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Northern-Hemisphere Snow Cover Patterns and Formation Conditions in Winter 2007 and 2012

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Abstract The Arctic sea ice minimum records appeared in the Septembers of 2007 and 2012, followed by high snow cover areas in the Northern Hemisphere winters. The snow cover distributions show different spatial patterns in these two years: increased snow cover in Central Asia and Central North America in 2007, while increased snow cover in East Asia and northwestern Europe in 2012. The high snow cover anomaly shifted to higher latitudes in winter of 2012 compared to 2007. It is noticed that the snow cover had positive anomaly in 2007 and 2012 with the following conditions: the negative geopotential height and the related cyclonic wind anomaly were favorable for upwelling, and, with the above conditions, the low troposphere and surface air temperature anomaly and water vapor anomaly were favorable for the formation and maintenance of snowfalls. The negative geopotential height, cyclonic wind and low air temperature conditions were satisfied in different locations in 2007 and 2012, resulting in different spatial snow cover patterns. The cross section of lower air temperature move to higher latitudes in winter of 2012 compared to 2007.

Key words snow cover anomaly; atmospheric circulation; cyclonic wind anomaly; low air temperature

1 Introduction

The Arctic sea ice area has been decreasing since the satellite data started in 1979, with the most pronounced sea ice loss in September (Comiso *et al.*, 2008). In the past few years, North America, Europe and Mid-East experienced anomalously cold winters with snowstorms (WMO, 2010, 2011). A snowstorm hit central and southern China in January 2008 which was believed related with sea ice decrease in summer of 2007 (Liu *et al.*, 2012b), while snowfall pounded the coast of the Bohai Sea in the northeastern China in winter of 2012. Persistent snow, freezing rain and cold temperature can result in disruptions of transportation, energy supply and power transmission and damage agriculture (Coumou and Rahmstorf, 2012). Some explanations were offered for the recent cold winters from the perspective of dominant modes of climate variability (WMO, 2010, 2011; Tang *et al.*, 2013). However, the causes for the recent severe winters are still unclear, particularly in the context of amplified warming in the Arctic that has contributed to the reduction of sea ice (ACIA, 2005; IPCC, 2007). And autumn Arctic sea ice extent has declined rapidly during recent decades (Comiso *et al.*, 2008), while spring Eurasian snow cover extent has decreased over the past several decades (Brown *et al.*, 2010).

Previous studies investigated the relationship between snow cover and atmospheric circulation pattern (Liu *et al.*, 2012a; Lu *et al.*, 2012). Falarz (2013) defined a percentage ratio of the actual and the potential snow cover duration in the winter season, and investigated the seasonal stability of snow cover related to the atmospheric circulation in Poland. Peings *et al.* (2013) suggested a possible modulation of the teleconnection through the Quasi-Biennal Oscillation (QBO) between snow cover extent over Eurasia and the winter QBO variation in the predominant Northern Hemisphere. Earlier snow cover termination is systematically correlated with a positive temperature anomaly during the snow-melting month on a year-to-year basis (Peng *et al.*, 2013). The observed trends in snow cover are mainly driven by warmer air temperatures, with Northern Hemisphere mid-latitude air temperatures explaining 50% of the variance in Northern Hemisphere spring snow cover over the 89 years period analyzed (Brown and Robinson, 2011).

It has been demonstrated that the autumn Arctic sea ice can contribute to the cold and snowy winters in the Northern-Hemisphere continents (Honda *et al.*, 2009; Ghatak

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et al., 2010; Liu *et al.*, 2012a; Liu *et al.*, 2012b). The diminishing Arctic sea ice plays roles in changing the atmospheric circulation in Northern Hemisphere (Francis *et al.*, 2009; Blüthgen *et al.*, 2012). And the anomalous atmospheric circulation pattern can also affect the spatial distribution and intensity of winter snowfall in Northern-Hemisphere continents (Räisänen, 2008; Cohen *et al.*, 2012; Lu *et al.*, 2012). Strong evidence related the autumn snow-cover extent in Eurasia and Siberia to the subsequent winter Arctic Oscillation (AO) over recent decades (Cohen and Entekhabi, 1999). Coincidentally, a number of anomalous cold winters occurred over Northern-Hemisphere continents accompanied by high snowfalls (Ghatak *et al.*, 2010; Cohen *et al.*, 2012). The positive/negative abnormal signals of stratospheric AO downward propagate to the troposphere and their influences on the extreme cold and snowy weather at the mid-latitudes in the Northern Hemisphere have been discussed (Lu *et al.*, 2012). Brown and Mote (2009) showed the decrease in snow-cover duration during the period from 1966 to 2007 due to its high sensitivity to climate change. Henderson and Leathers (2010) confirmed the strong association between large/small snow-cover season and the negative/positive phase of the North Atlantic Oscillation (NAO). The relationship between the Northern-Hemisphere snowfall, the Arctic sea ice and atmospheric circulation has been intensively investigated (Räisänen, 2008; Cohen *et al.*, 2012; Tang *et al.*, 2013 and others). However, all above did not investigate the reason for the different spatial distributions of extreme snow covers in winters of 2007 and 2012.

In this study, based on snow cover data and the ERA-Interim reanalysis data (Dee and Uppala,, 2009; Dee *et al.*, 2011), we investigate the spatial distributions of winter snow cover and the related atmospheric environments in the Northern Hemisphere in 2007 and 2012: increased snow cover in central Asia and central North America in 2007, and increased snow cover in East Asia and northwestern Europe in 2012.

Data and analysis will be described in Section 2. The relationship between the atmospheric circulation and snow cover in the winters of 2007 and 2012 are shown in Section 3. Discussion and conclusions are given in Section 4.

2 Data

The daily Arctic sea ice data is from the National Snow and Ice Data Center (NSIDC) (http://nsidc.org/data/seaice/), which is retrieved from the Scanning Multichannel Microwave Radiometer and the Special Sensor Microwave/Imager based on the National Aeronautics and Space Administration (NASA) algorithm (Cavalieri *et al.*, 1996, 1999). The monthly snow cover extent is obtained from the Rutgers University Global Snow Lab, which has developed a satellite snow extent climate dataset all the way back to late 1966 (http://climate.rutgers.edu/snowcover). The 1000–300 hPa geopotential height, wind, air temperature, and specific humidity are obtained from the European Centre for Medium-Range Weather Forecasts, which are monthly mean variables with horizontal resolution of 1.5˚ by 1.5˚ (http://data-portal.ecmwf.int/data/d/interim-moda/). All the above data cover the period from 1979 to 2013. The autumn mean is the average of September, October and November (SON), and the winter mean is the average of December, January and February (DJF).

3 Results

The Northern-Hemisphere snow cover area reached high values in 2007 and 2012, with the snow cover value in 2012 being a little higher than that in 2007 (Fig.1). The correlation coefficient is −0.56 between Northern-Hemisphere snow cover anomalies in winter and the Arctic sea-ice area anomalies in autumn. With the autumn Arctic sea ice fast declining in the recent decade, the Northern-Hemisphere snow cover area significantly increases in winter, especially in 2007 and 2012. In this study, we mainly consider winter snowfall spatial distributions and formation conditions in these two years in the Northern-Hemisphere continents, in order to study the connection between the increasing of snowfall in winter and Arctic sea ice in autumn.

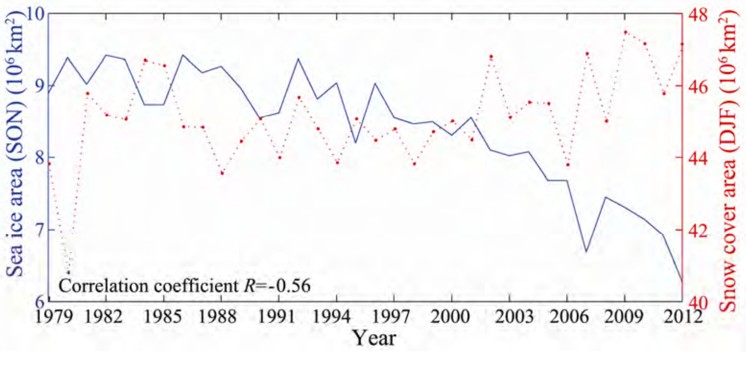

Fig.1 Time evolution of the Arctic sea-ice area in autumn (SON; blue) and the snow cover area north of 30˚N in winter (DJF; red) from 1979 to 2012.

During the past few winters, North America, Europe and Central Asia experienced anomalously cold conditions, along with record snowfalls (WMO, 2009, 2010, 2011). The winter snow cover area had high values in

2007 and 2012 (Fig.1), but the spatial distributions of snow cover were quite different (Fig.2). In winter of 2007/08, the larger snow cover anomaly was mainly in central Asia and North America, while the snow cover in Europe showed negative anomalies. In winter of 2012/13, the unusually large snow cover mainly appeared around the coast of the Bohai Sea in northeastern China and in northwestern Europe, different from those in winter of 2007/08. Furthermore, the positive anomaly distribution of snow cover shifted to higher latitudes particularly in Western Europe in winter of 2012/13. 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. Whether the sea ice loss in the Arctic is connected with the snow cover anomalies or not, it needs more investigation in the future.

Using observations and reanalysis data in the period of 1979–2012, we noticed that the anomalies of winter snowfall are related to the inter-annual variability of winter atmospheric circulation pattern in the Northern Hemisphere in 2007 and 2012.

The anomalies of vertically-averaged geopotential height and wind fields throughout the whole troposphere provide dynamical conditions for Northern-Hemisphere winter terrestrial snowfall. Fig.3 shows that the geopotential height and wind anomaly patterns were much different in these two years, except for the North Pacific Ocean. The geopotential height shows significantly positive anomaly over North Pacific for winters of both 2007 and 2012. Meanwhile, there are anti-cyclonic anomaly fields in the same region (Fig.3). In winter of 2007/08, there were negative geopotential height in the mid-latitude continental regions, such as central Asia and central North America, which corresponded to larger winter snow cover areas.

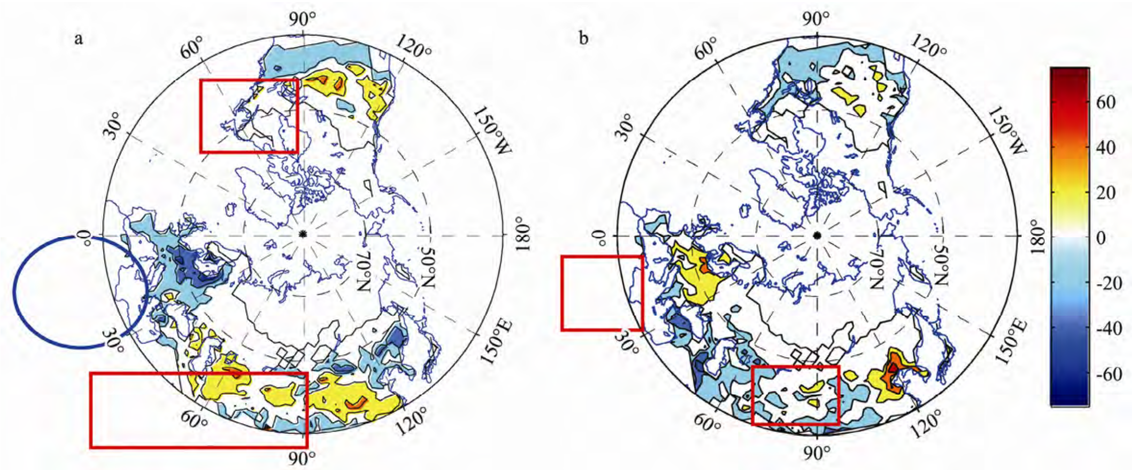

Fig.2 Spatial distributions of snow cover anomalies (%) for winter of 2007 (a) and winter of 2012 (b). The climatological snow cover is from 1979–2012. The indicated 4 positive areas and 1 negative area for snow cover are mainly discussed in this paper.

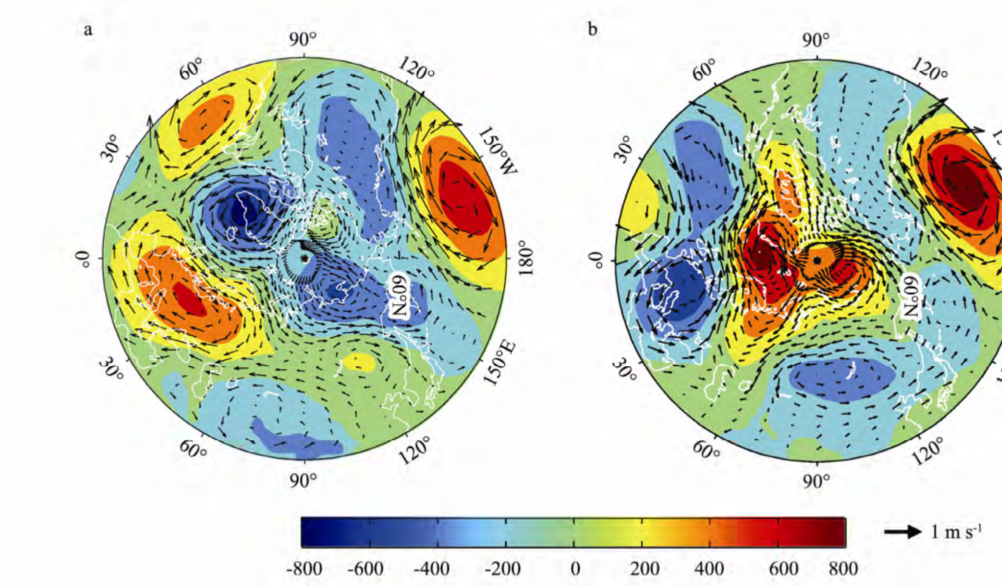

Fig.3 Maps of 1000–300 hPa averaged geopotential height anomalies (shaded; $m^2\ s^{-2}$) and wind anomalies (vectors; $m\ s^{-1}$) for winter of 2007 (a) and winter of 2012 (b). The climatological geopotential height and wind are from 1979–2012.

The anomalous geopotential height was positive in European Continent, agreeing well with the negative anomalous winter snowfall there. The wind anomalies formed two cyclonic circulations in central Asia and central North America, which enhanced the convergence and ascending motion in the troposphere. An anti-cyclonic anomaly field was formed in Europe, corresponding to reduction in snowfall there. For winter of 2012/13, the geopotential height showed negative anomalies in the mid-latitude Europe and East Asia; the wind pattern showed two cyclonic anomalies in these two areas. Similarly, it favored convergence and upward motion conductive to the snow in winter of 2012/13. The geopotential height and wind fields were favorable for the snowfall in winter of 2012/13.

Besides geopotential height and wind anomalies, low temperature is also needed for the formation of snowfall anomaly. Compared with rainfall, the formation of snowfall needs lower air temperature. Low air temperature can promote water droplets to form snowflakes from ice crystals. Fig.4 shows the air temperature anomalies were quite different in the winters of 2007 and 2012. The central Asia and central North America had stronger negative temperature anomalies in 2007, in good agreement with the areas of more snowfall in that winter. The air temperature in European continent showed positive anomaly in 2007, which was not favorable for the formation of snowfall. It explains the negative snow cover anomaly in Europe in that winter. There were two low temperature anomalies in the mid-latitude European and East Asia continents in the winter of 2012/13, which corresponded to areas with larger winter snow cover. However, the air temperature show significantly positive anomaly over North Pacific for winters of both 2007 and 2012, which is similar to geopotential height anomalies (Fig.4). Whether the circulation anomaly patterns over North Pacific is connected with the snow cover anomalies or not, it needs us to pay much attention in the future.

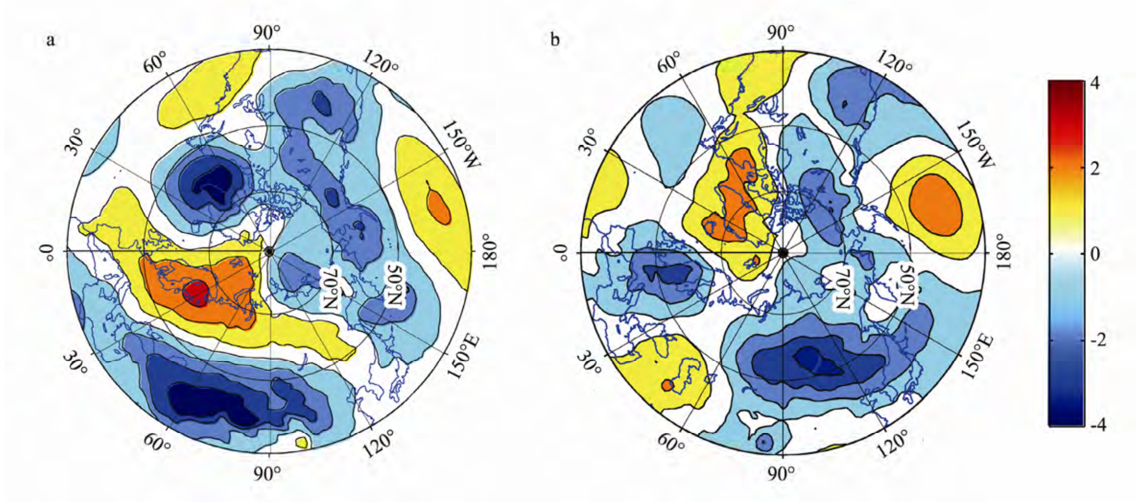

Fig.4 Air temperature anomalies (℃) averaged from surface to 300 hPa for winter of 2007 (a) and winter of 2012 (b). The climatological air temperature is from 1979–2012.

Next, we examine the vertical cross section of temperature in the troposphere by plotting air temperature in terms of zonal mean and meridional mean (from 30˚N to the North Pole). The vertical distributions of zonal-mean air temperatures in the winters of 2007 and 2012 (Figs.5a and b) show that the lower air temperature primarily was in the latitude band of 30˚–55˚N in 2007, which was in accordance with the anomalous snow cover in the mid-latitude continents. The lower temperature moving to higher latitudes of 42˚–70˚N in 2012, which was consistent with the observed snowfall moved to higher latitudes, especially in the Europe. We also checked the vertical distribution of meridionally-averaged air temperature (Figs.5c and d). Fig.5c shows that the lower meridionally-averaged air temperature mainly stays in the region 90˚–140˚W, which corresponds with the more extensive snow cover in 2007 (Fig.2a). But there was not significant lower meridionally-averaged air temperature in the region 60˚–120˚E (Fig.5c), which had more extensive snow cover in 2007 (Fig.2a). Fig.5d shows that the lower meridionally-averaged air temperature mainly stays in the region 100˚–150˚E, which corresponds with the more extensive snow cover in 2012 (Fig.2b). But there is not significant lower meridionally-averaged air temperature in the region 0˚–30˚E (Fig.5d), which had more extensive snow cover in 2012 (Fig.2b).

If the surface air temperature is high, the snow cover will melt easily. So, the surface air temperature plays an important role in maintaining the snowfall. The surface air temperature in winter of 2007 showed negative anomalies in central Asia and central North America (Fig.6), thus, the snow cover could last longer. Lower surface air temperature also appeared in winter of 2012. The lower surface air temperature appeared in higher latitudes in winter of 2012 compared with 2007, especially in the Eurasia.

Water vapor is another necessary condition for the formation of snowfall. In order to investigate the causes of positive anomalous distribution of winter snowfall in 2007 and 2012, we plot vertically-averaged (from surface to 300 hPa) specific humidity and wind anomalies to check the transportation of water vapor (Fig.7). Air temperature and water vapor have a close relationship: air with higher temperature contains more water vapor, and vice versa. This explicit correspondence can be obtained from Figs.4 and 7. Furthermore, the wind anomalies in atmosphere circulation and the water vapor distribution are considered in Fig.7. The strong westerly wind in 2007/08 (Fig.7a) and the anomalous easterly winds in 2012/13 (Fig.7b) are consistent with a positive and negative AO in the respective winters. As shown in Fig.7a, some water vapor of the winter snowfall in North America came from the North Pacific Ocean in 2007. And some water vapor of the winter snowfall was transported from central Asia to the Barents Sea in 2007. The water vapor was primarily transported from Western Europe to the plateau region of Southeastern Europe and the North Atlantic Ocean in 2012. The above transportation of the water vapor was favorable for the formation of snowfall. Where the snow cover had positive anomaly in 2007 and 2012, the anomaly wind could take more water vapor from high specific humidity regions.

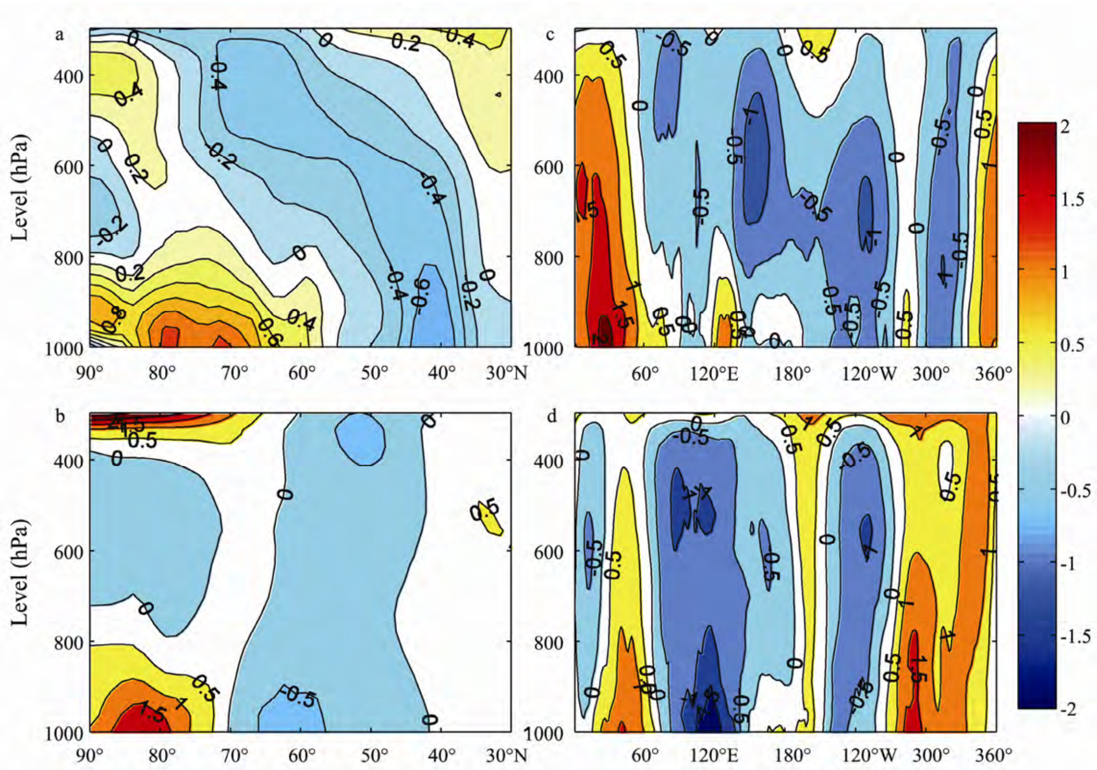

Fig.5 Zonally-averaged air temperature anomalies (℃) for winter of 2007 (a) and winter of 2012 (b). Meridional-averaged air temperature anomalies (℃) north of 30˚N for winter of 2007 (c) and winter of 2012 (d). The climatological air temperature is from 1979–2012.

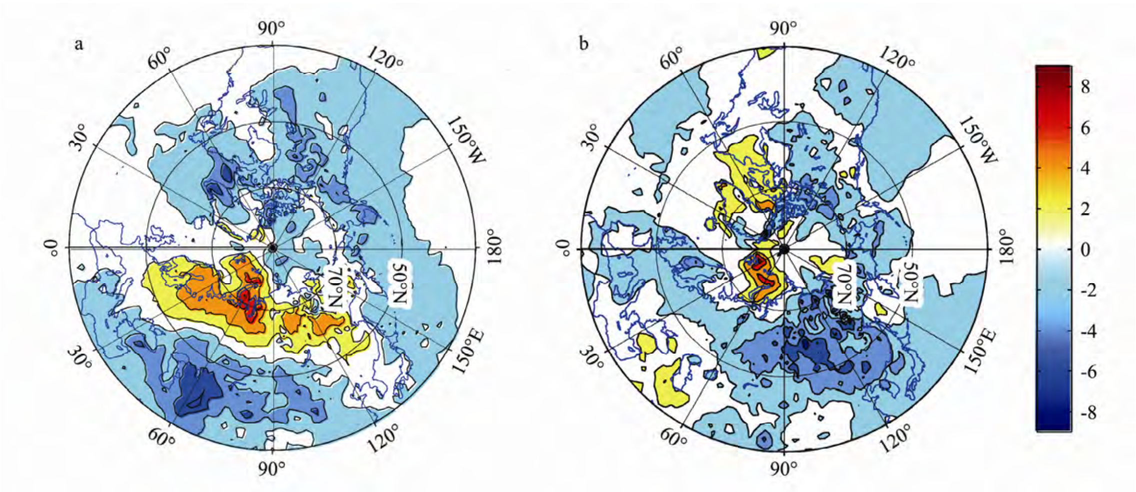

Fig.6 Surface air temperature anomalies (℃) for winter of 2007 (a) and winter of 2012 (b). The climatological surface air temperature is from 1979–2012.

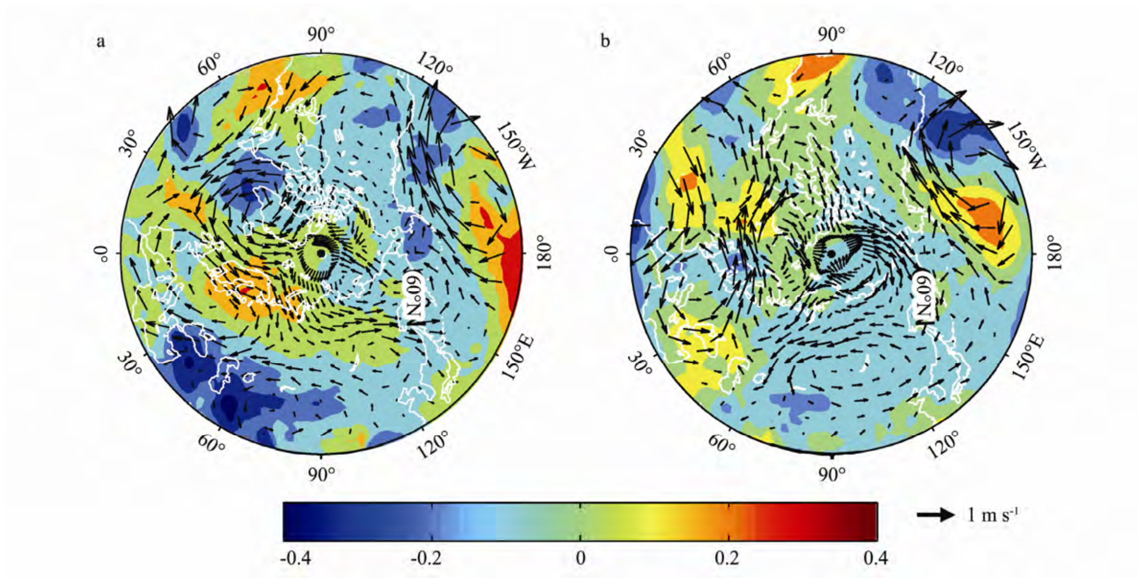

Fig.7 Specific humidity anomalies (shaded; kg kg^{-1}) and wind anomalies (vectors; m s^{-1}) averaged from surface to 300 hPa for winter (DJF) of 2007 (a) and winter (DJF) of 2012 (b). The climatological specific humidity and wind field are the average of 1979–2012 for winter.

4 Discussion and Conclusions

In this study, we analyzed the spatial distributions of snow cover in the Northern Hemisphere in the winters of 2007 and 2012 when the autumn Arctic sea ice area reached minima. The results indicate that the winter snow cover with positive anomalies in the Northern Hemisphere show different spatial patterns. In winter of 2007/08, the positive anomalous snow cover was mainly distributed in central Asia and central North America, and the negative anomalous snow cover mainly appeared in Northwestern Europe. In the winter of 2012/13, the major positive anomalous snow cover was around the Bohai Sea and Northwestern Europe. The results show that the unusually large winter snowfall in the Northern Hemisphere required simultaneously negative geopotential height, cyclonic wind and low air temperature in the winters of 2007 and 2012. Negative geopotential height forms cyclonic wind anomaly, which is favorable for upwelling. The lower air temperature anomaly and water content are favorable for the formation and maintaining of snowfalls. They are conducive to the increasing of snow cover.

Based on the above analysis, there are other issues remaining unclear, for example, the relationships between autumn Arctic sea ice, geophysical variable anomalies, winter snow cover, and low air temperature. Another example is why the circulation patterns over the Arctic, North Atlantic and Eurasia are apparently different, but have the similar features over North Pacific. This paper presents a case study for the two years of 2007 and 2012. In order to better understand the features of snowfall winter weather in Northern Hemisphere, there are other climate variability and natural chaotic variability of the general circulation needed to be investigated. NAO index usually has significant positive correlations with warm temperature extremes and negative correlations with cold temperature extremes over most of the region, because during high-NAO index winters, the Bermuda/Azores High extends to the northeastern America, so that this positive pressure anomaly blocks the polar jet stream from entering this region and the east-to-west pressure gradient induces southerly wind anomalies, leading to positive temperature anomalies (Ning and Bradley, 2014). The association between El Niño-Southern Oscillation and extended winter precipitation extremes in North America was examined by stationary, linear nonstationary, and nonlinear nonstationary fitting (Cannon, 2015). In boreal winter, the declining Arctic sea-ice in autumn plays an important role in the following winter atmospheric circulation system, which causes the colder events and snowfalls (*e.g.*, Liu *et al.*, 2012a). Thus, comprehensive research is still needed for fully understanding the snowfall winter in Northern Hemisphere.

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