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Analysis of recent climate change over the Arctic using ERA-Interim reanalysis data

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Abstract This study investigates recent climate change over the Arctic and its link to the mid-latitudes using the ERA-Interim global atmospheric reanalysis data from the European Center for Medium-Range Weather Forecast (ECMWF). Since 1979, substantial surface warming, associated with the increase in anthropogenic greenhouse gases, has occurred over the Arctic. The greatest warming in winter has taken place offshore in the Kara-Barents Sea, and is associated with the increase in turbulent heat fluxes from the marginal ice zone. In contrast to the marked warming over the Arctic Ocean in winter, substantial cooling appears over Siberia and eastern Asia, linked to the reduction of Arctic sea ice during the freezing season (September–March). However, in summer, very little change is observed in surface air temperature over the Arctic because increased radiative heat melts the sea ice and the amount of turbulent heat gain from the ocean is relatively small. The heat stored in the upper ocean mixed layer in summer with the opening of the Arctic Ocean is released back to the atmosphere as turbulent heat fluxes during the autumn and through to the following spring. This warming of the Arctic and the reduced sea ice amplifies surface cooling over Siberia and eastern Asia in winter.

Keywords **Arctic climate, Arctic sea ice, cold surge, surface temperature, sea surface temperature, Arctic Oscillation**

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1 Introduction

Since the onset of industrialization, global mean surface temperature has increased by approximately 1℃[1]. This degree of warming during the last century is much greater than the surface temperature fluctuation over the past millennium. For example, between 500 AD and 1900 AD, the average surface temperature over the northern hemisphere has varied within a range of approximately 0.5℃[2]. This result indicates that the variability of global mean surface temperature might be even lower than 0.5℃ because the southern hemisphere has a larger volume of ocean, which is generally more stable than land. Instrumental and paleo proxy data suggest that the surface temperature has fluctuated to a much greater degree in the higher latitudes[3-5]. Even though substantial warming occurs in West Antarctica, which includes the Antarctic Peninsula, the surface temperature over East Antarctica shows little change over the past several decades[6-7]. However, the surface warming over the Arctic appears to be substantially greater than the northern hemisphere or global mean surface temperature change in the reanalysis data[8-9] and in numerical models in response to the increase in greenhouse gas emissions[1,3,10]. The much greater warming over the Arctic is referred to as the Arctic amplification[11-12], and is also found in the paleoclimate proxy records[13].

Several hypotheses have been suggested to explain the cause of the Arctic amplification[14]. Graverson and Wang[14] found substantial warming in the mid-troposphere instead of at the surface in the northern high latitudes and suggested that the main contribution to the Arctic amplification is through the transport of greater meridional heat from lower latitudes to higher latitudes via atmospheric eddies.

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However, using a different version of reanalyzed data, Screen and Simmonds[9] observed marked surface warming at the northern high latitudes and linked this to the reduction of sea ice and associated heat transfer from the ocean to the atmosphere. They also attributed the increase in cloud cover to the amplified surface warming through an increase in downward long-wave radiation, which is greater than the reduction of short-wave radiation caused by the increase in cloud cover. In any case, positive albedo feedback seems to be at work in response to the change in external forcing because high latitudes are covered by snow and ice, which have a higher albedo than bare earth or ocean.

The substantial warming over the Arctic is linked closely with the reduction in sea ice, which showed the greatest annual decline in September of 2012 based on satellite observations. Some numerical studies have suggested that the reduction of Arctic sea ice led to climate change over the mid-latitudes, especially in winter[15-23]. Other studies have suggested that the increase in snow over Siberia leads to a cooling over the mid-latitudes[24-31] by enhancing planetary wave activities, which weakens the northern hemisphere polar vortex[32-35]. Even though high uncertainties remain, the increase in snow over Siberia appears to be linked to the reduction of Arctic sea ice[36-38].

These previous results suggest that the recent rapid decline of Arctic sea ice is important in relation to the climate change over the Arctic and even over the mid-latitudes. This study investigates recent climate change over the Arctic associated with changes in sea ice. We also examine the role of sea ice in climate change over the mid-latitudes.

2 Data

We used ERA-Interim global atmospheric reanalysis data from the ECMWF for the atmospheric variables and sea ice. The data are reproduced from an improved atmospheric model and data assimilation system compared with those of the ERA-40 reanalysis dataset[39]. The main improvement over ERA-40 data is the higher resolution at T255 (about 80 km), model physical parameterizations, a better hydrological cycle, four-dimensional variational data assimilation and variational bias correction of satellite radiance data[39]. The ECMWF ERA-Interim data are available beginning 1979. Brunke et al. evaluated the biases of ocean surface turbulent fluxes from six reanalyzes, four satellite derived fluxes, and two combined products based on ship measurements from 12 cruises over the tropics, mid- and high latitudes[40]. They found that the ERA-Interim reanalysis is one of the best performing models for the turbulent fluxes.

3 Results

The globally averaged surface temperature increased consistently at approximately 0.11℃ per decade since 1979 (Table 1). The Fourth Assessment Report of the Inter-Governmental Panel for Climate Change (IPCC)[1] suggests that the global-mean surface temperature increased by about 0.74℃ over the past century. In comparison to the surface warming over the past century, the rate of recent surface warming has been greater. Note that the recent rapid warming of the globe is unprecedented for the past millennium during which surface temperature fluctuated within ±0.5℃[2]. Compared with the global-mean surface temperature rise, in the high northern latitudes the surface warmed more rapidly throughout all seasons. The greatest warming occurred in boreal autumn at approximately 0.91℃ per decade, which was followed by warming in spring and winter at 0.85℃ and 0.77℃ per decade, respectively. Over the past 30 years, the least amount of Arctic warming occurred in summer when the surface warmed up by approximately 0.3℃ per decade.

Table 1 Trend per decade for the SAT, SST, and sea ice from 1979 to 2012

Season	Variable and averaged area			
	SAT/℃		SST/℃	Sea ice/%
	Global	65°N−90°N	65°N−90°N	65°N−90°N
Spring	0.12	0.85	0.007	−1.25
Summer	0.12	0.28	0.037	−3.06
Autumn	0.15	0.91	0.071	−3.77
Winter	0.09	0.77	0.024	−1.50

Compared with the change in surface air temperature (SAT), sea surface temperature (SST) showed an order of magnitude less variation. Consistent with the change in SAT, the greatest surface ocean warming occurred in boreal autumn at 0.07℃ per decade. The second greatest ocean surface warming occurred in boreal summer by approximately 0.04℃ per decade. This substantial ocean warming in summer is different from the atmosphere, where the least warming occurred during the summer. In the ocean, the least warming occurred in boreal spring at 0.007℃ per decade. Consistent with the change in SAT and SST, the sea ice over the Arctic changed substantially since 1979. The greatest sea ice reduction occurred in boreal autumn by approximately −3.8% per decade, which was followed by a summer reduction of −3.1% per decade. Note that the marked declining trend in sea ice during autumn and summer is mainly due to the change over recent decades. In winter and spring, the rate of sea ice reduction was less than half that of other seasons.

The Arctic-averaged quantity of SAT, SST, and sea ice has changed substantially since 1979. We now examine in detail the inter-annual variability of these variables since 1979. Figure 1 shows the temporal variation of SAT and SST anomalies averaged globally and from 65°N to the North Pole for all seasons since 1979. There was little change in global-mean SAT in all seasons. However, the SAT anomaly over high northern latitudes showed an increase and a decrease even though a long-term trend of increase persisted. Overall, SAT increased and sea ice decreased rapidly from about the mid-1990s onwards (Figure

2). For example, in boreal winter the SAT increased by approximately 5℃ from about 1995 to the present and in autumn it increased by approximately 4℃ from the 1990s to the present. In spring, since the year 2000 the surface warmed up by approximately 3℃. The least SAT change occurred in boreal summer. For the winter and spring seasons, sea ice showed the greatest melting trend until 1996 and since then the sea ice melting trend has decreased slightly. However, for boreal summer, sea ice showed a steadily decreasing trend with time (Figures 1 and 2).

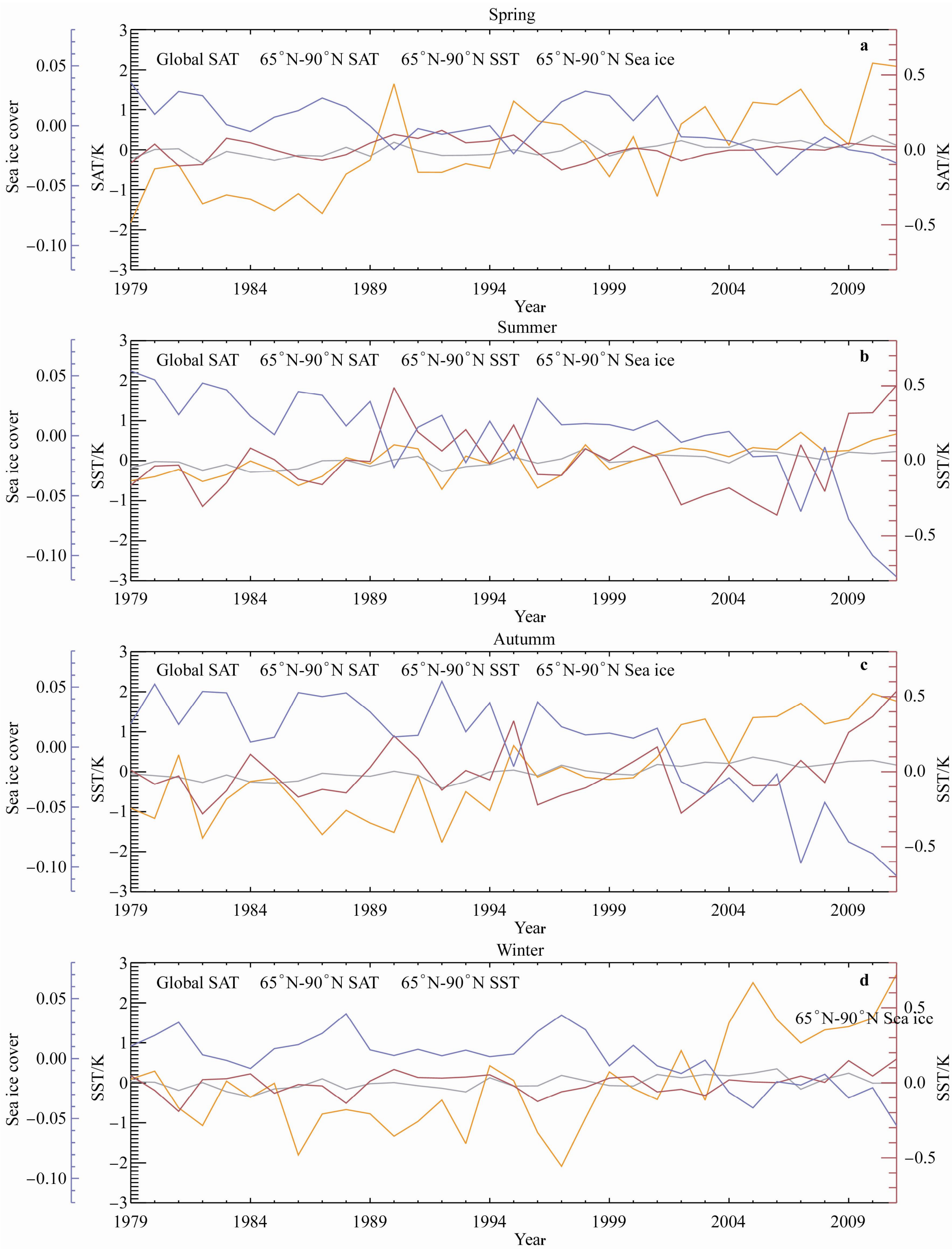

Figure 1 Temporal variations of SAT averaged globally (gray) and from 65° to 90°N (orange). SST (purple) and sea ice (blue) are averaged from 65° to 90°N for spring (**a**, March—April—May), summer (**b**, June—July—August), autumn (**c**, September—October— November), and winter (**d**, December—January—February).

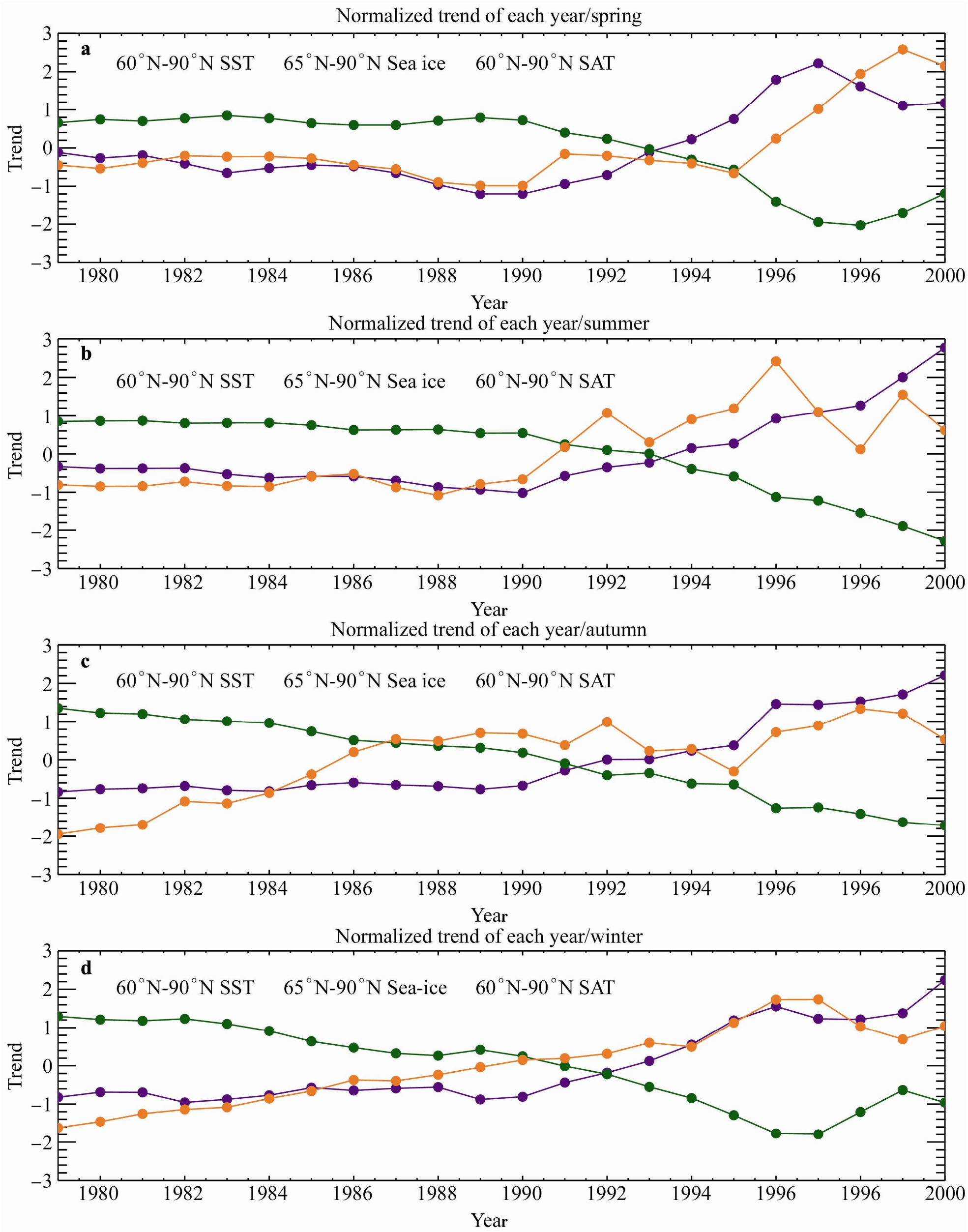

Figure 2 Temporal variation in SAT (orange), SST (purple), and sea ice trends (green) from 1979 to 2012 for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**). Each trend is normalized by its standard deviation.

In general, the temporal variation of the Arctic sea ice matched the SAT (Figure 1) showing a strong negative correlation (Table 2). In all seasons, the SAT and sea ice were correlated by more than −0.7 with the strongest correlation (−0.89) in autumn. In the temporal variation of the Arctic sea ice, the most prominent feature was the marked reduction of sea ice in summer and autumn. This reduction in sea ice in autumn was consistent with the marked surface warming, but in summer the surface temperature increase was not substantial even though there was a marked reduction of sea ice. In the summer season, surface ocean warming was more consistent with the sea ice. Serreze and Barry[12] suggest that the increased short-wave energy in summer melts the sea ice and warms up the ocean mixed layer, and the heat stored in the ocean mixed layer during summer is released back to the atmosphere as sensible and latent heat fluxes the following autumn. This explains the occurrence of the greatest surface warming in autumn. The correlation between sea ice and SST was also high, with coefficients of more than −0.5 in all seasons that are statistically significant at the 95% confidence level. Nevertheless, the correlation of sea ice with SST was not as high as that with SAT. Moreover, the highest correlation appeared in winter rather than in autumn when the weakest correlation occurred.

Table 2 Correlation coefficients between SAT and sea ice (SICE) and SST and SICE for all seasons. Bold letters represent correlations statistically significant at 95% confidence level

Variables	Season			
	Spring	Summer	Autumn	Winter
SAT and SICE	−0.74	−0.78	−0.89	−0.84
SST and SICE	−0.62	−0.62	−0.59	−0.66

For the past three decades, the SAT change was not spatially uniform. Figure 3 shows the SAT trend from 1979 to the present. In this figure, the areas of SAT change that are statistically significant at the 95% confidence level are represented as dots. We performed a two-sided significance test using bootstrap resampling. Since 1979, the greatest warming has occurred over the Barents Sea in winter. The warming over Baffin Bay also showed an increase in winter. The second greatest warming occurred in autumn over the Eurasian sector of the Arctic Ocean and the Chukchi Sea including a section of the Canadian Basin. From Figure 1b, the least Arctic warming occurred in summer. Over land, a substantial warming occurred over most of the northeastern North America and Eurasia. One peculiar exception occurred in winter over Siberia, where a substantial surface cooling trend was visible. Note, however, that some of the cooling in some areas was not statistically significant. This winter cooling trend over Siberia seems counterintuitive to the global warming trend. Cohen et al.[31] also found a cooling trend over Europe, Siberia, and eastern North America using CRUTEM3 data (third version of surface temperature data from Climate Research Unit at the University of East Anglia) between 1988 and 2010. Jeong et al.[41] found that the Siberian high pressure system increased over the past two decades in association with the increase in snow over Siberia. These findings are consistent

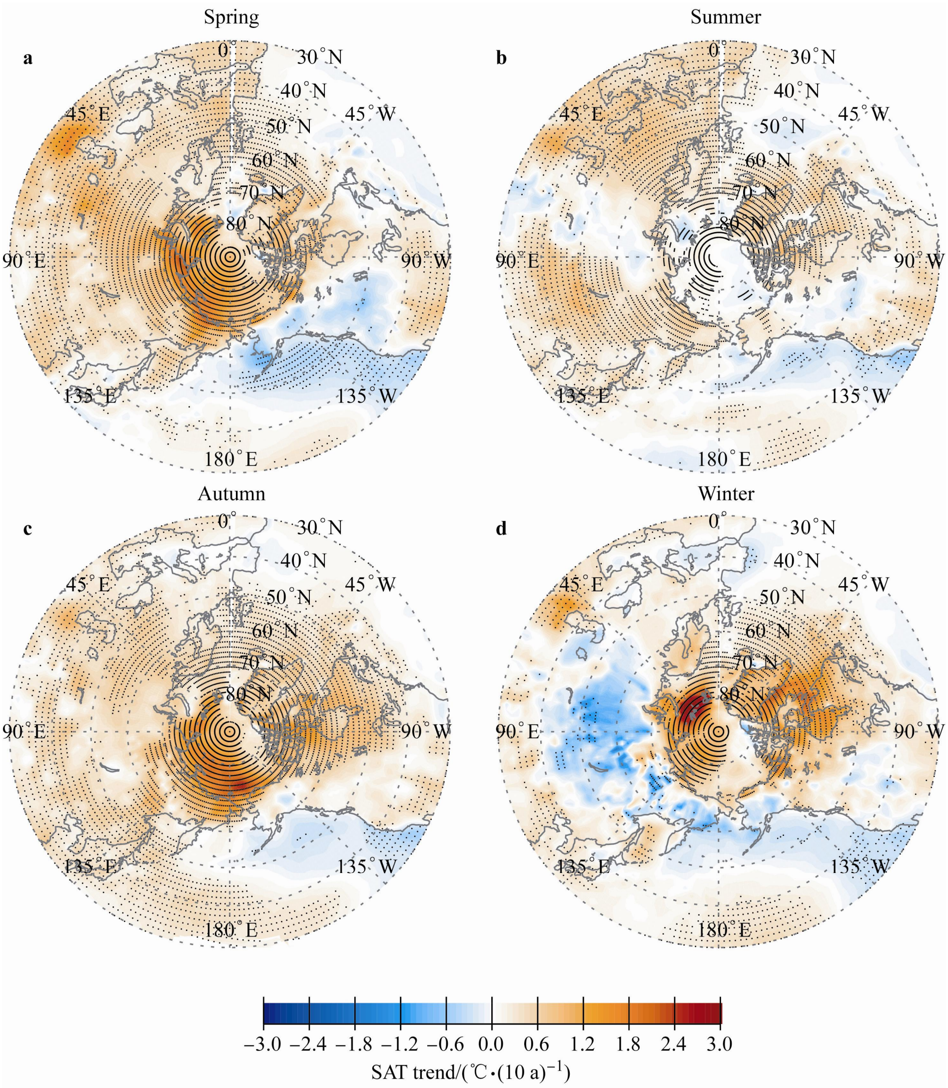

Figure 3 Geographic distribution of SAT trend from 1979 to 2012 for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**). The areas marked by dots are statistically significant at the 95% confidence level (two-sided significance test using bootstrap resampling).

with our results. Outten and Esau[42] found a cooling trend over Eurasia in January from 1989 to 2009 and they attributed this surface cooling to warming around the Kara Sea. As illustrated in Figure 3, this anomalous cooling trend appears to be related to the change in sea ice extent. Another feature was the cooling SST over the northeastern Pacific. Conversely, a warming trend was observed from the northwestern to the central Pacific. Overall, since 1979, a substantial warming has occurred over the entire Arctic and adjacent land areas, except for the anomalous cooling over Siberia.

Because the correlation between the SAT and sea ice over the Arctic is high, as stated above, we examined the trend of the sea ice over the Arctic (Figure 4). The greatest trend of sea ice decline appeared in autumn from the Canadian Basin to the Kara Sea through the Eurasian basin with a marked trend in the Chukchi Sea. In summer, Arctic sea ice showed a trend of substantial decline similar to those in autumn. In winter, the greatest sea ice reduction occurred across the Kara Sea. A comparison between the SAT and sea ice trends showed that the SAT change was tightly connected with the change in sea ice, especially in autumn.

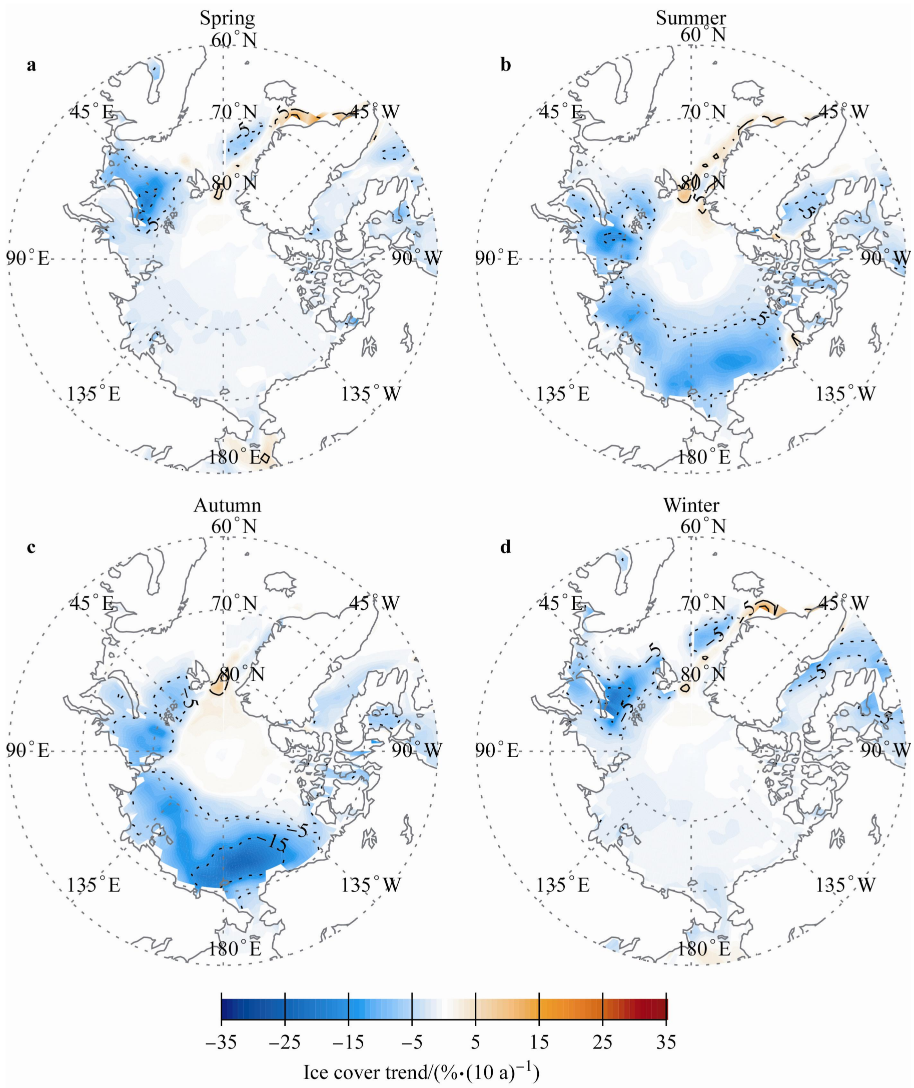

Figure 4 Geographic distribution of the sea ice cover trend from 1979 to 2012 for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**).

To check how much of the SAT change is explained by the change in sea ice, we regressed the SAT onto the sea ice cover. Before regression, we eliminated the trend of both variables to exclude a spurious relation. Figure 5 shows the regression coefficients between the two variables. When sea ice melts over the Arctic, SAT tends to increase. This is the case mainly in winter. In spring and autumn, SAT over the Arctic and neighboring regions increased with the reduction of sea ice, even though the impact of the sea ice melting on the SAT increase was not as great as it is in winter. In seasons with little or almost no short-wave radiative heat fluxes, the sea ice reduction allows the ocean to release heat to the atmosphere, warming the surface over the Arctic and sub-Arctic regions. However, in summer, the sea ice reduction does not play a role in the SAT increase. This relation was also inferred from the comparison of the SAT and sea ice trends in Figures 3 and 4. As illustrated by Serreze and Barry[12], this is because the increase in short- and long-wave radiative heat fluxes in summer mainly melts the sea ice and warms the upper mixed layer. Moreover, because the difference in temperature between the ocean and atmosphere is relatively small in the summer compared with during other seasons, the amount of heat transfer from the ocean to the atmosphere by sensible heat flux is small.

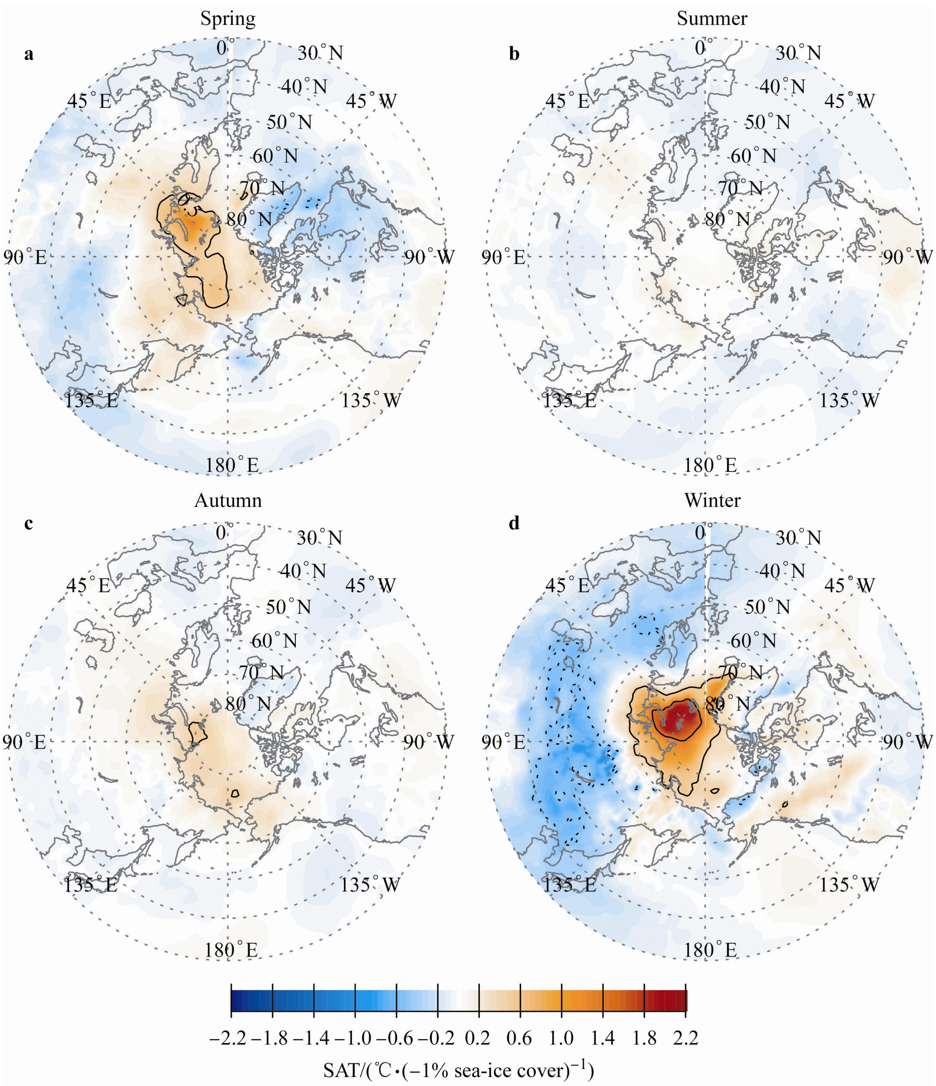

Figure 5 Regression coefficients of SAT plotted against sea ice cover from 1979 to 2012 for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**).

The regression between the SAT and the Arctic sea ice showed a marked surface cooling over northeastern Asia when the sea ice over the Arctic is reduced, especially in spring and winter (Figure 5). In winter, the cooling over Europe was also pronounced and there was a cooling signature in autumn along approximately 40°N. This result suggests that the surface cooling occurring over northeastern Asia, and parts of North America and Europe during winter for the past 20 years is in part related to the sea ice reduction over the Arctic. From an analysis of surface temperature for the past 20 years, Cohen et al.[31] found that the trend of surface cooling occurred over the whole of Eurasia and the southeastern United States in winter. They attributed the winter northern hemisphere cooling to the increase in the October Eurasian snow cover that primarily leads to a diabatic cooling and a strengthening of the Siberian high. The increase in autumn snow cover secondarily increases the upward propagation of planetary waves and subsequently weakens the westerly polar vortex, leading to the strengthening of meridional circulation. The weakening of the polar vortex caused by the increase in Siberian snow cover has been investigated in many previous studies[24-27,31,34].

In addition to the increase in snow over Siberia, the marked reduction of the Arctic sea ice in September leads to colder climatic conditions over Eurasia and part of North America. For example, Honda et al.[17] analyzed the reduced sea ice over the Kara-Barents Sea from September to December and found surface cooling from Eurasia to northeastern Asia through Siberia in December and February. However, in a recent study, Cohen et al.[31] found that the September Arctic sea ice change does not influence the surface cooling over Eurasia in winter, and that the increase in snow and negative Arctic Oscillation pattern only highlights the surface cooling feature. We further examined whether the reduced summer and autumn sea ice over the Arctic influenced the cooling in the following winter (Figure 6). The results show that the sea ice reduction in September led to the cooling over Eurasia in winter to some degree, but the greatest Eurasian cooling was led by the sea ice reduction in December. Specifically, from summer to winter, the impact of the Arctic sea ice reduction to the Eurasian cooling became greater and the winter sea ice reduction played a more important role than in summer. The cause of the Eurasian cooling in response to the Arctic sea in early winter will be examined in a future study.

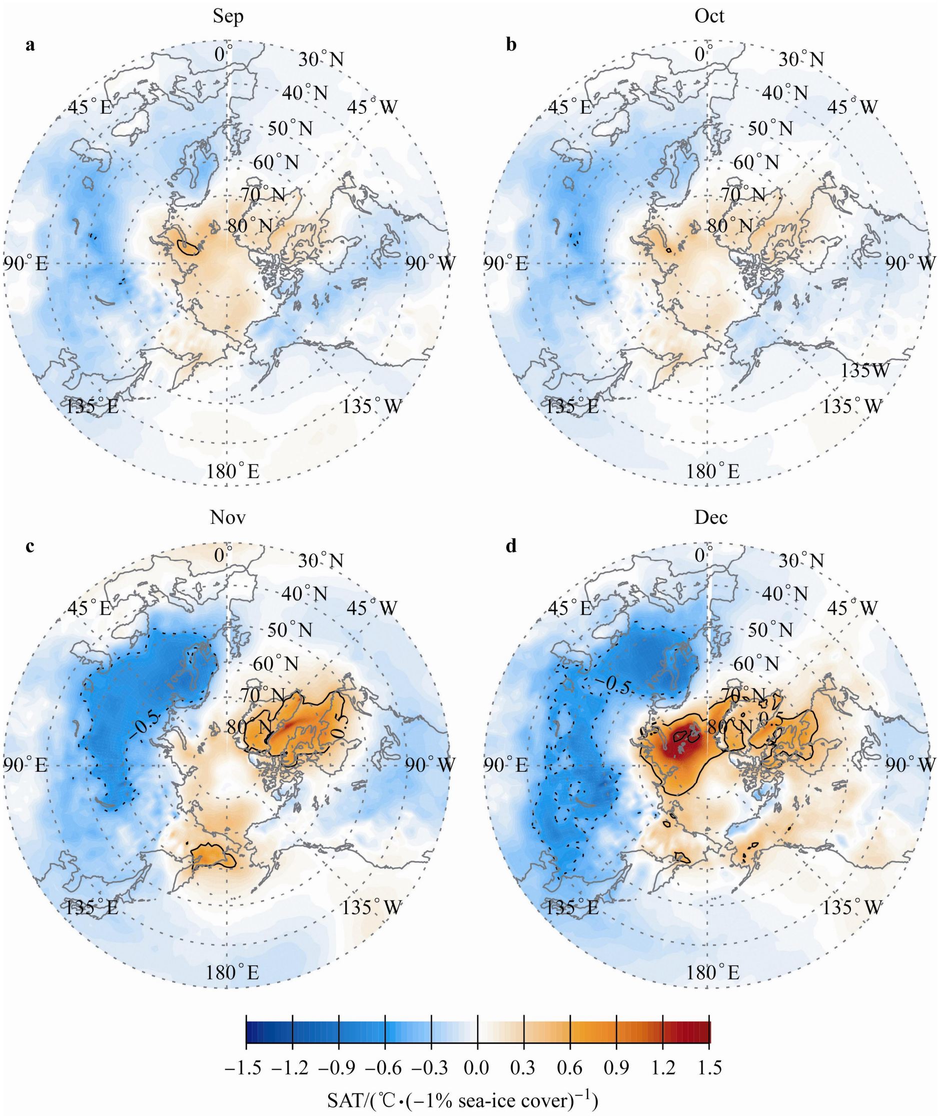

Figure 6 Regression coefficients of winter SAT plotted against sea ice cover of September (**a**), October (**b**), November (**c**), and December (**d**).

To check what caused the surface temperature trends over the Arctic, we examined the trends of the radiative and turbulent heat fluxes. Since 1979, the short wave radiative heat flux increased substantially in summer over the Arctic, especially in the Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas (Figure 7). These were the seas with the greatest sea ice reduction trends (Figure 3b). In spring, the greatest increase in the short-wave radiative heat flux occurred in the Barents Sea, where the greatest sea ice reduction appeared as well. The increase in the short-wave heat fluxes in the locations where there was also a marked sea ice reduction appeared to be caused by the ice-albedo feedback. Because sea ice and snow have a much higher albedo than the ocean, when the sea ice was reduced, more short-wave energy was absorbed. In winter, because there is little incoming short-wave energy, the ice-albedo feedback shuts down.

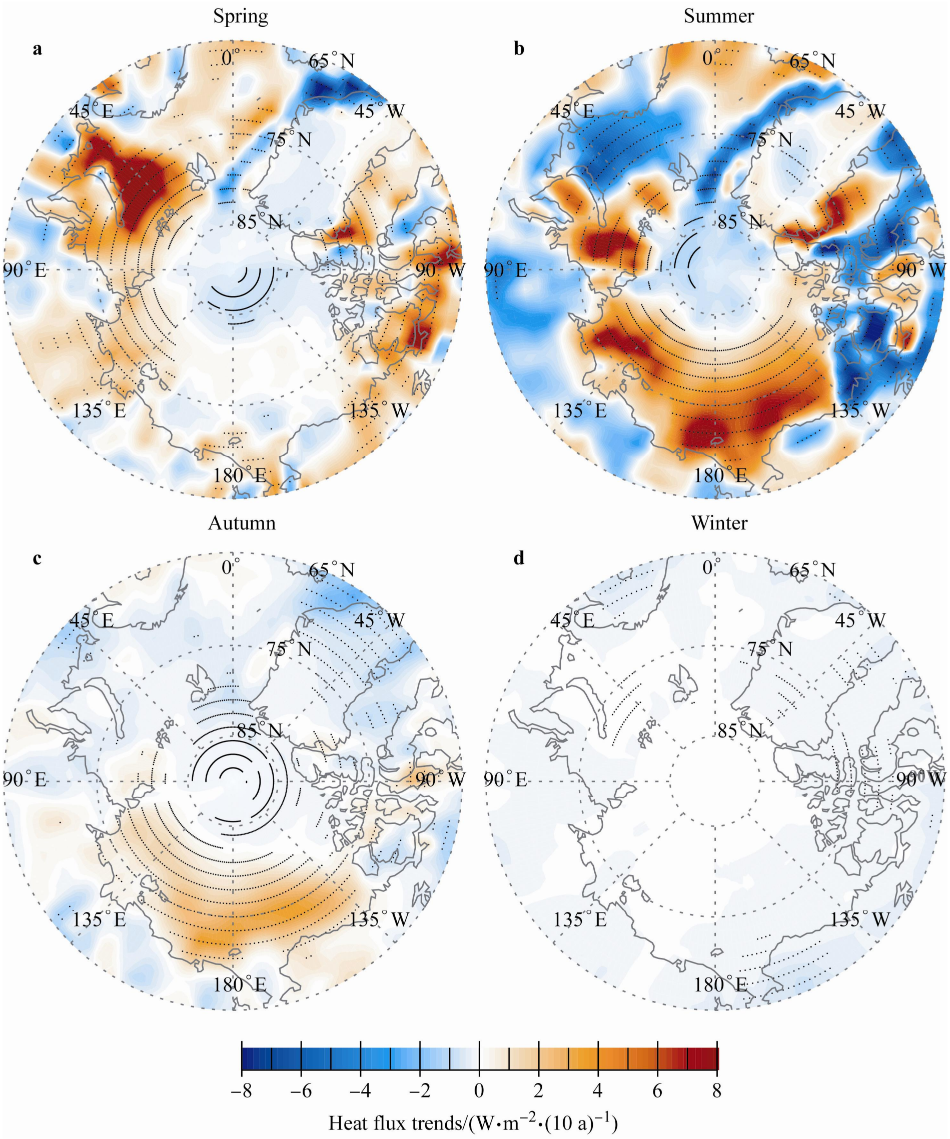

Figure 7 Geographic distribution of short-wave heat flux trends for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**). The areas marked by dots are statistically significant at the 90% confidence level.

In summer, the long-wave heat flux displayed a generally increasing trend over the Arctic (Figure 8). The rate of increase of the long-wave heat flux was slightly greater in the Canadian Basin. In autumn and winter, the long-wave heat flux showed increasing trends in the Atlantic sector of the Arctic Ocean, whereas in spring in the Pacific sector of the Arctic, long-wave heat fluxes showed a slightly increasing trend. The net long-wave heat flux was governed by the outgoing long-wave heat flux given by the Stefan-Boltzmann Law and the incoming long-wave heat flux that was dependent on cloud cover and the vertical distribution of absorbers. Because the outgoing long-wave heat flux was generally constant for the seasonal average, the trend was primarily determined, for example, by the change in atmospheric water vapor, clouds, or trace gases. The overall increase in the longwave heat fluxes in the Pacific sector of the Arctic Ocean in summer and the Atlantic sector in autumn and winter appeared to be caused by an increase in water vapor associated with the increase in evaporation due to either the sea ice reduction or increased surface ocean temperature. In fact, the trend of the long-wave heat flux was broadly consistent with the evaporation trend shown in Figure 9.

The latent heat flux was mainly from the evaporation at the surface followed by condensation in the atmosphere. In summer, there was an increasing trend in latent heat flux

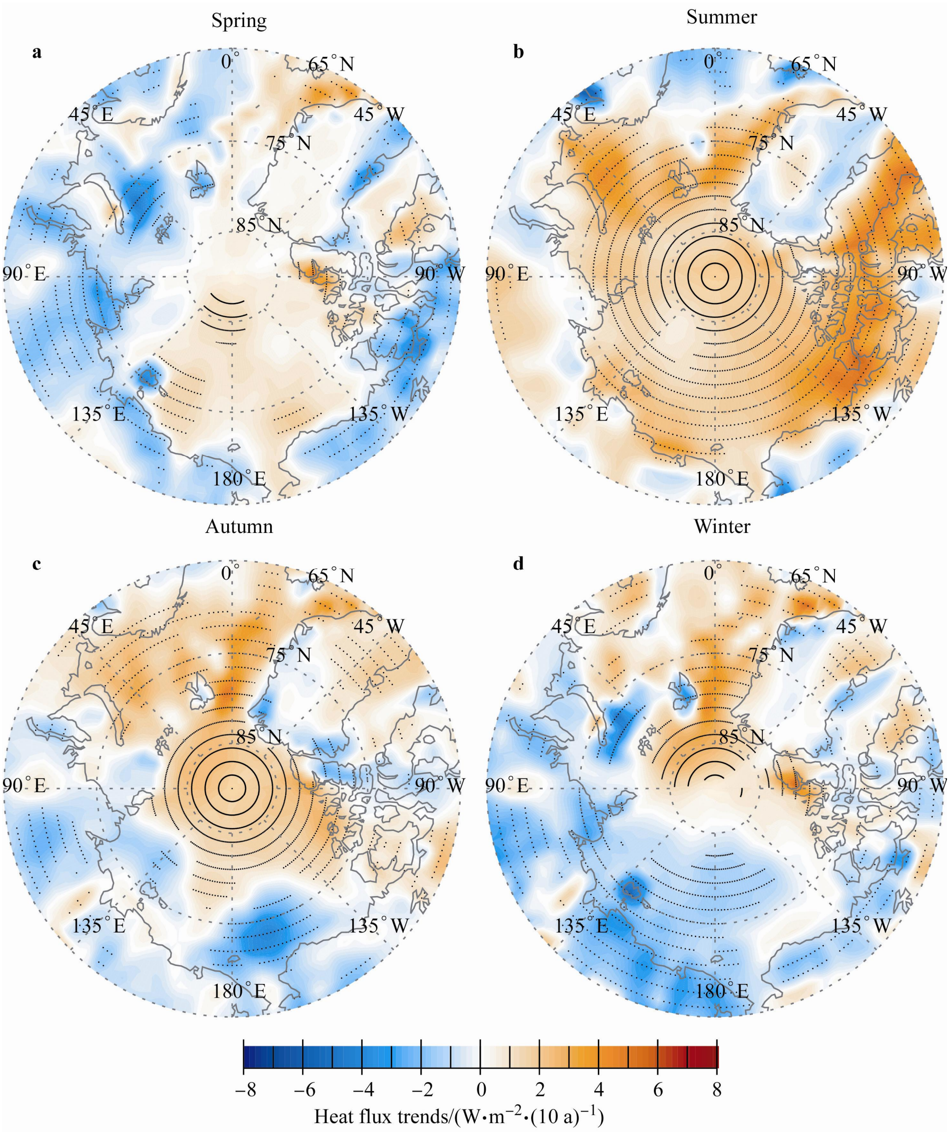

Figure 8 Geographic distribution of long-wave heat flux trends for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**). The areas marked by dots are statistically significant at the 90% confidence level.

over most of the Arctic Ocean (Figure 9b). In other seasons, the substantial increase in latent heat flux occurred only in the northern North Atlantic. In summer, autumn and winter, the increasing trend in the Barents Sea was substantial. The sensible heat flux showed a marked increase in the Barents Sea as well, especially in autumn and winter (Figure 10) where SST showed an increasing trend (not shown). In summer, because there was no great difference in temperature between the ocean and atmosphere, there was not a notable trend in sensible heat flux over the Arctic. Overall, the radiative heat flux in summer has displayed an increasing trend in for the past 30 years, likely associated with the ice-albedo and water vapor feedback. The increased radiative heat melted the sea ice and subsequently warmed the upper ocean mixed layer. Towards autumn and winter, the added ocean heat was released back to the atmosphere via turbulent heat fluxes through areas of the reduced sea ice and eventually warmed the surface air.

4 Conclusions

We investigated climate change over the Arctic using the ERA-Interim reanalysis data from ECMWF, which is an updated and improved version of the ERA-40 reanalysis data with a higher-resolution (T255) numerical mode and a more accurate assimilation technique. The Arctic and surrounding regions have undergone substantial surface warming associated with increased atmospheric anthropogenic greenhouse gases since 1979. The greatest Arctic warming occurred across the Kara-Barents Sea, and was associated with an increase in heat from the ocean due to the increase in turbulent heat fluxes as the sea ice extent

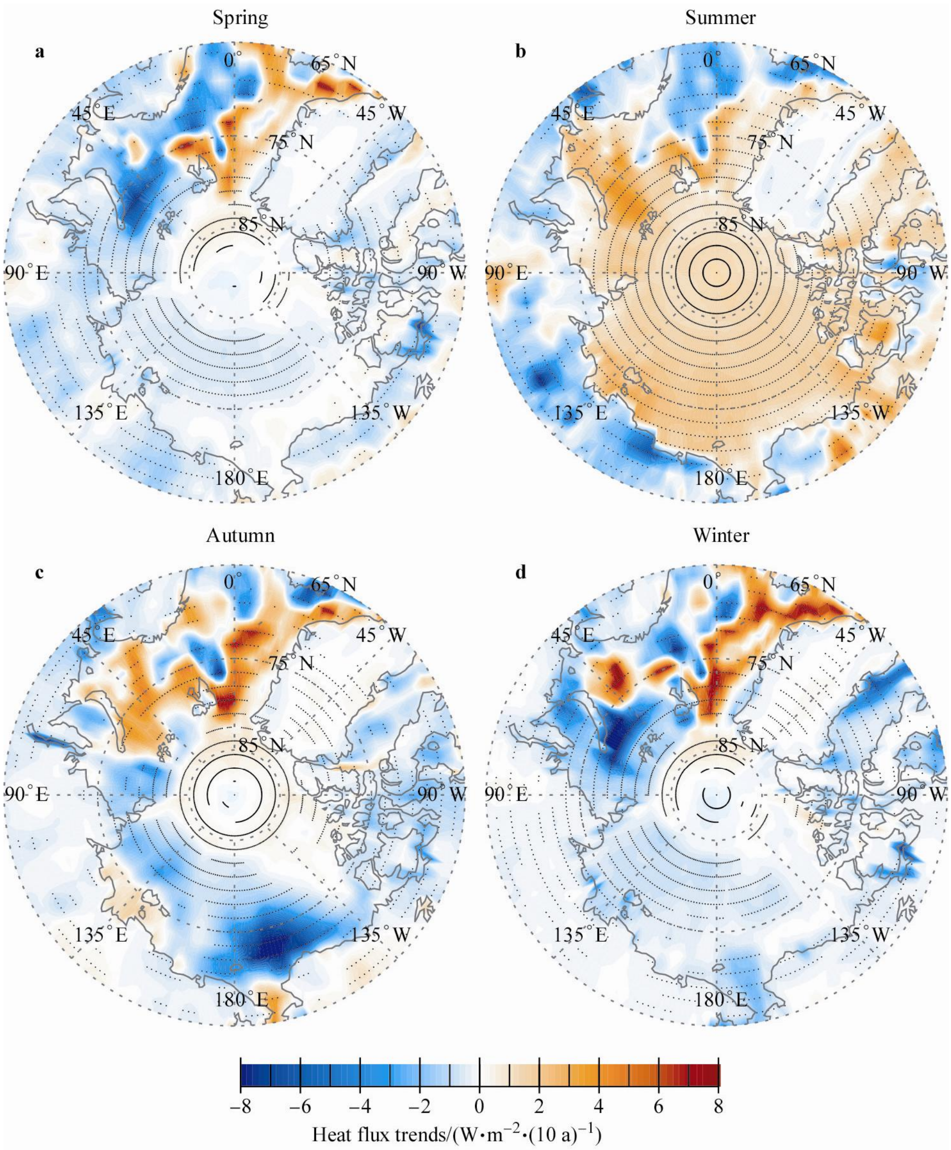

Figure 9 Geographic distribution of latent heat flux trends for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**). The areas marked by dots are statistically significant at the 90% confidence level.

declined markedly. In contrast to the marked warming over the Arctic Ocean, substantial cooling occurred over Siberia in winter. Our results indicate that the cooling over Eurasia was linked to the reduction in Arctic sea ice extent from September to winter. Substantial warming also occurred in spring and autumn in locations where the sea ice was reduced. In summer, on the other hand, there was very little change in surface temperature over the Arctic because increased radiative heat in summer melted the sea ice, in agreement with previous work[12]. Towards the cold season, sea ice increases and the atmosphere becomes cold and dry. Heat that was stored in the upper mixed ocean layer in summer with the opening of the Arctic Ocean is then released back to the atmosphere in the autumn and through to the following spring in the form of turbulent heat fluxes, thus warming the Arctic surface air. Moreover, the heat released in autumn and winter leads to the surface cooling over Eurasia in winter via a weakening of the polar vortex in the northern hemisphere. Overall, the anthropogenically-driven decline in Arctic sea ice in summer leads to cooling over mid-latitudes in the following winter.

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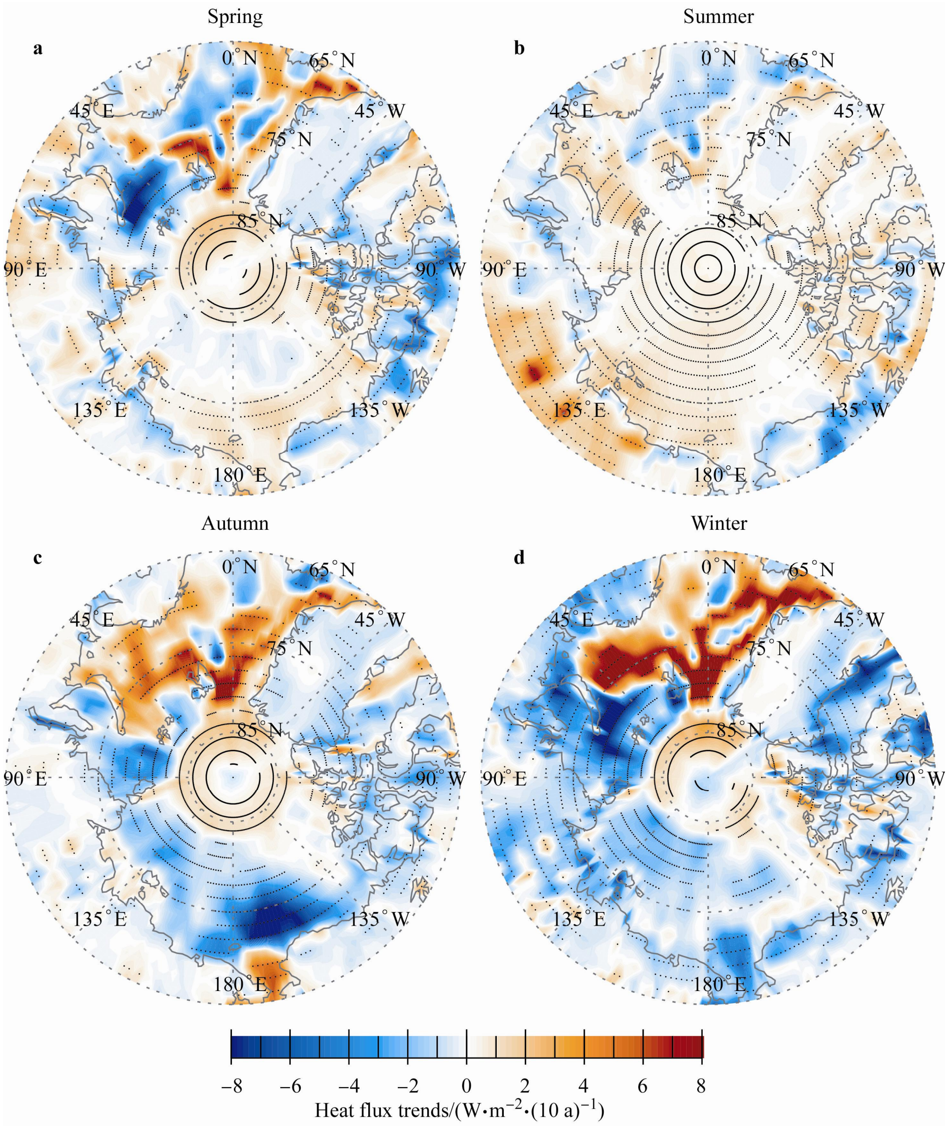

Figure 10 Geographic distribution of sensible heat flux trends for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**). The areas marked by dots are statistically significant at the 90% confidence level.

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