The Melting Arctic and Midlatitude Weather Patterns: Are They Connected?*

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ABSTRACT

The potential of recent Arctic changes to influence hemispheric weather is a complex and controversial topic with considerable uncertainty, as time series of potential linkages are short (<10 yr) and understanding involves the relative contribution of direct forcing by Arctic changes on a chaotic climatic system. A way forward is through further investigation of atmospheric dynamic mechanisms. During several exceptionally warm Arctic winters since 2007, sea ice loss in the Barents and Kara Seas initiated eastward-propagating wave trains of high and low pressure. Anomalous high pressure east of the Ural Mountains advected Arctic air over central and eastern Asia, resulting in persistent cold spells. Blocking near Greenland related to low-level temperature anomalies led to northerly flow into eastern North America, inducing persistent cold periods. Potential Arctic connections in Europe are less clear. Variability in the North Pacific can reinforce downstream Arctic changes, and Arctic amplification can accentuate the impact of Pacific variability. The authors emphasize multiple linkage mechanisms that are regional, episodic, and based on amplification of existing jet stream wave patterns, which are the result of a combination of internal variability, lower-tropospheric temperature anomalies, and midlatitude teleconnections. The quantitative impact of Arctic change on midlatitude weather may not be resolved within the foreseeable future, yet new studies of the changing Arctic and subarctic low-frequency dynamics, together with additional Arctic observations, can contribute to improved skill in extended-range forecasts, as planned by the WMO Polar Prediction Project (PPP).

1. Introduction

The assessment of the potential for recent Arctic changes to influence broader hemispheric weather is a complex and controversial topic. There is little agreement on problem formulation, methods, or robust mechanisms in the research community. The topic, however, is consequential and a major science challenge, as continued Arctic changes are an inevitable aspect of anthropogenic global change (Jeffries et al. 2013) and may

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be an opportunity for improved extended-range forecasts at midlatitudes (Walsh 2014). An intriguing question is whether recent extreme weather—such as the cold eastern U.S. winters of 2009/10, 2010/11, January 2014, and November 2014–February 2015; record floods in the United Kingdom in 2007, 2012, and 2013/14; and cold outbreaks in eastern Asia—were merely random events or were related to recent global or Arctic climate change (e.g., Jaiser et al. 2012; Tang et al. 2013; Wallace et al. 2014; Kim et al. 2014; Mori et al. 2014; Cohen et al. 2014; Feldstein and Lee 2014; Lee et al. 2015; Barnes and Screen 2015). There is also the potential for midlatitude (e.g., Sato et al. 2014; Perlwitz et al. 2015) and tropical (e.g., Ding et al. 2014) variability to affect the Arctic, further complicating the story.

Four recent reviews of the Arctic's influence on midlatitude weather (hereafter "linkages") are provided by Vihma (2014), Walsh (2014), the National Academy of Sciences (2014), and Cohen et al. (2014). These reviews present the state of this rapidly evolving research topic that spans regression analysis of observations, modeling experiments, and physical reasoning. They summarize a number of papers that address the question of linkages that have contrasting conclusions based on different subsets of data, approaches, metrics, and interpretations (e.g., Petoukhov and Semenov 2010; Francis and Vavrus 2012; Screen and Simmonds 2013; Barnes 2013; Woollings et al. 2014; Francis and Vavrus 2015). Large uncertainty, mostly induced by a short record of recent Arctic amplification and chaotic variability at midlatitudes, results in poor signal-to-noise ratios in efforts to determine cause and effect. Viewpoints often contrast the evolution of random weather features versus a shift in the externally driven probability of occurrence (Dole 2008; Otto et al. 2012). These reviews were unable to reach consensus between studies presenting circumstantial supporting evidence versus those that raise uncertainties. Given the complexity of the physics and the importance of the topic, it is not unreasonable to say that we are in a preconsensus period and that we should expect diversity, disagreements, and fragmentation of the scientific community. Examples of preconsensus from the past are earth plate tectonics around 1970 (Katili 1971) and the role of equatorial ocean physics and atmospheric teleconnections in ENSO around 1980 (Rasmusson and Wallace 1983).

Nevertheless, the topic provides a major science challenge, as continued Arctic change offers an opportunity for improved extended-range forecasts at midlatitudes (Jung et al. 2014). The wider public wonders about the potential linkage of known Arctic changes and recent weather events, as evidenced by intense interest in the recent "polar vortex" in eastern North America (Hamilton and Lemcke-Stampone 2014). Even given the controversy in the atmospheric community, various national and international agencies have prioritized the challenge—such as the WMO Polar Prediction Project (PPP) and World Climate Research Programme (WCRP)'s Climate and Cryosphere (CliC) core project, the Atmosphere Working Group of the International Arctic Science Committee (IASC), the U.S. Interagency Arctic Research Policy Committee (IARPC), the Met Office Hadley Centre, the Icelandic Meteorological Office, and the U.S. National Oceanic and Atmospheric Administration (NOAA).

All four previous reviews state that progress in understanding the impacts of Arctic changes on midlatitude weather depends on further understanding of 1) the fundamental dynamics of atmospheric circulation features, such as jet stream meanders, blockings, polarity of the Arctic Oscillation (AO), teleconnections, stratosphere–troposphere interactions, wave train propagation, and shifts in planetary wavenumbers; and 2) the atmospheric response to Arctic amplification, that is, disproportionate increases in Arctic temperatures due to a number of predominantly positive feedback processes, including those involving the loss of snow and sea ice, ocean and land heat storage, and changes in wind and current patterns (Duarte et al. 2012).

The goal of this paper is to provide an updated synthesis of recent studies on linkages and to present new analyses of regional and seasonal mechanisms. This approach is motivated by two recent papers: the first is that of Cohen et al. (2014), who demonstrate that winter [December–February (DJF)] temperatures from 1990 to 2013 over Northern Hemisphere continents exhibit regional cooling trends in midlatitudes, in contrast to the continental warming trends observed over the longer period from 1960. Recent cooling is localized over the eastern United States and central Eurasia, indicating that a variety of mechanisms may be operating at different longitudes that may be masked by analyses based on zonal averaging (Screen 2014; Perlwitz et al. 2015). The second study, by Davini (2013), suggests a possible physical mechanism connecting the Arctic–midlatitude weather systems through high-latitude blocking (HLB) events located near Greenland and northeastern Siberia based on instantaneous blocking frequency (Fig. 1). HLBs lie north of the climatological jet stream position and tend to divert the jet stream southward rather than completely blocking the westerly flow. This is dynamically distinct from midlatitude blocking that is located in the central Atlantic to Europe and western Pacific along eddy-driven jet streams (Woollings et al. 2010; Davini et al. 2012a,b; Rajewicz and Marshall 2014).

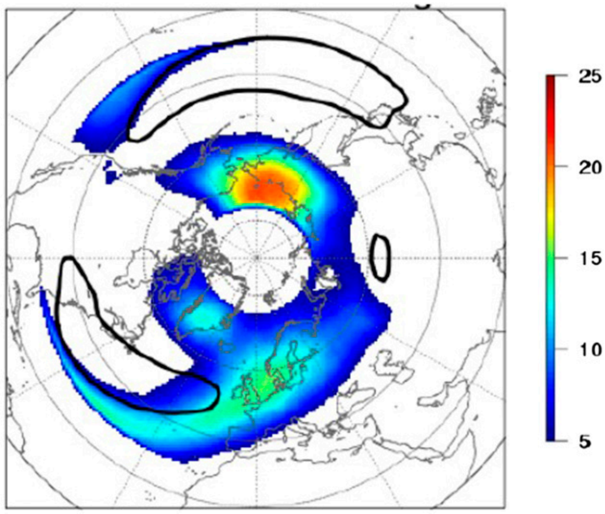

FIG. 1. Instantaneous blocking frequency during DJF from 1951 to 2010. Colors represent the percentage of blocked days with respect to total days. Note the HLB near Greenland and north of Siberia. Black contours show eddy-driven jet regions in the North Atlantic and Pacific (from Davini 2013).

The four recent reviews, together with Screen and Simmonds (2014), suggest a way forward through a study of regional and seasonal mechanisms. Occurrences of HLB near northeastern Siberia and Greenland in the past decade suggest a possible early-winter mechanism for Arctic–midlatitude linkage. We present composite case studies of wave trains of high and low pressures over northern Siberia that propagate into eastern Asia, and of an amplification of the North American ridge–trough structure related to Greenland blocking. Both features show amplification of quasi-stationary waves influencing certain types of extreme weather. Studies of this Arctic–midlatitude weather connection may be useful for forecast improvements, without necessarily providing a proven linkage to Arctic amplification as the ultimate causation. A limitation of such studies is that positive Arctic-wide temperature anomalies have strongly emerged only recently, during 1990–present and especially after 2007, providing a limited number of cases that include a large random component; models are often seen as a solution to this lack of data, but they also often seem limited in their ability to resolve regional complex dynamic circulation features (e.g., Vihma 2014; Walsh 2014; Cohen et al. 2014).

This paper extends these recent reviews to address a series of questions outlined by the schematic in Fig. 2: Is Arctic amplification large enough to affect regional atmospheric circulation? How does an overall increase in geopotential height (GPH) over the Arctic influence the frequency and amplitude of jet stream meanders and blocking? Does the topography and location of surface changes [e.g., sea ice, snow cover, and sea surface temperature (SST)] create a regional preference for locations of midlatitude impacts?

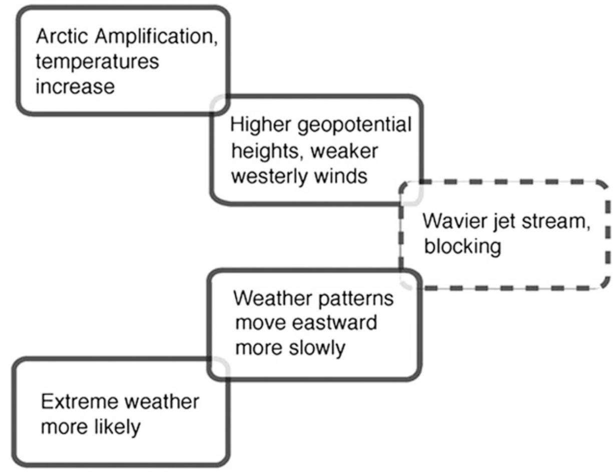

FIG. 2. Hypothesized steps linking Arctic amplification with extreme weather events in Northern Hemisphere midlatitudes.

2. A conceptual model of Arctic–midlatitude linkage

Figure 2 shows a set of "links" to further parse the potential connections from the Arctic to midlatitudes. The top link is well known, in that Arctic temperatures are increasing 2–3 times faster than at midlatitudes. Increased Arctic temperatures are one of the most conspicuous aspects of climate change on the planet, and losses of September sea ice extent and spring snow cover exceed 40% since the mid-1990s (Jeffries et al. 2013; Overland et al. 2014). The second link connects increased Arctic temperatures to weaker zonal winds through changes in the GPH field. As high-latitude temperatures increase disproportionately, the air becomes less dense, which increases the high-latitude geopotential thickness, reduces the poleward GPH gradient, and thus weakens upper-level westerly winds through the thermal wind relation (Overland and Wang 2010; Francis and Vavrus 2012, 2015; Cvijanovic and Caldeira 2015). The last two links suggest that large-amplitude planetary waves in the jet stream tend to progress more slowly, which creates persistent weather conditions that may cause extreme weather events (Screen and Simmonds 2014).

The dashed link in the middle of the chain relates to regional dynamics and represents the largest uncertainty in the Arctic–midlatitude causal linkage. This link is the focus of our paper. During the last five years (2009/10–2013/14), December and January have exhibited twice

TABLE 1. Monthly AO and GBI index from 2007/08–2013/14 for winter months. When the GBI is greater than one standard deviation, the numbers are shown in boldface; the same is true for negative AO. When the negative GBI (or positive AO) is greater than one standard deviation, numbers are shown in italic. The year in the far right column indicates the corresponding January to its left.

	November		December		January		
	AO	GBI	AO	GBI	AO	GBI	
2007	−0.5	0.2	0.8	−1.1	0.8	−0.4	2008
2008	0.10	0.5	0.6	−0.7	0.8	0.05	2009
2009	0.5	−0.1	**−3.4**	**2.8**	**−2.6**	**2.1**	2010
2010	−0.4	**1.9**	**−2.6**	**3.6**	**−1.7**	**1.6**	2011
2011	*1.5*	−0.5	*2.2*	*−1.4*	−0.2	−0.0	2012
2012	−0.1	0.2	**−1.7**	**1.6**	−0.6	0.1	2013
2013	*2.0*	**−1.0**	*1.5*	*−1.5*	**−1.0**	0.4	2014

the expected number of negative AO events (Table 1) based on the number of cases that meet or exceed 1.0 standard deviation. Negative AO phases are often, but not always, associated with amplified meridional jet stream patterns, more frequent blocking events, and persistent weather conditions (Woollings et al. 2010; Hanna et al. 2014; Hall et al. 2015). The recently more variable AO conditions may signify a destabilization of the polar jet stream and an increased susceptibility to external influences, such as pulses of tropical energy, varying SST patterns, or geographic obstacles. Whether such destabilization is random or related to Arctic amplification remains an open question.

3. Recent East Asia cold surges associated with regional sea ice loss

The surface temperature over East Asia is largely governed by the East Asian monsoon, whose winter system is composed of the couplet of the Siberian high and Aleutian low, generated by the climatological ridge–trough position of the jet stream. The strength of the winter East Asian monsoon is closely linked with cold-air outbreaks over East Asia, which are often accompanied by snow and severe socioeconomic impacts. East Asian cold surges are influenced by large-scale teleconnections through the AO (Jeong and Ho 2005; Park et al. 2008, 2011), El Niño–Southern Oscillation (Chen et al. 2004), and the Madden–Julian oscillation (Jeong et al. 2005). The atmospheric circulation during the negative phase of the AO favors cold-surge development through intensification of the Siberian high and deepening of the East Asian coastal trough (Gong et al. 2001; Jeong and Ho 2005). Over the last decade, cold-air outbreaks in winter have occurred more frequently over East Asia, and they are stronger and longer lasting than in the 1990s, consistent with a more dominant negative phase of the AO (Kim et al. 2014). Arctic amplification of global warming may be contributing to the shift toward a negative AO (e.g., Alexander et al. 2004; Seierstad and Bader 2009; Deser et al. 2010; Jaiser et al. 2012; Outten and Esau 2012).

As suggested by Fig. 1, northeastern Asia is a geographic region where HLB may be a factor in linkages. Sea ice loss in the Barents and Kara Seas (BK) during recent years (Fig. 3) has contributed to anomalously warm Arctic autumns and winters. Consequently, the poleward temperature gradients in the region have lessened, which in turn has weakened the westerly component of upper-level winds (Outten and Esau 2012). Warming also raised GPHs aloft, which augmented the upper-level ridge east of the Ural Mountains and strengthened the Siberian high (Takaya and Nakamura 2005a; Takano et al. 2008; Jeong et al. 2011; Inoue et al. 2012; Son et al. 2012; Cohen et al. 2014; Kim et al. 2014; Mori et al. 2014). Evidence of an increased frequency in amplified jet stream events during October–December is presented in Fig. 4 and in Francis and Vavrus (2015). Amplified events are identified when the latitude range of the 5600-m contour of the daily 500-hPa GPH exceeds 35° of latitude over Eurasia (15°W–150°E). From the period 1979–92 to 2000–13, the frequency of high-amplitude events during autumn/early winter (October–December) increased by 55%. Note that variability in the frequency of amplified events is negatively correlated with the AO index ($r = -0.53$, $p < 0.002$), suggesting that amplified jet stream patterns tend to occur when the AO index is negative.

The sea ice reduction over the BK in late autumn and early winter since the early 2000s was closely linked with stronger and longer-lasting cold surges in East Asia. The enhanced ridging initiated episodic eastward-propagating wave trains that caused cold-air outbreaks over eastern Asia (Woo et al. 2012; Kim et al. 2014; Mori et al. 2014). Table 2 presents significant correlations between BK sea ice and December 2-m air temperatures (T2m) for central Eurasia (45°–60°N, 60°–120°E), supporting the notion that sea ice decline in the BK is associated with anomalous winter cooling. Figure 5 displays the cold anomaly over Eurasia from December to February in response to reduced sea ice over the BK. November and December sea ice reduction over the BK elicited the largest response over Eurasia with one month lag. The dynamical connection is complex, however, as monthly forcing manifests at synoptic time scales in the form of eastward-propagating wave trains. Both observational data and model experiments indicate that reduced sea ice over the BK causes increased surface turbulent heat fluxes into the atmosphere during early

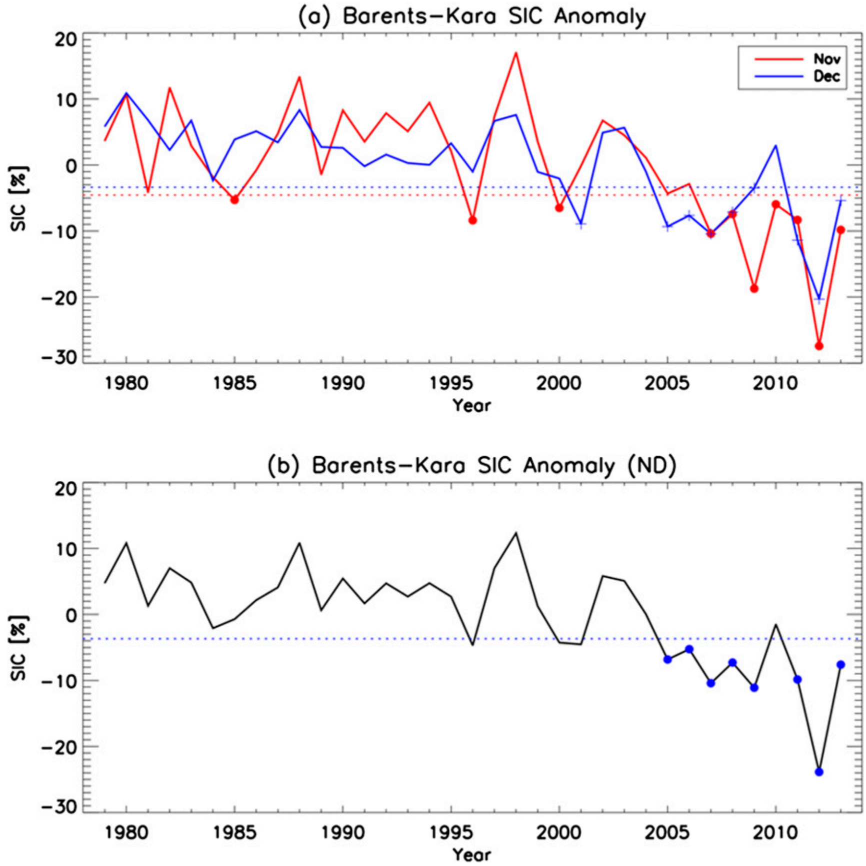

FIG. 3. Time variation of sea ice concentration anomaly in the Barents–Kara Seas in (a) November and December and (b) their average. Dotted lines represent the percent of sea ice anomaly when it is 0.5 standard deviation lower than normal years. Data are from HadISST1 (Rayner et al. 2003).

winter owing to strong air–sea heat and moisture contrasts (e.g., Honda et al. 2009; Liptak and Strong 2014). The resulting enhanced ridging over the BK favors vertical propagation of planetary wave energy that eventually weakens the Northern Hemisphere polar vortex, inducing the negative phase of the AO (Cohen et al. 2014; Kim et al. 2014). The disrupted polar vortex and negative AO excite a Rossby wave train that propagates southeastward, amplifying the Siberian high and East Asian trough (Honda et al. 2009; Mori et al. 2014).

To illustrate this BK–Asian linkage, atmosphere circulation patterns in winter (DJF) starting six days prior to cold-surge events over East Asia (35°–45°N, 120°–130°E) are shown in Fig. 6. Events are composited for BK sea ice extents below 0.5 standard deviation relative to climatology during early winter (November and December; Fig. 3b). Cold-surge occurrences are identified when the daily mean surface air temperature averaged over East Asia decreases within two days by more than 1.5 standard deviation from the average surface temperature for 1979–2013. When the sea ice extent is lower than normal over the BK, an anomalous flow from the Arctic is created east of the anticyclonic sea level pressure anomaly over the Barents Sea and Ural Mountains (Figs. 6a,e), creating a cold air mass over central Asia. Subsequently, the cold anomaly migrates southeastward and becomes stronger, associated with the expansion and strengthening of the Siberian high. Downstream of the ridge, an enhanced trough develops along the east coast of Asia in association with quasi-stationary propagating wave trains (Takaya and Nakamura 2005a,b). This pattern is evident on the day of cold-surge occurrence (denoted D-Day in Fig. 6). In contrast, under extensive sea ice conditions in the BK, surface cooling on D-Day is less severe with a weaker Siberian high, consistent with weaker upper-level wave trains. In the development stage of the cold surge in extensive ice conditions, the upper-level ridge and trough are relatively weak (not shown).

Other recent studies identify this linkage between BK ice loss, the enhanced ridge–trough pattern, and cold

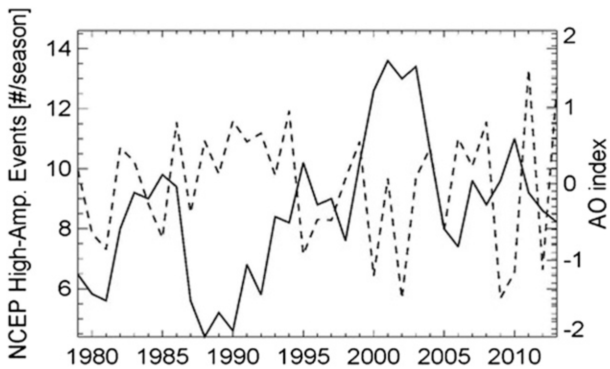

FIG. 4. Frequency of high-amplitude 500-hPa geopotential height patterns over Eurasia (15°W–150°E) during October–December 1979–2013. Events are identified when the latitude range of daily 5600-m contour exceeds 35°. A 5-yr running smoother has been applied. Data are from the NCEP–NCAR reanalysis (from NOAA/ESRL at http://www.esrl.noaa.gov/psd/). The Arctic Oscillation (AO) index is shown as a dashed line.

Asian winters. Hori et al. (2011) found that five days before a cold surge over Japan, a wave train develops from Europe to East Asia, strengthening in time. An anomalous anticyclone forms over Siberia along with a low pressure anomaly over eastern Asia coast, consistent with the present study. Another investigation by Mori et al. (2014) used a 100-member ensemble of simulations with an atmospheric general circulation model driven by observation-based sea ice concentration anomalies. They found that, as a result of sea ice reduction in the BK, the probability of severe winters in central Asia is more than doubled.

Other studies suggest that sea ice reduction in the BK may also be related to a larger teleconnection pattern associated with the position of the Gulf Stream in the northwest Atlantic. Northward shifts in the Gulf Stream can favor enhanced advection of warm air and wave energy into the BK region (Sato et al. 2014; Nakanowatari et al. 2014; Simmonds and Govekar 2014). This potential midlatitude–Arctic linkage deserves further investigation to understand the combined influence of both local ocean–atmosphere turbulent heat fluxes in the BK area and remote influences on sea ice extent by atmospheric heat advection.

This synthesis of recent publications and new results, performed independently with differing analysis approaches and based on both observations and model experiments, provides a consistent suite of evidence for a linkage between regional sea ice loss in the BK and the tendency for more amplified wave trains that lead to cold surges in central Asia accompanied by stormy regimes along the east coast of Asia.

4. The influence of Greenland on eastern North America

Figure 1 motivates a more careful investigation of the Greenland region as a potential connection between Arctic change and eastern North American midlatitude weather during winter. The incidence and intensity of blocking high pressure over Greenland has been defined by a Greenland blocking index (GBI; Fang 2004; Woollings et al. 2010; Hanna et al. 2013, 2014, 2015); GBI is the normalized 500-hPa GPH anomaly over 60°–80°N, 20°–80°W. There is an indication of increased variability of the GBI since 2007 in December with three large positive events (2009, 2010, and 2012) along with two large negative events (2011 and 2013) (Table 1). The year 2007 is a reasonable start date for this investigation, as it is associated with a substantial shift in Arctic temperatures and sea ice loss (Jeffries et al. 2013). Changes in GBI, Rossby wave structure, and wave propagation may be associated with Arctic amplification, but other factors are also likely, such as SST anomalies in the Atlantic (Rajewicz and Marshall 2014; Peings and Magnusdottir 2014).

To gain insight, we examine the spatial pattern of monthly GPH anomalies during recent years (2007/08–2013/14) relative to earlier years in the NCEP–NCAR reanalysis period (Kalnay et al. 1996). Anomalies in October 2007–13 (Fig. 7a) exhibit enhanced GPH to the west and north of Greenland, especially in the Labrador Sea region, along with slightly below-normal GPH in

TABLE 2. Sea ice area (SIA) in the Barents and Kara Seas correlated against T2m in central Eurasia (45°–60°N, 60°–120°E) in 1979–2012. The correlation coefficients marked in boldface are statistically significant ($p < 0.05$).

	Sep T2m	Oct T2m	Nov T2m	Dec T2m	Jan T2m	Feb T2m	Mar T2m
Sep SIA	−0.26	−0.33	−0.18	**0.46**	0.22	0.13	−0.12
Oct SIA		−0.33	−0.21	**0.53**	0.26	0.31	−0.24
Nov SIA			−0.16	**0.53**	**0.44**	**0.39**	−0.22
Dec SIA				**0.38**	0.31	0.16	−0.15
Jan SIA					0.21	0.22	**−0.40**
Feb SIA						−0.29	**−0.40**
Mar SIA							−0.33

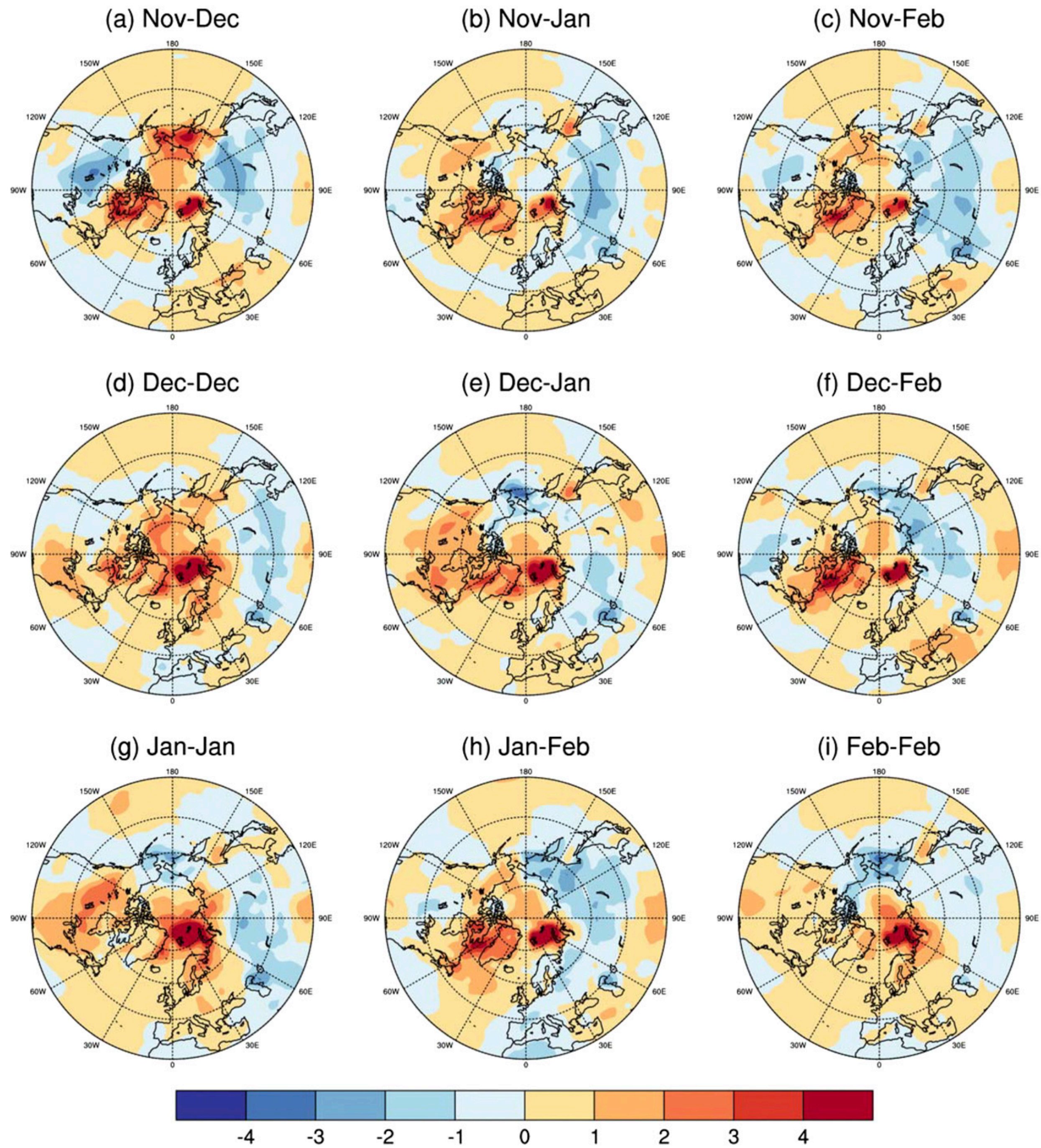

FIG. 5. Composite monthly mean difference in surface air temperature (°C) when the sea ice cover is lower by 0.5 standard deviation than normal in the Barents–Kara Seas. We examined 1–3-month lag between sea ice anomaly and temperature response to find the relation shown in Table 2.

central North America and in the western North Atlantic. In November (Fig. 7b) the strongest positive GPH anomaly shifts to the extreme North Pacific, with slightly more negative anomalies over Greenland as a whole, although with positive values in southeastern Greenland. Negative GPH anomalies occur over Alaska and over the central Arctic north of Greenland, extending southward over the United Kingdom and Iberia.

The recent pattern of height anomalies in December (Fig. 7c) differs from October and November, with strong positive height anomalies over much of the Arctic, North Pacific, eastern Europe, and western

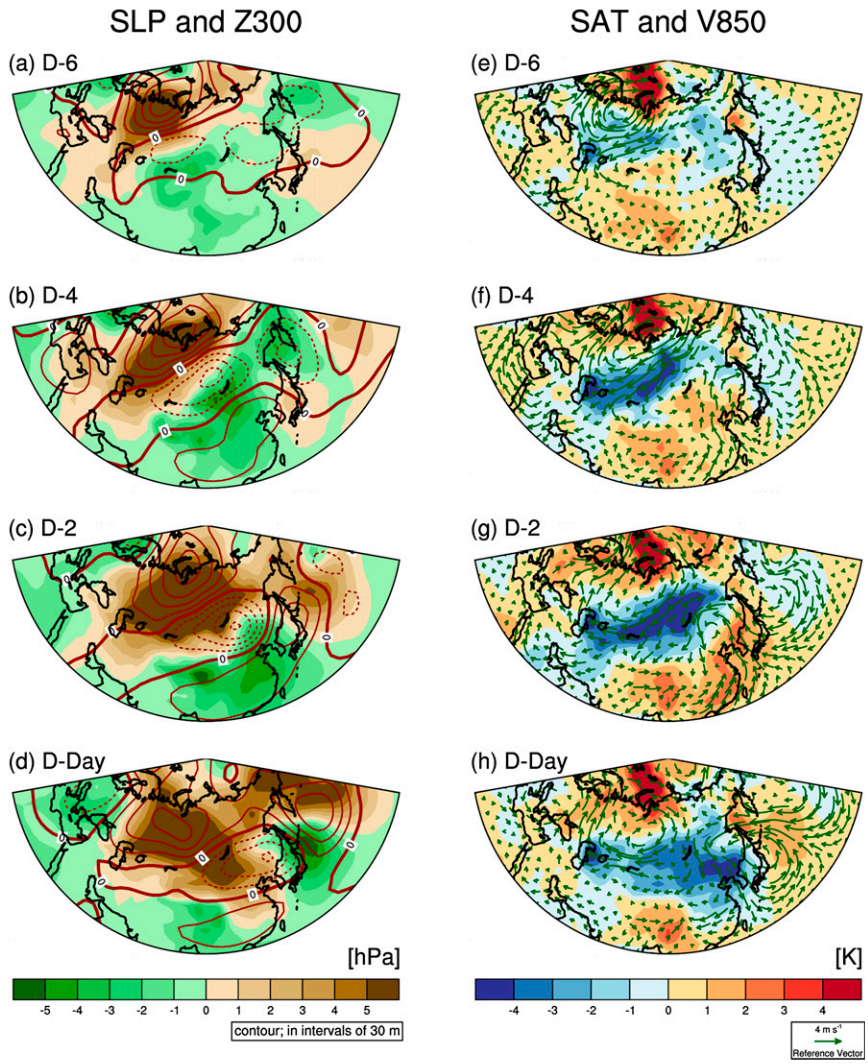

FIG. 6. Composite anomaly maps of winter (DJF) (left) sea level pressure (SLP; shading) and upper-level (300 hPa; contour, dashed are negative) geopotential heights and (right) surface air temperature (SAT; shading) and low-level (850 hPa) winds (vectors) prior to and during the cold surge occurrence for the years with blue dots in Fig. 3b. Data are from the NCEP–NCAR reanalysis (Kalnay et al. 1996).

North Atlantic, including Greenland. This pattern is reminiscent of a negative AO. Negative GPH anomalies occur over North America, the United Kingdom, and East Asia. Positive GPH anomalies persist over Greenland, the eastern North Pacific, and western Asia in January (Fig. 7d), but negative anomalies are evident over the North Pacific.

Greenland blocking typically occurs in conjunction with an upstream trough located near Labrador, as well as a ridge farther west over North America. This jet stream configuration often causes persistent winter cold spells in eastern North America owing to more frequent cold air outbreaks, which appear to be linked with more frequent high-amplitude jet stream patterns over North America since 2000 (Francis and Vavrus 2015). The amplified jet wave over North America typically exhibits a western ridge–eastern trough configuration, as has predominated in the past two winters (2013/14 and 2014/15), coincident with positive SST anomalies in the North Pacific (Hartmann 2015). Although positive GPH anomalies tend to lie over the BK in December and January, the height anomalies north and east of Greenland also exceed 50 m, which has a major influence on perturbing the regional circulation.

Positive GPH anomalies can be generated by dynamics through vorticity advection and/or by thermodynamics through lower-level advection of temperature anomalies or low-level heating, as given by the geopotential tendency

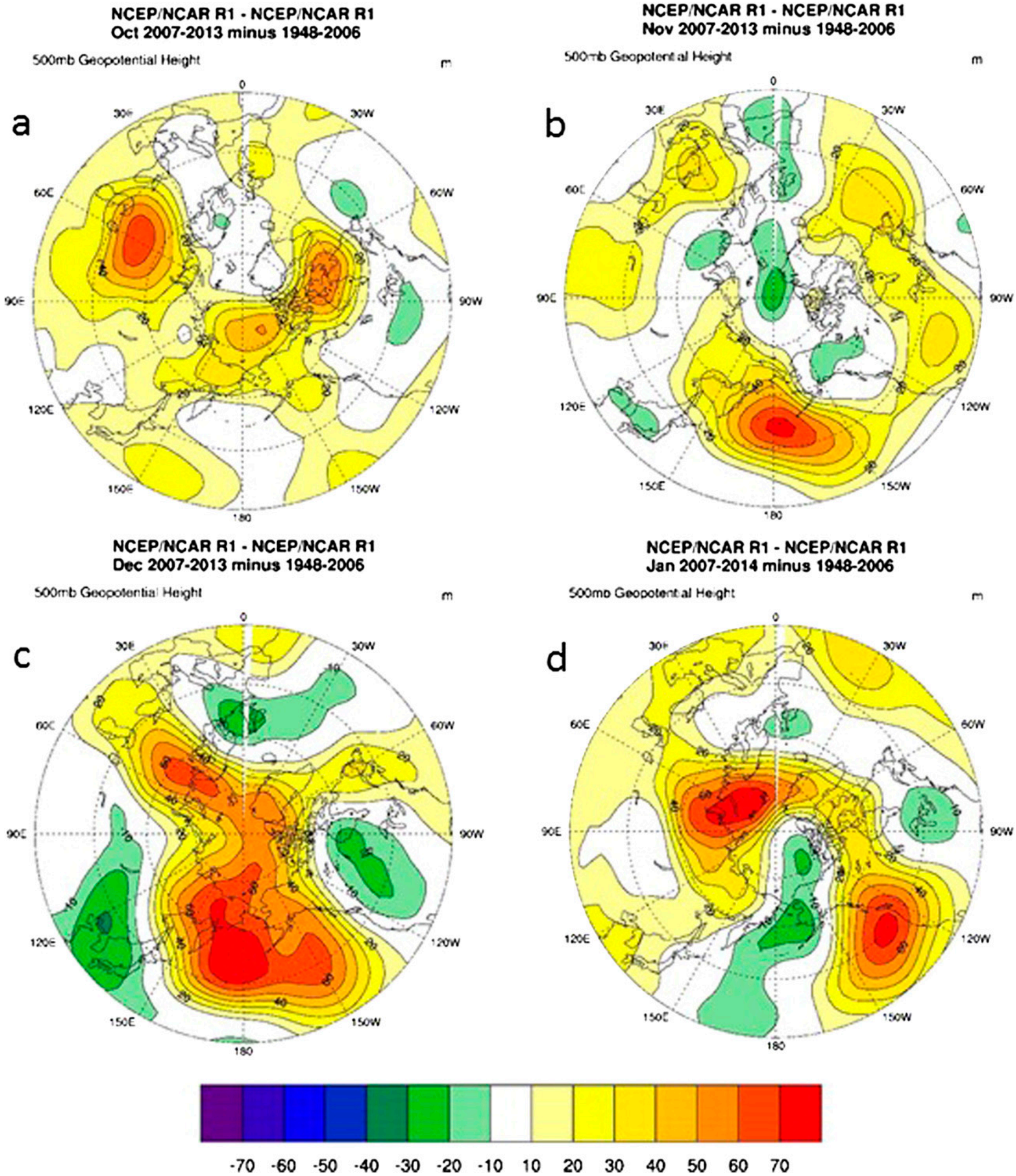

FIG. 7. Differences in 500-hPa geopotential height (m) between recent years (2007–2013/14) and earlier years (1948–2006) during (a) October, (b) November, (c) December, and (d) January. Data are from the NCEP–NCAR reanalysis (Kalnay et al. 1996) (obtained from http://www.esrl.noaa.gov/psd).

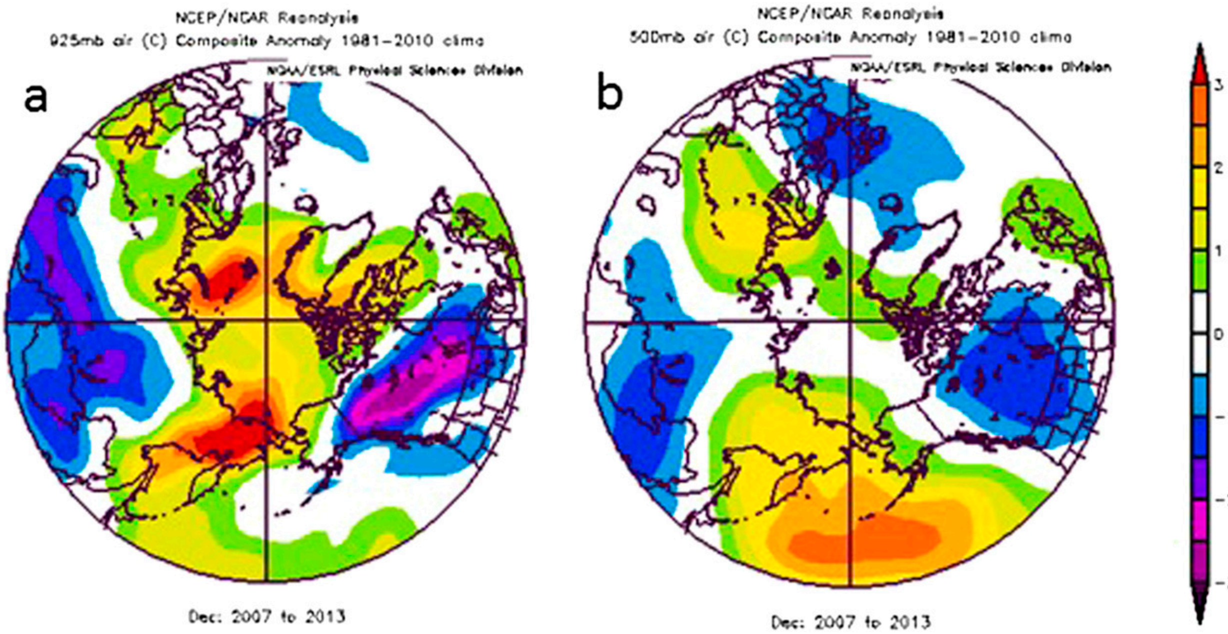

FIG. 8. Anomalies in air temperature (°C) at (a) 925 and (b) 500 hPa during December 2007–13 relative to climatology for 1981–2010. Data are from the NCEP–NCAR reanalysis (Kalnay et al. 1996) (obtained from http://www.esrl.noaa.gov/psd).

equation (Holton 1979, p. 131). December appears to be an important month for an atmospheric response to Arctic amplification (Fig. 7c); Fig. 8 illustrates a decrease in Arctic December temperature anomalies with height for the same years as in Fig. 7, suggesting that increases in 500-hPa GPH have a low-level thermodynamic contribution that can be associated with recent Arctic temperature amplification. Maximum 925-hPa temperature anomalies (Fig. 8a) occur in Baffin and Hudson Bays, the Barents Sea, and the East Siberia Sea, known to be regions of sea ice loss in recent years. Low-level warm air advection is suggested by the high–low dipole in 850-hPa heights (southerly winds) west of Baffin Bay in December (not shown). Further, low-level heating is evident in the composite anomaly of the NCEP surface skin temperature fields for December of 2009, 2010, and 2012 that exhibit maxima in excess of +5°C over Baffin Bay and Hudson Bay. These anomalously warm locations had less sea ice in October during these years and could therefore represent regions where thin sea ice has been persistent into December (National Snow and Ice Data Center analyses; http://nsidc.org/data/seaice_index/).

Although the record length is short, evidence suggests that low-level positive temperature anomalies, often collocated with regions of sea ice loss, contributed to recent midlevel GPH changes that amplified the planetary wave pattern over eastern North America in 6 of the last 10 December–January periods (Table 1). Even though autumn conditions provide more low-level heat transfer, December is an important month as amplification appears to need to act on an existing early winter jet stream wave pattern. The amplified pattern is associated with an increase in the Greenland blocking index and a tendency for persistent ridge–trough jet stream configuration upstream of Greenland (North America) as well as downstream (Europe). While changing SST patterns in midlatitude oceans also influence jet stream configurations, interannual variability in regional locations of substantial sea ice loss in the previous seven years may have reinforced the position and persistence of height anomalies at midlevels, which in turn affects the location of anomalous ridges and troughs (Lee et al. 2015). Thus, highly regional loss of sea ice (e.g., BK and Baffin–Hudson Bay) is important to linkages, rather than an Arctic-wide zonal influence. Indeed, major sea ice loss regions in the Chukchi and Beaufort Seas are too far north to interact with Northern Hemisphere jets in early winter.

Enhanced troughing over eastern North America is likely related to a combination of multiple factors: internal variability, low-level temperature anomalies over northeastern Canada, and midlatitude and equatorial teleconnections.

5. Uncertain evidence for linkages in the eastern North Atlantic and northern Europe

Potential Arctic linkages in Europe are more complex in the sense that severe weather involves multiple

TABLE 3. Sea ice area (SIA) in the Barents and Kara Seas correlated against T2m in northern Europe land areas (55°–72°N, 5°–42°E) in 1979–2012. The correlation coefficients marked in boldface are statistically significant ($p < 0.05$).

	Sep T2m	Oct T2m	Nov T2m	Dec T2m	Jan T2m	Feb T2m	Mar T2m
Sep SIA	−0.23	−0.27	−0.14	−0.04	−0.01	0.20	0.03
Oct SIA		**−0.38**	**−0.36**	0.07	−0.04	0.28	−0.04
Nov SIA			−0.27	0.09	0.18	0.24	0.05
Dec SIA				−0.24	−0.24	0.24	−0.09
Jan SIA					**−0.35**	0.04	0.05
Feb SIA						−0.11	−0.03
Mar SIA							−0.34

causes. Greenland blocking supports a southern location of the storm track and polar jet stream across the eastern Atlantic, with associated cold winters in northwestern Europe (Woollings et al. 2010). Evidence of connectivity between BK sea ice loss and winter weather in northern Europe has been reported (e.g., Petoukhov and Semenov 2010; Orsolini et al. 2012), but variability in this region is principally associated with the North Atlantic Oscillation (NAO). The NAO in turn can be regarded as an index reflecting the variability of the storm tracks (Vallis and Gerber 2008) and the Atlantic polar front jet stream (Woollings et al. 2010). Figure 1 shows that much of the climate variability in northern Europe is primarily influenced by shifts in the eddy-driven jet stream across the Atlantic that have a number of potential drivers (Hall et al. 2015), of which the Arctic is only one. These include El Niño (e.g., Bell et al. 2009), the quasi-biennial oscillation (QBO; e.g., Boer and Hamilton 2008), solar activity (Ineson et al. 2011), Atlantic SST anomalies such as the Atlantic multidecadal oscillation (AMO; e.g., Peings and Magnusdottir 2014), Gulf Stream variability (Sato et al. 2014), and eastern Atlantic blocking (Davini et al. 2014).

Cohen et al. (2014) report a small winter (DJF) cooling trend for northern Europe since 1990. During 1979–2013, however, the four coldest winters in northern Europe (land areas in 55°–72°N, 5°–42°E) occurred before 1990: 1978/79, 1984/85, 1985/86, and 1986/87. A straightforward correlation of area-averaged ERA-Interim (Dee et al. 2011) surface temperature over northern Europe with BK sea ice area reveals some significant values during the period 1979–2012, but they are all negative, indicating that reduced sea ice area is related to warm conditions (Table 3). Because of the dominating effects of westerly winds from the North Atlantic and the proximity to the Barents Sea, present evidence indicates that northern Europe is outside the region where the climate is directly affected by large-scale changes in the Arctic. The T2m in northern Europe in DJF correlates more strongly with 10-m zonal wind (U10; Fig. 9a) than with 10-m meridional wind (V10; Fig. 9b). However, 10-m meridional wind does have a significant positive correlation with T2m in most of northern Europe, and over the Barents Sea; both the 10-m and midtropospheric southerly winds are clearly associated with a high T2m, as also shown by Sato et al. (2014) and Nakanowatari et al. (2014). In large parts of northern Europe, however, the correlations between 500-hPa meridional wind and T2m are near zero (not shown), suggesting that the meridional heat advection related to midtropospheric planetary waves may have a less direct impact on T2m in northern Europe than in other midlatitude regions.

Recent years have seen instances of extreme latitudinal shifts in the North Atlantic polar jet stream (Fig. 10). During much of winter 2009/10 the polar jet was displaced southward in association with a negative NAO phase, bringing prolonged cold temperatures to northwestern Europe. In the winter of 2011/12, the jet was displaced northward as a result of persistent ridging in the Atlantic, consistent with a positive NAO phase (Santos et al. 2013). Winter 2013/14 followed neither of these patterns, and was instead dominated by a centrally located jet that created exceptionally wet, stormy, and mild weather in the United Kingdom (Slingo et al. 2014; Matthews et al. 2014). As shown in Fig. 11, the southern jet–negative NAO pattern has been linked to blocking high pressure over Greenland (Woollings et al. 2008, 2010; Hanna et al. 2015), while the northern jet–positive NAO pattern has been linked with European blocking. The central jet mode is associated with low-latitude blocking (Davini et al. 2014). The 2009/10 and 2013/14 winters are extreme examples of seasons dominated by the southern and central jet modes respectively, occurring in quick succession. Evidence suggests that the interannual position of the polar jet has become more variable in DJF in recent years, consistent with similar increased variability in the NAO and GBI (Hanna et al. 2015).

In the North Atlantic, multiple forcing signals are able to affect jet stream variability and the NAO index in similar ways, so it is difficult to distinguish the relative impacts of the different drivers, both from each other and against the background of large atmospheric internal variability. While Greenland blocking can be

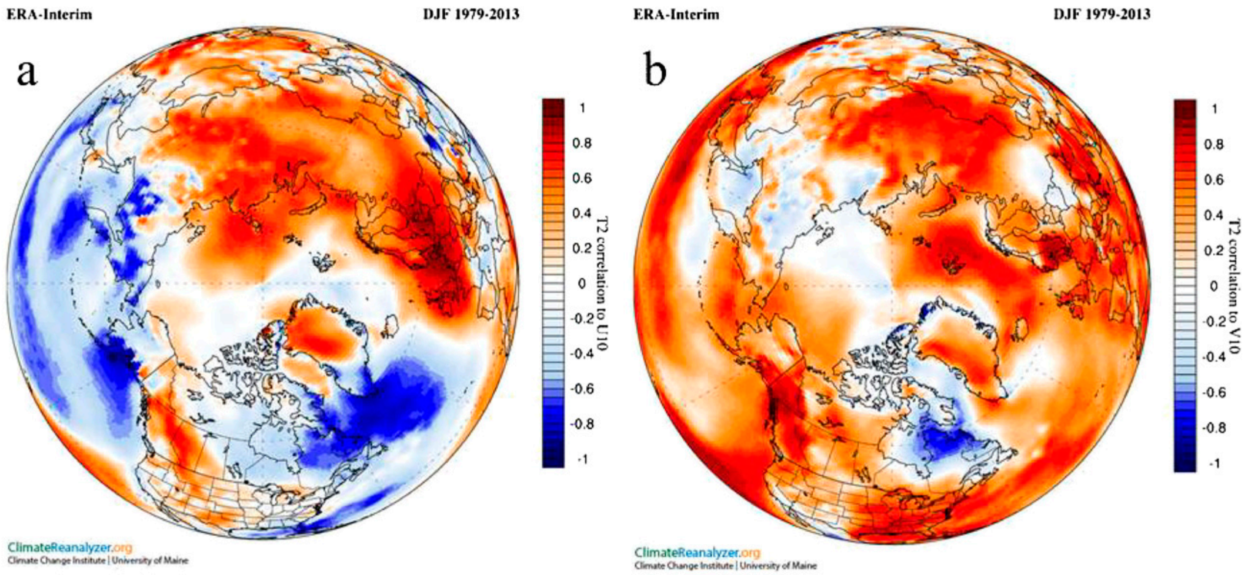

FIG. 9. Correlation coefficients between T2m and (a) U10 and (b) V10 during 1979–2013. Data are from ERA-Interim (Dee et al. 2011).

related to a southward displacement of the North Atlantic jet on a case-study basis, it is likely that multiple factors and internal chaos dominate the variability of winter weather in northern Europe, which introduces substantial challenges in potential attribution to Arctic amplification, although there are intriguing signs of changes in jet stream variability that coincide with the recent changes in Arctic amplification.

6. What about the North Pacific?

Cold-air outbreaks in midlatitudes are often associated with the negative phase of the AO (Thompson and Wallace 2001). The AO is associated with the first mode of Northern Hemisphere sea level pressure variability, while the Pacific has a separate second mode of variability, the Pacific–North American (PNA) pattern

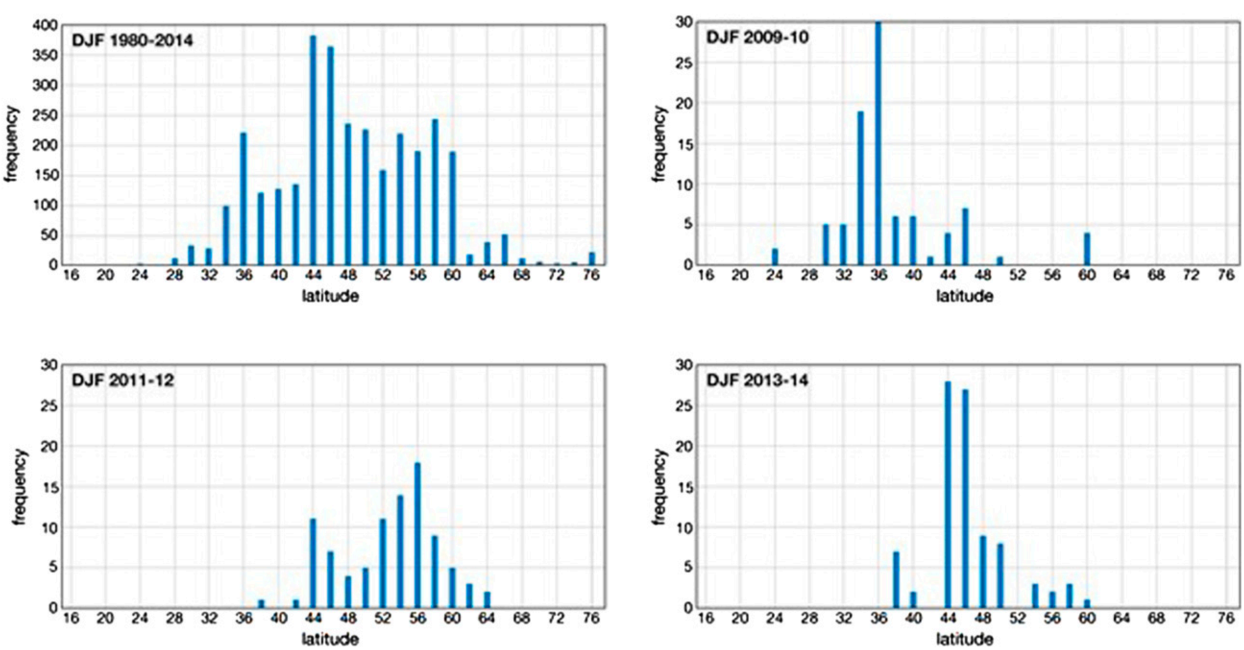

FIG. 10. DJF frequencies of daily mean polar jet latitudes, 1980–2014, and the frequencies for 2009/10, 2011/12, and 2013/14, from ERA-Interim (Dee et al. 2011). The Atlantic sector is 16°–76°N, 0°–60°W. Jet stream latitude is calculated according to Woollings et al. (2010).

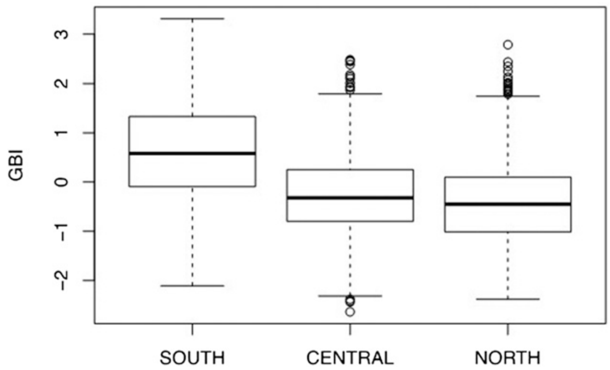

FIG. 11. Boxplot showing spread of DJF daily jet locations with the GBI. Data are from the Twentieth Century Reanalysis (Compo et al. 2011). South peak days are when jet latitude is at 36°–40°N, central peak days are at 44°–46°N, and north peak days are at 56°–60°N.

(Overland et al. 2008). This separation has been well demonstrated over the last decade. Regions north of the Bering Strait contribute to pan-Arctic amplification of warming, while the southern Bering Sea has exhibited periods of above- and below-normal temperatures associated with a westward or eastward displacement of the Aleutian low pressure center in the North Pacific (Overland et al. 2012).

Of interest for case studies of midlatitude extreme events are the possible combined effects of an amplified (wavy) polar jet together with influences from the Pacific, such as tropical storms, pulses of wave energy from deep convection, or superposition of the polar jet with the subtropical jet. Two or more factors can produce an extreme event, while a single influence may not. For example, the ''Snowmageddon'' storm that occurred in February 2010 and caused major disruptions in many U.S. East Coast cities resulted from a deep trough in the polar jet over eastern North America along with a subtropical jet fueled by El Niño. Abundant cold air combined with tropical moisture is a recipe for heavy snow.

The exceptional storminess and recent flooding in the United Kingdom during winter 2013/14 had a number of contributory factors leading to an exceptionally strong jet stream in the North Atlantic (Slingo et al. 2014; Matthews et al. 2014), but the unusual persistence of the pattern may have been related to an extremely amplified jet stream configuration upstream, in which Arctic amplification appears to have played a role, together with an influence from tropical and extratropical North Pacific SST (Lee et al. 2015).

We hypothesize that combined impacts from the Pacific and Arctic may be more intense when the zonal winds of the polar jet are weaker, as a weaker jet may be more easily deflected, and tropical impulses would represent a larger fraction of kinetic energy in a weaker jet. Extensive ridging over the North Pacific, whether random or related to changes in the subtropics, can reinforce the eastern North American troughing, which may then be enhanced by Arctic processes to give more extreme conditions as discussed in section 4. Such events resulting from combinations of natural variability and system-wide changes are difficult to capture in monthly or seasonal statistics and in zonal averages; thus new metrics and modeling experiments are required to understand these complex interactions.

7. Conclusions

The Arctic has undergone remarkable change in recent decades, including the loss of two-thirds of its sea ice volume in a span of three decades (e.g., Overland et al. 2014; Lindsay and Schweiger 2015). A variety of positive feedback mechanisms involving snow, ice, and unique aspects of the Arctic atmosphere result in a heightened sensitivity of the Arctic–global temperature changes, a phenomenon termed Arctic amplification. How the character of the jet stream will respond to the Arctic's transformation is the topic of much research and considerable controversy. While weaker zonal winds are generally associated with negative phases of the AO and a wavy meridional path of the jet stream, it is a challenge to quantify the impact of Arctic forcing amid the substantial natural variability combined with the short time span of the clear Arctic amplification signal. The Arctic may serve as an amplifier rather than a cause. If the future jet stream does become more meridional, even on an episodic basis, it is likely that an increased frequency in high-amplitude jet configurations and perhaps also blocking patterns will occur, both of which favor persistent weather conditions that can lead to a variety of extreme events (Fig. 2). The impacts of improved understanding of changes in jet stream dynamics for seasonal weather forecasts are difficult to overstate.

This paper combines recent literature with new analyses to conclude that evidence for linkages between Arctic amplification and midlatitude weather patterns may be emerging, but that mechanisms are likely to be regional, episodic, and seasonally and interannually varying, making systematic detection a major challenge. Current synthesis suggests that there will be no net midlatitude cooling, only a potential for severe events (Barnes and Screen 2015). In north-central Asia, changes in baroclinicity due to the loss of sea ice in the BK forces a sustained regional response, but the impact farther east is the result of a propagating wave train, involving time scales from days to months. The ridge–trough system that persisted over North America throughout many of the early winters since 2007 is a climatologically favored pattern that can be amplified by internal dynamic processes, local surface temperature anomalies, low-level temperature advection, and remote influences. Analyses based on decadal temperature trends or zonal-mean dynamics will not detect such events. Models are important tools, but are currently providing conflicting results.

BK and northeastern North America are of particular interest for Arctic–midlatitude linkages impacting skill in extended-range weather forecasts (Jung et al. 2014). New metrics and approaches are needed to identify regionally and seasonally varying mechanisms linking substantial thermodynamic changes in the Arctic to shifts in the chaotic atmospheric circulation of the Northern Hemisphere. Additional challenges emerge as other changes in the climate system occur simultaneously; the interactions of these effects are complicated and may be different from anything humans have witnessed before.

Given the complexity of the physics and the multiple approaches taken to study these phenomena, it is not surprising to find diversity, disagreements, and fragmentation of the scientific community, as research in this field gains attention and momentum. A warmer climate is predicted for the future (Wallace et al. 2014; Screen 2014), yet warm Arctic–cold continent linkages of a regional and episodic nature have a potential to amplify extreme midlatitude weather events, and therefore affect billions of people, in coming decades.

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