2008; Sedlar and Devasthale, 2012). Screen et al. (2011) discussed the dramatic inter-annual changes of perennial Arctic sea ice linked to anomalous summer storm activity. Apart from the factors mentioned above, it is noted that increased greenhouse gas forcing is actually the primary driver for the rapid onset of the sea ice decline (Notz and Marotzke, 2012). However, they did not give the causes for the different spatial distributions of extreme ice events in Septembers in 2007 and 2012.

There are many studies on the relationship between the Arctic sea ice and the Arctic temperature amplification (e.g., Screen and Simmonds, 2010; Steele et al., 2010). This study aims to reveal the causes for the different spatial distributions of sea ice when the Arctic sea ice reached minima in the Septembers of 2007 and 2012. In Section 2, the data sources are introduced. In Section 3, the paper shows the sea ice distributions in the Septembers of 2007 and 2012 were quite different using the National Snow and Ice Data Center (NSIDC) data. We investigate the influences of surface atmospheric circulation and upper-ocean temperature on melting of the Arctic sea ice in summer, and explain why the distributions of sea ice were different when the Arctic SIE reached minima in the Septembers of 2007 and 2012. Conclusions and discussion are given in Section 4.

2 Data

In this study, we use data from a reanalysis product, the ERA-Interim from the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011). The variables include surface air temperature (SAT), sea level pressure (SLP), surface wind, specific humidity (SH), sea surface temperature (SST). The data set has some key improvements, including resolution, model physics, hydrological cycle, 4-D variation data assimilation, and variation bias correction of satellite radiance data (Dee and Uppala, 2009; Dee et al., 2011). The variation bias correction of satellite radiance data accounts for the biases that change in time, for instance, owing to changes in the observing network or drift of satellite orbits. ERA-Interim depicts more realistic Arctic tropospheric temperatures and probably suffers less from spurious trends than any previous reanalysis data sets (Dee and Uppala, 2009). In this paper, the summer includes June, July and August (JJA), and the autumn includes September, October and November (SON).

The Arctic sea ice is obtained from the NSIDC, which is retrieved from the Scanning Multichannel Microwave Radiometer and the Special Sensor Microwave/Imager using the National Aeronautics and Space Administration (NASA) team algorithm (Fetterer et al., 2002). The Arctic SIE is defined as the total grid area with at least 15% of sea ice concentration (Cavalieri et al., 1999).

3 Results

The Arctic SIE has a downward trend in recent decades in autumn, especially from 1996. Particularly, the first minimum of the low Arctic SIE appeared in September 2012, and the second minimum happened in September 2007 (Fig. 1). We calculate the correlation coefficient of the Arctic sea ice area anomalies and SAT anomalies from 1979 to 2012, and the SAT is averaged from 60°N to the North Pole. The correlation coefficient is as high as –0.84, indicating a close relationship between the Arctic sea ice and SAT. The 34-year decreasing trend of the autumn Arctic sea ice significantly accelerated after 1996, while the Arctic SAT increased dramatically (Fig. 1). When the record autumn SIM appeared in 2007 and 2012 in the Arctic, the summer SAT reached high values in these two years, especially in 2012 the SAT increased by about 0.7°C (Fig. 1). The rise in Arctic near-surface air temperatures has been almost twice as large as the global average in recent decades, and this feature is known as the "Arctic amplification". Furthermore, SAT anomalies caused changes in the atmospheric circulation. Simultaneously, the "Arctic amplification" affected the sea ice melting.

The Arctic SIE on September 16, 2012 was 3.41 million square kilometers, less than the record low of 4.14 million square kilometers on September 16, 2007 (Fig. 2). The NSIDC data show the

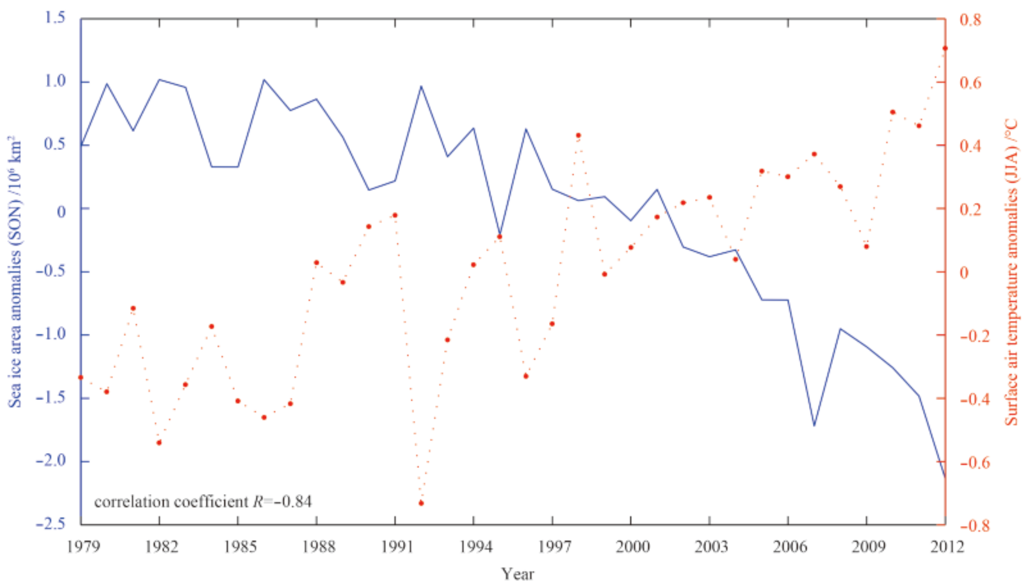

Fig. 1. Arctic sea ice area anomalies in SON and surface air temperature anomalies in JJA from 1979 to 2012. The climatological surface air temperature is from 1979 to 2012.

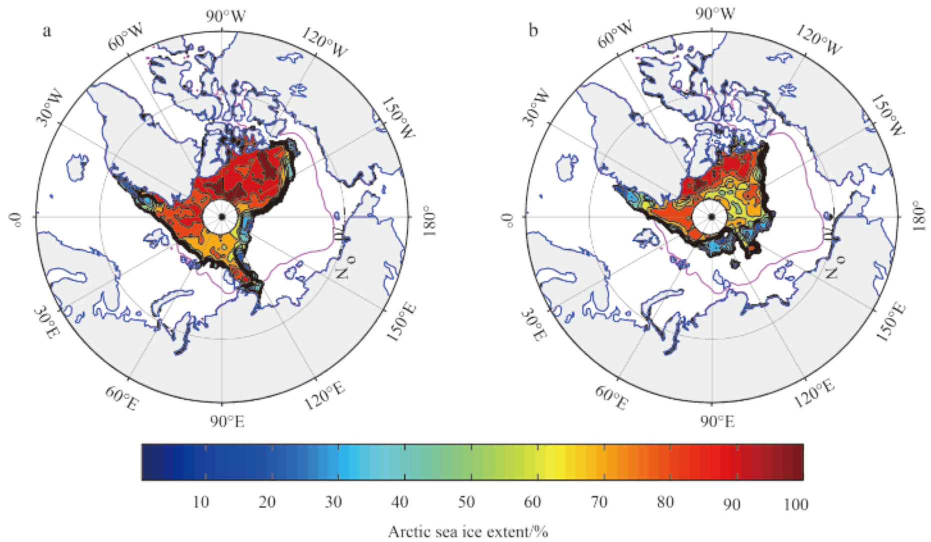

Fig. 2. The Arctic sea ice extents on September 16, 2007 (a) and on September 16, 2012 (b). The color shadings indicate the sea ice concentration exceeding 15% in the total grid area. The magenta line shows the long-term-mean sea ice extent on September 16 during 1979–2000.

Arctic SIE values in 2007 and 2012 were much less than two standard deviations of 1979–2000, especially in September.

Although the Arctic SIE reached the minimum values in 2007 and 2012, the spatial patterns of sea ice concentration are different when compared with the climatological sea ice concentration in September (Fig. 2). The sea ice loss in 2007 was mainly in the East Siberian Sea of the Arctic Ocean, while that in 2012 was in the Beaufort Sea, the northern of Barents Sea and Kara Sea and Laptev Sea of the Arctic Ocean compared with the magenta line. In the central of Arctic Ocean, there was always covered sea ice in the both two years. However, the long-term-mean sea ice extent on September 16 during 1979–2000 is almost covered the whole Arctic Ocean. The loss of sea ice in 2007 and 2012 mainly occurred in the edge of Arctic Ocean in spite of being different regions. This study intends to explain these differences. Since the Arctic sea ice melts fast in summer from June until the end of August, this paper analyzes the ocean temperature and atmospheric circulation conditions in summer to explain the rapidly melting of sea ice in different regions in these two years.

Melting of the Arctic sea ice is related to many factors, such as the increased concentration of atmospheric greenhouse gases due to the anthropogenic climate change (Solomon et al., 2007), and the changes in atmospheric and oceanic circulation (Simmonds and Keay, 2009). The roles of cloud cover and water vapor are still matters of debate (Schweiger et al., 2008). Many global climate models significantly underestimate the recent Arctic sea ice decline (Stroeve et al., 2007). Here, we consider the contributions of surface atmospheric circulation anomalies and upper-ocean temperature anomalies to the Arctic sea ice melting in summer. Above the Arctic sea ice, the changes of SAT can influence the sea ice melting in summer forming ice-SAT feedback. The SAT is one of the mostly important factors in the surface atmospheric circulation. The change of SAT also induces the changing of SLP, wind and SH, which are contributes to the sea ice melting forming a positive feedback between sea ice and SH. Below the Arctic sea ice, SST plays an important role in melting sea ice, which exists ice-SST feedback. Generally speaking, there are three feedbacks among sea ice, SAT, SST, and SH, and SLP, wind anomalies in different regions in summers of 2007 and 2012 contributing with the sea ice melting. The following is a detailed analysis.

First, the Arctic SAT anomalies in summer 2007 are checked (Fig. 3). The SAT showed positive anomalies in the East Siberian Sea of the Arctic Ocean, which was the dominant factor in atmospheric circulation leading the sea ice melting in that area in Fig. 3. In contrast, with the sea ice melting more solar radiation reached to the surface ocean and caused the SAT and SST to increase, which form two positive feedbacks. In June 2012, there was a wide range of positive SAT anomalies in Western Asia (60°–90°E), which continued until July 2012 (Fig. 3). So, the warmer air caused the Arctic sea ice melting in the northern of Barents Sea, Kara Sea and Laptev Sea. There was a positive anomalous SAT directly linked to the melting of sea ice in the Beaufort Sea in summer 2012 as well (Fig. 3). So, the increasing SAT in East Siberian Sea in summer of 2007 and in the northern of Barents Sea and Kara Sea, Laptev Sea and Beaufort Sea in summer of 2012 is one of reasons inducing the different distributions of Arctic sea ice in these two years.

The SLP pattern also played an important role in the process of summer sea ice melting. There was a high pressure anomaly center in the Arctic Ocean in June 2007 (Fig. 4). It gradually moved to the eastside of the Arctic Ocean in the next two months, which caused changes in surface wind over the Arctic Ocean. Figure 4 shows the surface wind blew from the East Siberian Sea to the Arctic Ocean, which could bring more warm air to the Arctic region from the lower latitudes, particularly in August 2007. The wind anomaly brought the warmer moist air to the westward East Siberian Sea and promoted the sea ice melting in this area. In contrast, in June 2012, there were two high SLP anomalies in Western Asia and nearby the Greenland, centered about at (70°N, 90°E) and (65°N, 45°W), respectively (Fig. 4). The poleward wind strengthened apparently and accompanied the higher SLP in Western Asia. It was likely the reason that led to the sea ice melting in the northern of Barents Sea and Kara Sea and Laptev Sea, especially in June 2012. Due to another larger higher pressure center that maintained in the Greenland area, the warmer and wetter air blew from the Beaufort Sea of the lower latitude to the polar area, which caused the sea ice melting in this sector in

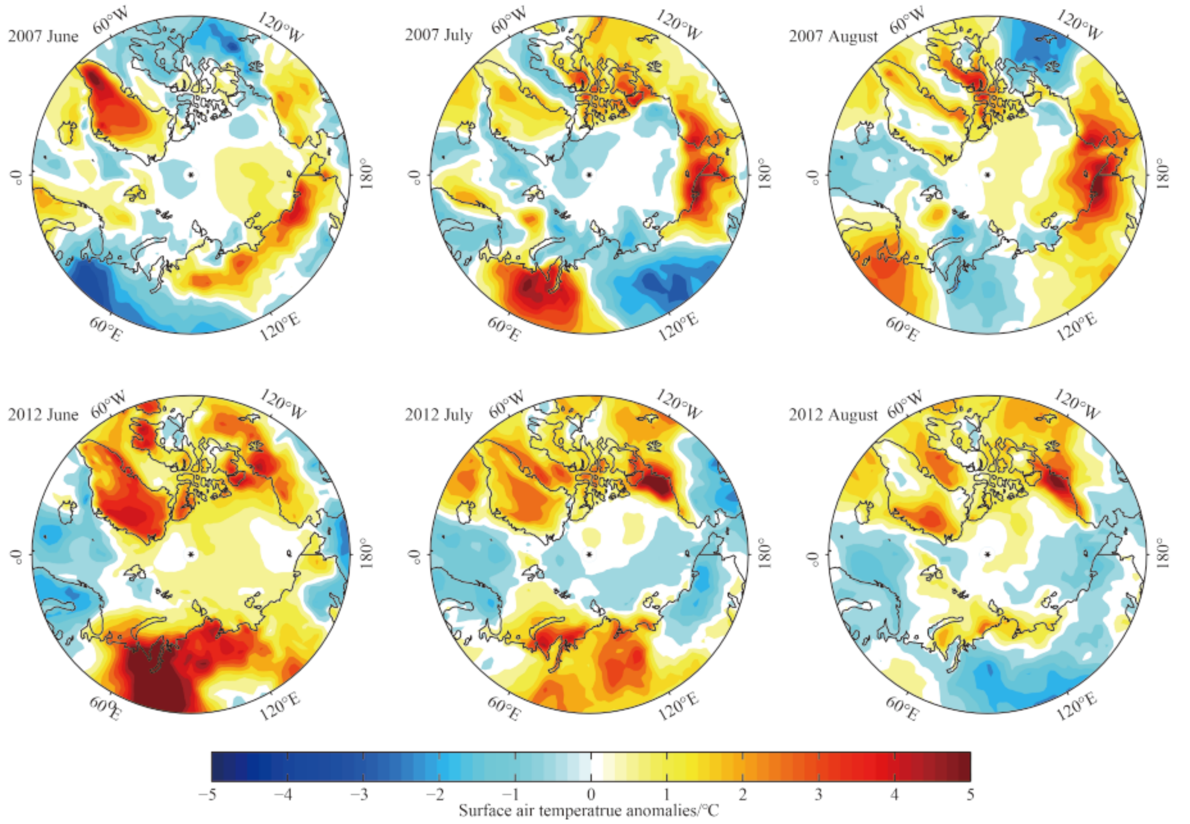

Fig. 3. Surface air temperature anomalies in the boreal summer (JJA) in 2007 (top) and 2012 (bottom). The climatological surface air temperature is from 1979 to 2012.

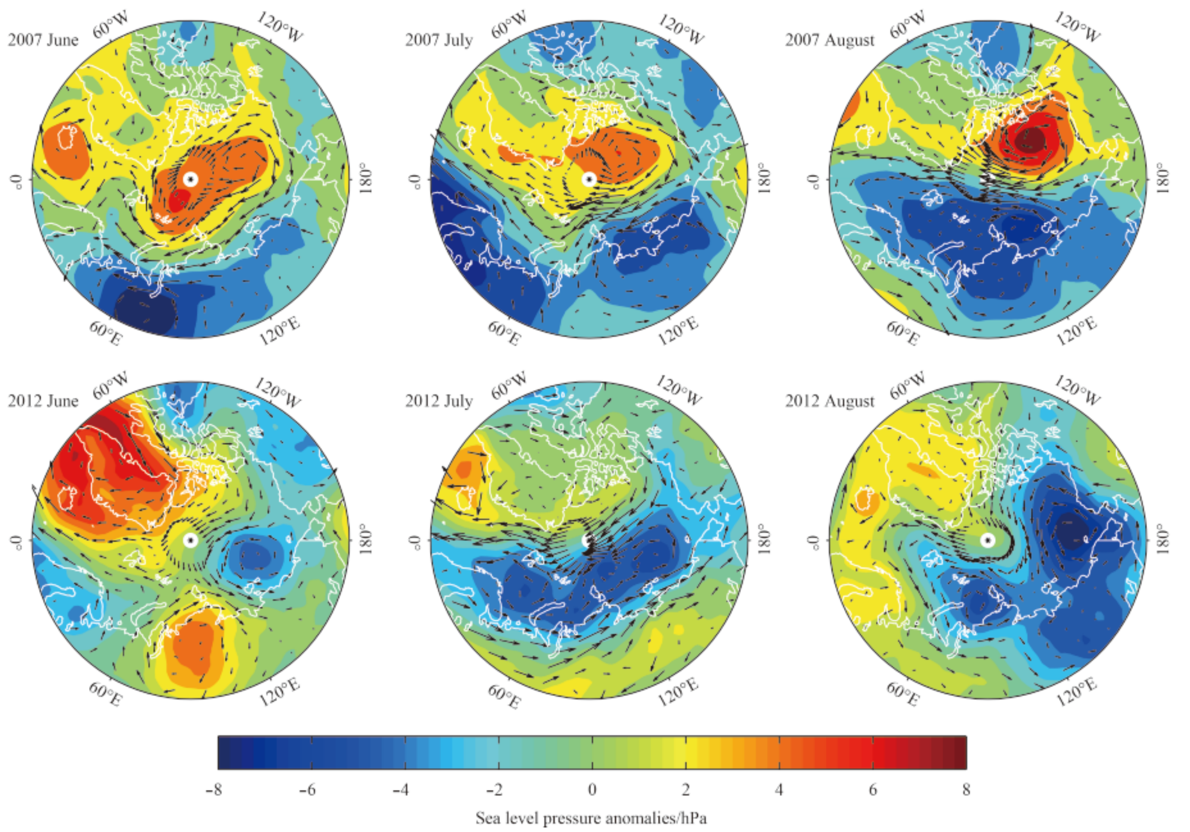

Fig. 4. Sea level pressure anomalies and 925 hPa surface wind anomalies in the boreal summer (JJA) in 2007 (top) and 2012 (bottom). The climatological sea level pressure and surface wind are from 1979 to 2012.

summer 2012. Along with the SAT anomalies, the SLP and surface wind patterns of the atmosphere circulation also changed differently in summers of 2007 and 2012, which formed the other favorable conditions benefiting the different regions sea ice melting in these two years.

Accompanied the summer SAT increased in the area, the surface SH also increased (Figs 3 and 5). SH as a measure of water vapor, which is greenhouse gas, plays a key role in melting sea ice. As a kind of the greenhouse gases, the higher water vapor can prevent the long-wave radiation from the surface to the outer space. The increased long-wave radiation to the surface is responsible for the increase of surface air temperature and water content. The surface moister air is in favor of melting sea ice in the Arctic Ocean; the large melting of sea ice can produce much more water vapor. On the other hand, without the protection of sea ice, the sea also evaporates and produces more water vapor. So, there is a positive ice-water vapor feedback. With the higher water vapor content, the Arctic sea-ice melts (Fig. 5). There was much more water vapor in the East Siberian Sea of the Arctic Ocean in summer of 2007, especially in July and August (Fig. 5). In 2012, there were positive water vapor anomalies in the northern of Barents Sea and Kara Sea, Laptev Sea and the Beaufort Sea of the Arctic Ocean, particularly in the northern of Barents Sea and Kara Sea and Laptev Sea (Fig. 5). So, the positive SH anomaly in different regions in summers of 2007 and 2012 is another reason influencing the different reduction of sea ice in these two years.

We also calculate the correlation coefficient of the Arctic sea ice area anomalies and surface SH anomalies from 1979 to 2012, and the SH is averaged from 60°N to the North Pole (Fig. 6). The correlation coefficient between the Arctic sea ice area anomalies in SON and SH anomalies in JJA reached –0.71. Figure 6 shows that the Arctic surface SH increased dramatically from 1979, by about 0.1 g/kg per decade. With the areas of the autumn Arctic sea ice dropped to minimum values in 2007 and 2012, the surface SH reached higher values in these two years. Figure 6 also indicates the increasing surface SH companied by the decreasing Arctic sea ice from 1979 to 2012. The feedback between the sea ice and SH always exists in the long-term trend.

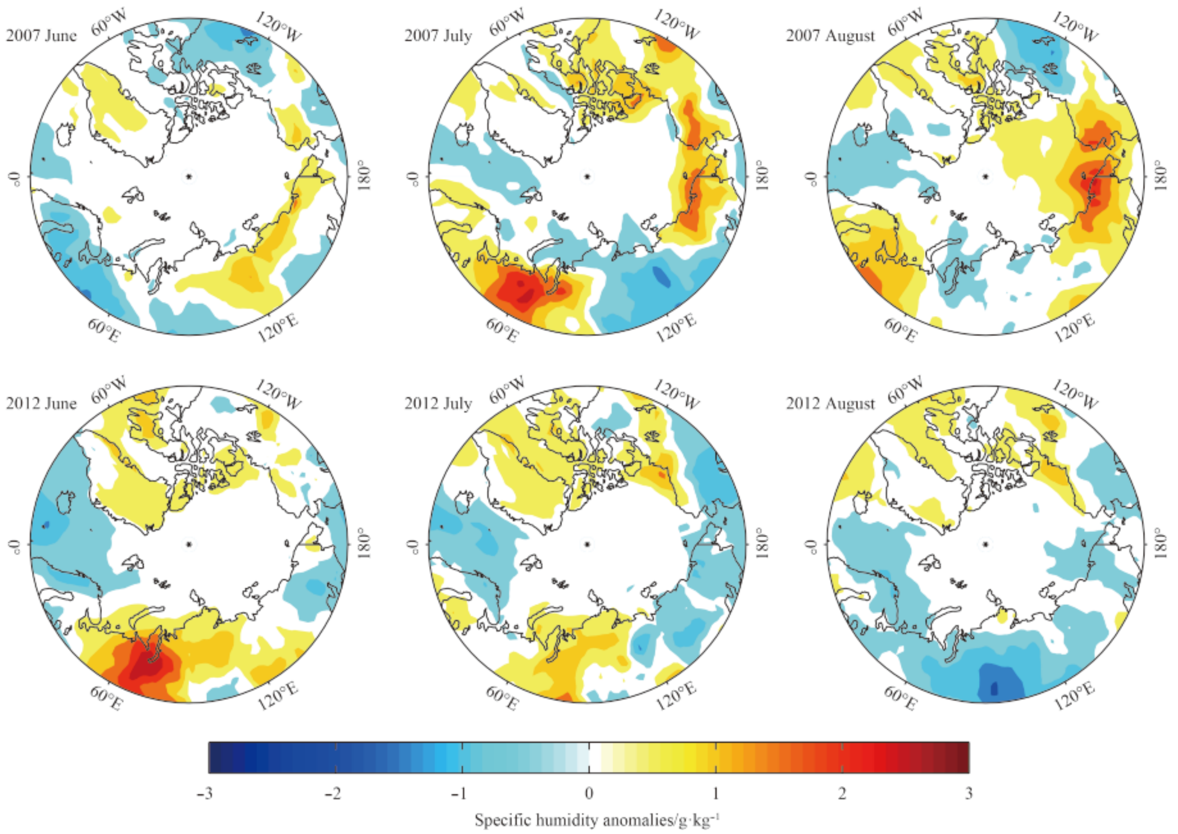

Fig. 5. Maps of 1 000 hPa specific humidity anomalies in the boreal summer (JJA) in 2007 (top) and 2012 (bottom). The climatological specific humidity is from 1979 to 2012.

In order to understand the different distributions of sea ice concentration in 2007 and 2012 (Fig. 2), the paper focuses not only on the role of atmospheric temperature (Figs 1 and 3), but also on the role of upper-ocean temperature (Figs 7 and 8). The correlation coefficient of the Arctic sea ice area anomalies and SST anomalies from 1979 to 2012 is calculated (Fig. 7). The SST is averaged from 60°N to the North Pole. The autumn Arctic sea ice area anomalies and summer SST anomalies are highly correlated, with a correlation coefficient of –0.73. Figure 8 shows that the Arctic SST increased significantly. The Arctic Ocean was in a warming state especially from 1996 to 2012 (Fig. 7). Specifically, the upper-ocean warming was more obvious in 2012, and the SST increased by about 0.22°C (Fig. 7). The SST showed positive anomalies in the East Siberian Sea of the Arctic Ocean in summer 2007 (Fig. 8), which was another significant factor leading to the sea ice melting in that area (Fig. 2a). The SST also showed positive anomalies in the Kara Sea and the Laptev Sea off the coast of Western Asia in summer 2012 (Fig. 8); and the Arctic sea ice in these areas was reduced as well (Fig. 2b). So, the higher SST caused the Arctic sea ice melting near the northern of Barents Sea and Kara Sea and Laptev Sea. Moreover, there were positive SST anomalies directly linked to the melting sea ice in the Beaufort Sea as well (Figs 8 and 2b). The different anomalous SST stays in summers of 2007 and 2012 effecting the different distributions of Arctic sea ice in September in these two years.

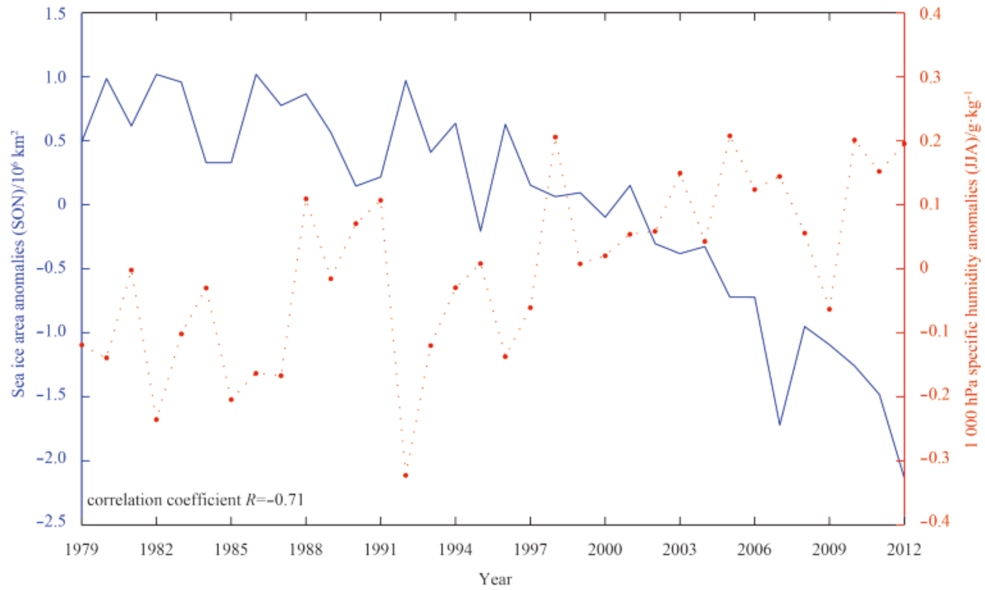

Fig. 6. Arctic sea ice area anomalies in SON and 1 000 hPa specific humidity anomalies in JJA from 1979 to 2012. The climatological Arctic sea ice and 1 000 hPa specific humidity are from 1979 to 2012.

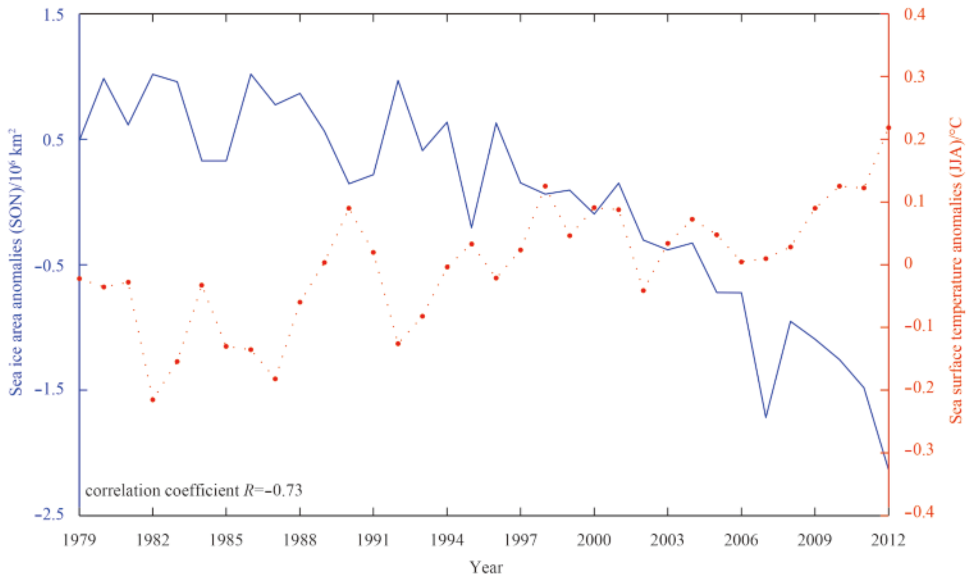

Fig. 7. Arctic sea ice area anomalies in SON and sea surface temperature anomalies in JJA from 1979 to 2012. The climatological Arctic sea ice and sea surface temperature are from 1979 to 2012.

Sea ice melting and upper-ocean warming have positive feedback effects. First, the positive SST anomalies can prompt the one-year sea ice reduction in the warmer SST area. Second, since sea ice and ocean water have different albedo values (Gill, 1982) (sea-ice's albedo is about 80% and ocean water's about 6%–8%), more heat flux is absorbed by the upper ocean after the sea ice melting, causing more upper-ocean warming. In another aspect, with the sea ice melting, large amount of low density freshwater floats on the surface ocean, causing the upper-ocean water being more stratified; the upper-ocean heat is trapped in the surface layer, which further strengthens the upper-ocean warming, advances the sea ice loss and prevents the recovery of sea ice in autumn, absorbing more solar heat and storing it in the upper ocean in turn (Hassol et al., 2004).

We adopt the empirical mode decomposition (emd) method to analyze the long-term trends of the SIE, SAT, surface SH, and SST. Results show that the trend of SIE dropped significantly, particularly from 1996. In contrast, the trends of SAT, surface SH and SST increased apparently. Meanwhile, the correlation coefficients of long-term trend between the autumn Arctic sea ice and SAT/SH/SST were the same as mentioned in this section, such as −0.84, −0.71 and −0.73. The figures are not shown in this paper.

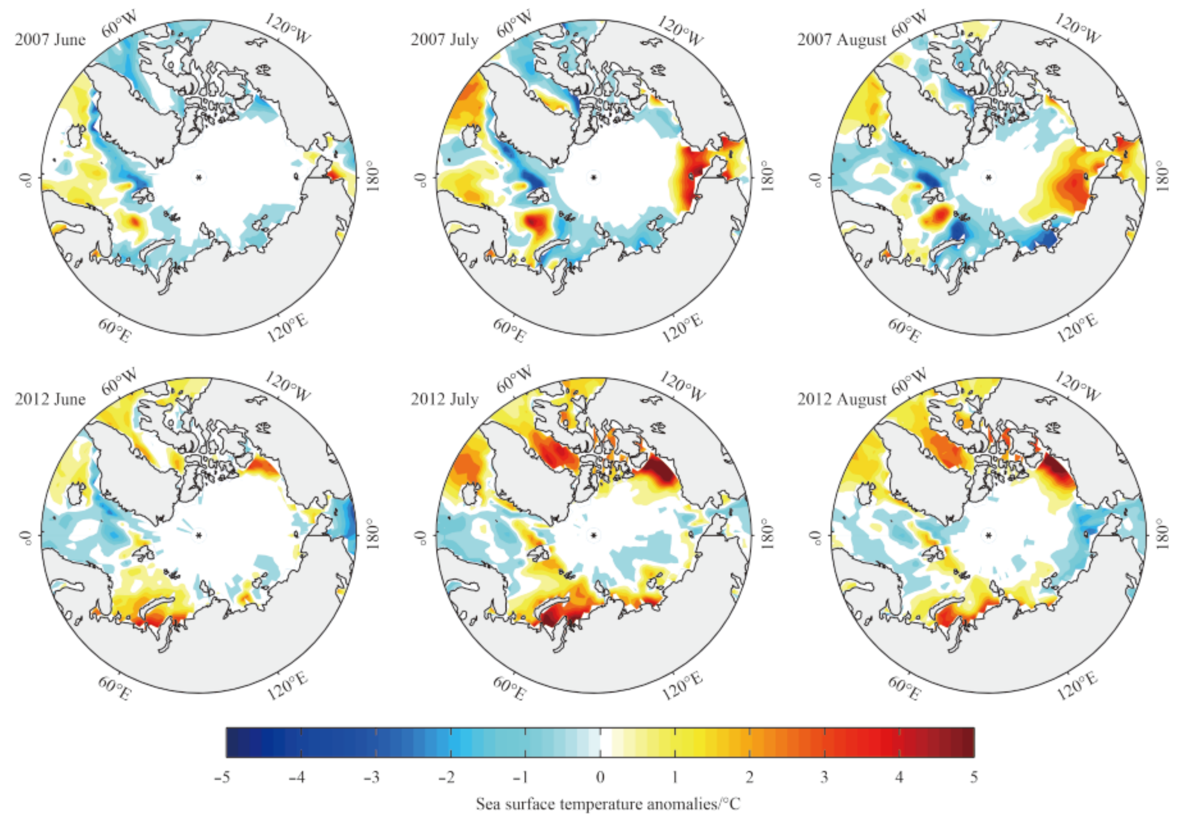

Fig. 8. Sea surface temperature anomalies in the boreal summer (JJA) in 2007 (top) and 2012 (bottom). The climatological sea surface temperature is from 1979 to 2012.

4 Conclusions and discussion

Although the Arctic SIM extents were observed in the summers of 2007 and 2012, the spatial distributions of them were quite different. The sea ice loss in 2007 was mainly in the East Siberian Sea of the Arctic Ocean, while that in 2012 was in the Beaufort Sea, the northern of Barents Sea and Kara Sea, Laptev Sea of the Arctic Ocean. The atmospheric circulation and the upper-ocean temperature over the Arctic Ocean in the boreal summer were discussed. Using the three feedbacks and five conditions, this paper explains the reasons of different distributions of Arctic sea ice in summers of 2007 and 2012. The results enhance the conclusions that strong positive ice-temperature (SAT, SST) and ice-SH feedbacks exist in the Arctic Ocean, increasing the chance of further rapid warming and sea ice loss. The SLP changed in response to the anomalous temperature pattern in the Arctic Ocean, accompanied by the anomalous wind brought the warmer and wetter air from lower latitudes to the Arctic Ocean directly, which promoted rapid sea ice retreat. The positive anomalous SAT, SH and SST were mainly in the East Siberian Sea of the Arctic Ocean in summer 2007, while in 2012 the positive anomalous SAT, SH and SST were mainly in the northern of Barents Sea and Kara Sea, Laptev Sea and the Beaufort Sea of the Arctic Ocean. This study shows that the different distributions of anomalous surface atmospheric circulation and the upper-ocean temperature induce the different spatial distributions of sea ice in September 2007 and 2012.

The close relationship of oceanic and atmospheric anomalies in summer with the Arctic sea ice in autumn may provide a way for sea ice prediction. However, there were many other factors that influenced the retreat of Arctic sea ice, such as clouds, solar radiation, thermohaline circulation, and so on (Kay et al., 2008; Devasthale et al., 2013). Their roles need to go more depth investigates. The most advanced satellite-based monitoring and in situ observations could provide critical information regarding atmospheric and ocean pre-conditioning, thus helping to predict extreme melting events in the Arctic Ocean. In future, using the latest observational data we hope to predict the smallest SIE in September, according the changes of some geophysical variables in summertime. Improving our understanding of the characteristics of the Arctic atmosphere and ocean environments has become more crucial, not only for improving prediction of minimum sea ice in autumn but also for predicting the distribution of reduced sea ice area in future.

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