Cold winter extremes in northern continents linked to Arctic sea ice loss

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Abstract

The satellite record since 1979 shows downward trends in Arctic sea ice extent in all months, which are smallest in winter and largest in September. Previous studies have linked changes in winter atmospheric circulation, anomalously cold extremes and large snowfalls in mid-latitudes to rapid decline of Arctic sea ice in the preceding autumn. Using observational analyses, we show that the winter atmospheric circulation change and cold extremes are also associated with winter sea ice reduction through an apparently distinct mechanism from those related to autumn sea ice loss. Associated with winter sea ice reduction, a high-pressure anomaly prevails over the subarctic, which in part results from fewer cyclones owing to a weakened gradient in sea surface temperature and lower baroclinicity over sparse sea ice. The results suggest that the winter atmospheric circulation at high northern latitudes associated with Arctic sea ice loss, especially in the winter, favors the occurrence of cold winter extremes at middle latitudes of the northern continents.

Keywords: Arctic, sea ice, cold winter extreme, northern continents

1. Introduction

Surface air temperature in the Arctic has increased in recent decades, accompanied by a rapid decrease in sea ice extent (SIE) (e.g., Screen and Simmonds 2010). Coincidentally a number of anomalously cold winters have occurred over northern continents along with record snowfalls (Cattiaux et al 2010, Ghattak et al 2010, Guirguis et al 2011, Cohen et al 2012, Cournou and Rahmstorf 2012). The Arctic atmospheric circulation changes may imprint a signature on surface air temperature anomalies (Rigor et al 2002) and sea level pressure (Maslanik et al 2007) over the Arctic or affect the wind anomalies and sea ice drift (Kwok 2009, Ogi et al 2010, Germe et al 2011, Wu et al 2012), leading to changes in sea ice (Deser and Teng 2008, Wang et al 2009b, Stroeve et al 2011, 2012). While changes in atmospheric circulation can affect sea ice, sea ice loss can also have an impact on the atmospheric circulation (Wu et al 2006, Francis and Hunter 2007, Overland and Wang 2010). Many studies have investigated the effects of the diminishing arctic sea ice on terrestrial snow cover (Liu et al 2012, Ghattak et al 2010), temperature (Petoukhov and Semenov 2010), and atmospheric circulation (Zhang et al 2008, Honda et al 2009, Francis et al 2009, Kumar et al 2010, Overland and Wang 2010). It has been demonstrated that the autumn Arctic sea ice plays a critical role in the following winter climate system (Francis et al 2009, Overland and Wang 2010, Blüthgen et al 2012, Hopsch et al 2012, Jaiser et al 2012) and the recent decline of...
autumn sea ice may contribute to the cold and snowy winters in northern continents (Liu et al 2012).

According to consistent satellite observations since 1979, Arctic SIE has declined in every season (Serreze et al 2007), mostly rapidly during summer when the perennial ice extent has decreased by $\sim 12\%$ per decade (Comiso 2012). Declines in winter are more moderate than that in the summer, although recent data suggest that the multyear ice extent is declining at an even more rapid rate of about $-15\%$ in the winters of 1979–2011 with record low value in 2008 followed by higher values in 2009, 2010 and 2011 (Comiso 2012). The decline in winter SIE is related to sea surface temperature anomalies and wind circulation patterns (Comiso 2006). The large seasonal difference in the rates of decline in SIE suggests that ice retreat in different seasons is driven by different mechanisms or strengths of the mechanisms (Nghiem et al 2007, Cottier et al 2007, Deser and Teng 2008, Eisenman 2010, Stroeve et al 2012). The SIE anomalies of winter may not be simply considered as the sea ice anomalies persisting of the preceding autumn. Moreover, recent studies have shown that much of the predictive information in the ice–ocean system is lost for lead times greater than about three months except for the long-term change trend (Lindsay et al 2008, Blanchard-Wrigglesworth et al 2011). These seasonal distinctions suggest that the response of the atmospheric circulation associated with autumn and winter SIEs may be different with distinct implications to extreme weather in middle latitudes (Francis and Vavrus 2012).

Here we extend previous studies on the linkage between declining Arctic sea ice and winter atmospheric circulation using observational data analyses, demonstrating the apparent difference between the effects of autumn and winter sea ice variability on cold winter extremes in northern continents.

2. Methods

Fields of sea level pressure, surface air temperature, and geopotential height north of 20°N were obtained from the latest reanalysis of the European Centre for Medium-Range Weather Forecasts (ERA-Interim, 1979–present). Monthly mean Arctic SIE (i.e., the area bounded by grid cells with at least 15% sea ice cover) derived from passive microwave satellite data (Cavaliere et al 1999) were obtained from the National Snow and Ice Data Center (NSIDC) for 1979 to present. The Arctic Oscillation (AO) index was obtained from the NOAA Climate Prediction Center (www.cpc.noaa.gov/). Blocking-high events are defined as intervals in which daily 500 hPa height from the reanalysis exceeds 1 standard deviation above the winter mean for each grid cell over five consecutive days (Thompson and Wallace 2001, Liu et al 2012). Cold events are defined as the days when ERA-Interim daily minimum surface air temperature drops below a specified threshold corresponding to 1.5 standard deviations below the local climatological seasonal mean (Thompson and Wallace 2001).

Because the SIE trend since 1979 is non-linear (Eisenman 2010, Comiso 2012), we use a second-order polynomial to fit the long-term change of the Arctic SIE in autumn and winter. Regressions of winter-mean anomaly fields upon the second-order detrended SIE anomaly (with a unit of km$^2$) were computed for both autumn and winter SIE anomalies. The regression slopes thus represent anomalies in a particular variable that occur in association with a half-million km$^2$ anomaly in the Arctic SIE. The regression slopes of blocking highs and cold events are further divided by their respective mean values in 1979–2011 to obtain percentage anomalies in association with half-million km$^2$ SIE anomalies. Autumn is defined as September through November, and winter is December through February of the next year.

3. Results

Autumn and winter Arctic SIE anomalies for 1979–2011 are presented in figure 1. Acceleration in the SIE decline is evident. Relative to the 1979–2000 average, the winter SIE has declined 10% ($\sim 99\%$ significance) for 1979–2011. Although winter SIE reduction in relative terms is smaller than autumn SIE reduction (24%), the winter reduction in absolute terms (1.5 million km$^2$) is comparable in magnitude to the autumn reduction (2.2 million km$^2$). After removing the second-order polynomial trend, the autumn and winter SIE indices have little correlation (0.20), suggesting that the winter SIE reduction exhibits a different interannual variability relative to the autumn SIE reduction. Furthermore, the winter AO index shows little correlation with either of the detrended SIE indices (autumn = 0.13, winter = 0.11), only accounting for approximately 2% of the shared variance.

Linear regression maps between winter sea level pressure (SLP) and the autumn and winter SIEs and AO are presented in figures 2(a)–(c). Linear regression maps between blocking-high events and autumn and winter SIEs and AO are presented in figures 2(d)–(f). Following low SIE in autumn, the winter SLP exhibits a significant response only in a region stretching from northern Europe into the Middle East, where SLPs increase (figure 2(a)), and bears some resemblance to the negative phase of the winter AO over the North Atlantic–Europe area. The response to winter SIE reduction, however, reveals a much larger region with a significant SLP response (figure 2(b)), with positive values extending over a
Figure 2. Linear regression of winter sea level pressure on (a) the second-order detrended autumn SIE (reversed sign), second-order detrended winter SIE (reversed sign), and winter AO index (c). (d)–(f) are the same but the regression is with the incidence of winter blockings high patterns, measured as the percentage relative to the winter blocking climatology during 1979–2011. Regions within black contours indicate the regression slope exceeds the 90% confidence level.

large fraction of northern Asia and North America along with significantly lower values over the northwest Pacific Ocean and much of the tropics. The winter pattern, which exhibits an expected negative SLP pattern over most of the Arctic in association with a reduced SIE, is significantly different from the pattern associated with the winter AO (figure 2(c)) or from the autumn SIE pattern. In contrast with the winter AO regression pattern, the winter SIE regression shows broader meridional meanders in middle latitudes. It should be noted that the regression patterns do not necessarily indicate causality. It is possible that the associations could reflect the response of SIE anomalies to changing SLPs, or the feedbacks of sea ice retreat could mediate the atmospheric circulation, or both. The deepened Aleutian low associated with winter SIE (figure 2(b)) favors easterly (from the east) winds in the Bering Sea and thus is likely related to ice-edge location in the Bering Sea (Francis and Hunter 2007). The high-pressure anomaly over East Siberia and Nordic Seas favors southerly wind (from the south) anomalies in the Barents Sea, perhaps contributing to reduced SIE in that area (Sorteberg and Kvindingdal 2006, Francis and Hunter 2007). Inoue et al (2012) proposed that the low-level baroclinicity over the Barents Sea during the light sea ice years, which resulted from a weak south–north gradient in sea surface temperature over the Barents Sea, hindered cyclone development and promoted a high-pressure anomaly over the Siberian coast. Given the complicated nature of ocean–ice–atmosphere interactions (Deser et al 2000), the causality cannot be confirmed from these results, but the anomalous SLP patterns associated with winter SIE suggest a substantial connection between winter SIE anomalies and mid-latitude weather patterns.

The high-pressure anomaly over much of Siberia associated with reduced winter SIE is corroborated by observed strengthening and expansion of the Siberian high (Inoue et al 2012), contributing to severe winters in the downstream East Asian region. The Aleutian low, meanwhile, has shifted southward and/or strengthened (figure 2(b)), which together with a stronger Siberian high, enhances the pressure gradient between them, which would strengthen the East Asian winter monsoon and favor anomalous cooling over large areas of East Asia (Wang et al 2009a, 2009b). The higher SLP anomaly in western North America is favorable for anticyclogenESIS (Jones and Cohen 2011). The zonal asymmetry in the high-pressure anomaly may also suggest a shift to weak westerly winds and a more meridional anomalous pattern of prevailing westerly winds that is likely
to form blocking patterns (Liu et al 2012, Outten and Esau 2012).

Figures 2(d)–(f) present regression patterns between winter blocking events and autumn SIE anomalies (d), winter SIE anomalies (e), and the winter AO (f). Associated with autumn SIE anomalies, areas of significant increases in the frequency of blocking highs appear in northern Europe and the north Pacific, with reduced blocking in a mid-latitude zone from the North Atlantic eastward across Eurasia. The decrease of blocking over the North Atlantic suggests that autumn SIE reduction is probably not responsible for extreme cold spells in recent winters in Europe (Cattiaux et al 2010) because these events are generally associated with cooling anomalies over Europe (Buehler et al 2011, Sillmann et al 2011). In the pattern for winter SIE reduction, there is a much larger area of increased incidence of winter blockings over subarctic areas, which favors more frequent incursions of cold air masses from the subarctic into mid- and low-latitudes of northern continents along with enhanced poleward transport of warm and moist air. Under the negative phase of the winter AO (figure 2(f)), the area of increased blocking is generally restricted to the Arctic, with reduced blocking in the mid-latitude zone.

Figures 3(a)–(c) present regression patterns between winter cold spells and autumn SIE anomalies (a), winter SIE anomalies (b), and the winter AO (c), while figures 3(d)–(f) present regression patterns between winter surface air temperature and autumn SIE anomalies (d), winter SIE anomalies (e), and the winter AO (f). Associated with reduced autumn SIE is an increased frequency of cold events (figure 3(a)) and decreased winter mean temperatures (figure 3(d)) extending southeastward from eastern Europe through central Asia to central China, consistent with Hopsch et al (2012), which is attributable to the increased incidence of blockings in eastern Europe (figure 2(d)). Associated with low winter SIE, cold events occur with much greater frequency over the middle latitudes of North America and central Asia (figure 3(b)), corresponding to negative temperature anomalies over central and eastern Asia. Comparing these patterns with the change of cold event frequency attributable to the AO (figure 3(c)) suggests that areas with frequent cold spells attributable to winter SIE loss are farther southward, with pronounced effects on temperature anomalies (1–3 °C below normal per half-million km$^2$ decrease in SIE) in a large area across southern Europe, East Asia, and into the northwest Pacific (figure 3(e)). Winter SIE anomalies are also associated with positive temperature anomalies over much of the Arctic Ocean and the far northern Pacific Ocean.
4. Conclusion and discussion

The regression relationships described in the manuscript illustrate the differences between the response of the mid-latitude atmosphere to sea ice loss during autumn and winter. The notion of a seasonally varying response to summer and autumn Arctic sea ice loss has been addressed by some modeling studies (e.g., Deser et al 2010, Kay et al 2011), but the distinct effects on the winter atmospheric circulation associated with winter sea ice loss has been less explored. Our observational analysis reveals that the change in the winter atmosphere circulation and frequency of cold events in mid-latitudes in response to winter sea ice loss is larger and more extensive than the response to autumn ice loss, even though the fractional change in ice loss is larger in autumn. Our results support the mechanism suggested by Cohen et al (2012) in which sea ice loss promotes additional surface evaporation, which results in earlier snowfall on high-latitude land (Ghatak et al 2010). The earlier snow cover insulates the soil and allows the surface to cool more rapidly, shifting the region of strongest poleward temperature gradient southward and consequently, a southward shift of the thermally induced wind flow. Positive pressure anomalies result further enhance negative temperature anomalies and the likelihood of cold spells and blocking highs, particularly over the mid-latitudes of North America and central Asia, along with anomalously cold winters in southern Europe and East Asia (Coumou and Rahmstorf 2012). The enhanced high-pressure anomalies can also lead to a reduced cyclone frequency in association with a weakened gradient in sea surface temperature and lower baroclinicity over areas of reduced sea ice (Inoue et al 2012). While the connections between sea ice loss and large-scale circulation patterns in the northern hemisphere cannot be confirmed through regression analysis, our results provide further evidence of the relationship. If the association between Arctic sea ice and cold winter extremes demonstrated in this study is robust, we would expect to see a continuation and expansion of cold winter extremes as the sea ice cover continues to decline in response to ever-increasing emissions of greenhouse gases.

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