

## PERSPECTIVE

# Warm Arctic—cold continents: climate impacts of the newly open Arctic Sea

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Climate change; sea ice; atmospheric circulation; North Atlantic Oscillation.

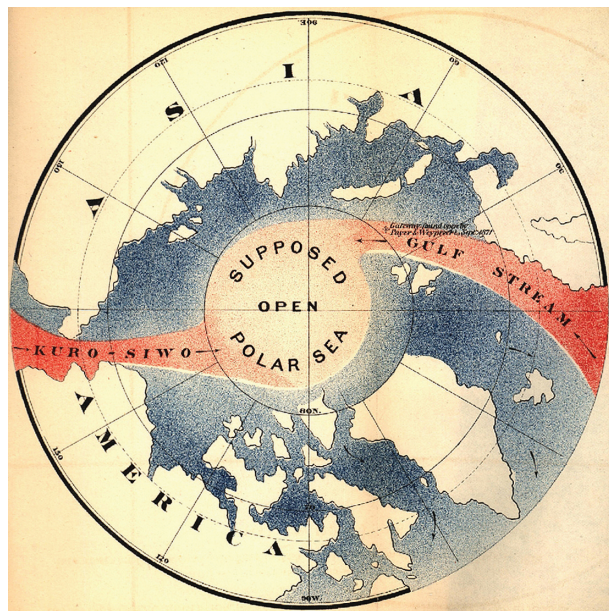
**Correspondence**James E. Overland, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115, USA.  
E-mail: james.e.overland@noaa.gov**Abstract**

Recent Arctic changes are likely due to coupled Arctic amplification mechanisms with increased linkage between Arctic climate and sub-Arctic weather. Historically, sea ice grew rapidly in autumn, a strong negative radiative feedback. But increased sea-ice mobility, loss of multi-year sea ice, enhanced heat storage in newly sea ice-free ocean areas, and modified wind fields form connected positive feedback processes. One-way shifts in the Arctic system are sensitive to the combination of episodic intrinsic atmospheric and ocean variability and persistent increasing greenhouse gases. Winter 2009/10 and December 2010 showed a unique connectivity between the Arctic and more southern weather patterns when the typical polar vortex was replaced by high geopotential heights over the central Arctic and low heights over mid-latitudes that resulted in record snow and low temperatures, a warm Arctic—cold continents pattern. The negative value of the winter (DJF 2009/10) North Atlantic Oscillation (NAO) index associated with enhanced meridional winds was the lowest observed value since the beginning of the record in 1865. Wind patterns in December 2007 and 2008 also show an impact of warmer Arctic temperatures. A tendency for higher geopotential heights over the Arctic and enhanced meridional winds are physically consistent with continued loss of sea ice over the next 40 years. A major challenge is to understand the interaction of Arctic changes with climate patterns such as the NAO, Pacific North American and El Niño–Southern Oscillation.

The Arctic is changing. In September 2007 the minimum Arctic sea-ice extent was 37% below climatology. Sea-ice minimums in all years since 2007 are below extents prior to 2007 and sea ice has remained at record low levels during the October freeze-up season (National Snow and Ice Data Center 2011). Sea-ice thickness and the amount of multi-year sea ice in the Arctic Basin have also continued downward (Kwok et al. 2009; Kwok & Untersteiner 2011). Consideration of an increasingly sea ice-free summer Arctic is not unique to the last decade. There was conjecture of open polar seas in the 19th century, and sea-ice extent was relatively low in the Atlantic sector of the Arctic during the early 20th century. We pursue the hypothesis that despite the strength of dominant negative radiative feedback in

high latitudes, the Arctic climate is in fact sensitive to multiple one-way amplification mechanisms and thus responsive to external forcing that can shift the state of the Arctic (Miller et al. 2010). This forcing may be episodic in the form of intrinsic variability expressed as atmospheric and oceanic circulation anomalies originating in the Arctic or at lower latitudes, persistent from an emerging influence from increasing anthropogenic greenhouse gases, or most likely from a combination of the two.

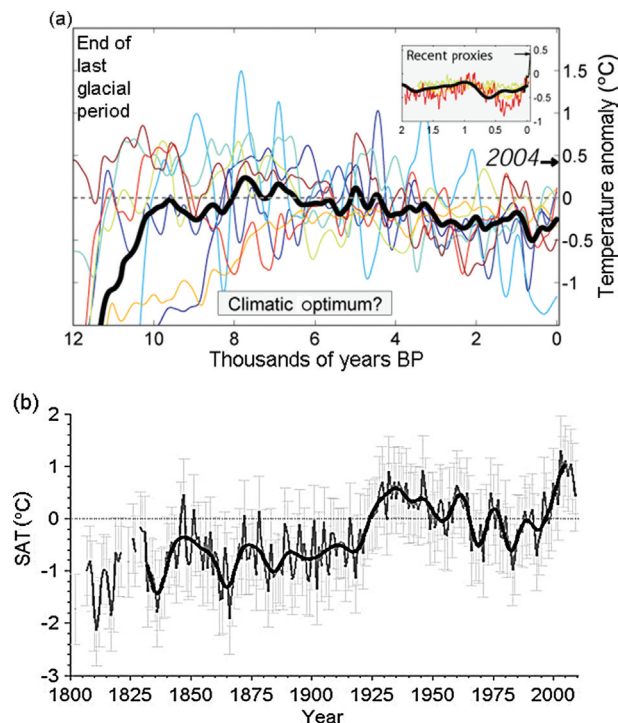
The idea that sea-ice cover in the Arctic polar sea is influenced by the enormous amount of heat transported from the south toward the Arctic is at least 142 years old. Silas Bent, an experienced US Navy hydrographer, advocated this theory in 1868 (Fig. 1). The so-called



**Fig. 1** The thermal pathways to the North Pole suggested by Bent (1872). (Image libr0568, Treasures of the National Oceanic and Atmospheric Administration Library Collection.)

“open polar sea” was hotly debated at the time, which was reasonable considering that the central Arctic was entirely unexplored (Bent 1870, 1872; Chavanne 1875). From today’s perspective it is easy to dismiss the speculative geography of the 19th century but often as not there are grains of insight behind the florid polemic typical of the day. There is a near equilibrium during winter in the atmosphere between heat loss to space, and gain from the ocean and by advection from mid-latitudes (Serreze et al. 2007; Rhines et al. 2008). In summer the atmospheric balance shifts to heat loss to space and into the ocean, and gain from solar radiation and advection from mid-latitudes. Fig. 1 implies such a budget, with the major northward pathways of heat in the correct locations from the Atlantic and Pacific sectors. The US National Center for Atmospheric Research (NCAR) climate model (CCSM3) shows that future Arctic sea-ice loss may be due in part to an ocean heat advection component (Holland et al. 2008). Silas Bent’s simplistic illustration seemed outlandish even a few years ago, but it is becoming less so as the Arctic ice pack becomes thinner, more mobile and more sensitive to heat fluxes and other local processes.

Long time series provide perspective to recent Arctic changes. The planet warmed considerably coming into the Holocene period about 10000 years ago (Fig. 2a). The Holocene optimum occurred about 6–8000 years ago due to an increased tilt of the polar axis and a more elliptical



**Fig. 2** (a) Temperatures for the Holocene from different data reconstructions. The black line is a composite. (The figure is a modified version of a graphic online at [http://commons.wikimedia.org/wiki/File:Holocene\\_Temperature\\_Variations.png](http://commons.wikimedia.org/wiki/File:Holocene_Temperature_Variations.png) and created by R.A. Rohde using data from various sources listed on the website.) (b) Extended annual mean surface air temperature (SAT) record for the Atlantic–Arctic boundary region based on composite land station records (Wood et al. 2010). Ninety-five percent confidence limits are shown. Decadal-scale variations are emphasized with a two-way Butterworth low-pass filter constructed to remove frequencies higher than 0.1 cycles per year (black line). The early 20th century warming episode and the recent temperature increase are evident. From Wood et al. (2010).

orbit. Arctic summers were warm, but due to Kepler’s second law (planets sweep out equal areas in equal time) summers would have been short, so that the net annual radiative effect on potential sea-ice loss during this interval is uncertain (Miller et al. 2010; Funder et al. 2011).

When we examine the time series of annual surface air temperature (SAT) for the northern North Atlantic beginning in 1802 (Fig. 2b), based on composite station records (Wood et al. 2010), we see generally cold temperatures in the 19th century relative to the 20th century. Essentially, cold and dark Arctic conditions dominate the annual heat budget. Temperatures were sufficiently low that an extensive year-round sea-ice cover and strong atmospheric polar vortex were maintained, which reduced the potential connectivity between the Arctic and regions further to the south. In contrast, the subsequent early 20th and early 21st

century periods stand apart with two distinct warming episodes: the early 20th century warming (ETCW) event that began around 1920s and the large-scale temperature increases currently unfolding. The ETCW provides an example demonstrating the sensitivity of the Arctic climate to external forcing, as presented in the next section. This is followed by a discussion of the present warming and evidence of increasing weather and climate linkage between the Arctic and sub-Arctic. We refer to this increasing connectivity as a warm Arctic—cold continent pattern, which was particularly strong during winter 2009/10 and December 2010.

### Early 20th century warming

Pronounced positive SAT anomalies were observed in the Atlantic sector of the Arctic beginning about 1920s. By the early 1930s it was recognized that a substantial climatic fluctuation had occurred over a broad area and was associated with important environmental and social impacts (Kincer 1933; Scherhag 1937; Wood & Overland 2010). The ETCW was not observed on the Pacific side of the Arctic at Barrow, Alaska (Fig. 3). Environmental impacts included a parallel warming from west Greenland to northern Russia, declines in glaciers and reduced sea-ice extent in the Atlantic and Barents Sea sectors, sea surface temperature anomalies in the Nordic seas, an increase in the rate of the trans-polar sea-ice drift and pervasive shifts in marine and terrestrial biogeography (e.g., Jensen 1939; Koch 1945; Ahlmann 1948). These impacts are similar in kind to those documented recently (Symon et al. 2005).

The ultimate cause of the ETCW remains unsettled. Whether intrinsic variability or some form of natural or anthropogenic forcing was a leading factor in the emergence of the ETCW is still debated (Veryard 1963; Hegerl et al. 2007). However, it was widely recognized at the time that a large variation in the atmospheric general circulation had occurred (e.g., Scherhag 1937; Zubov 1948; Bjerknes 1963). In particular, it was observed that the largest positive SAT anomalies around Svalbard and the northern North Atlantic were associated with an increase in southerly winds and more frequent storms in the region compared to previous decades (Petterssen 1949; Hesselberg & Johannessen 1957; Grant et al. 2009). It is becoming increasingly clear that increased meridional atmospheric circulation patterns contributed to the ETCW, but its duration is likely linked to longer term amplification via ocean advection and heat storage in the Atlantic–Arctic region and sea-ice processes (Wood & Overland 2010). A mechanism of this nature also helps explain one of the more puzzling features of the ETCW

fluctuation: the parallel warming of Greenland and northern Europe occurred while the prominent dynamically-induced winter temperature east–west see-saw known as the North Atlantic Oscillation (NAO) continued unabated.

Reduced sea-ice cover likely provided an amplifying mechanism that supported regional warming in the Barents Sea and added longevity to the ETCW. Based on data and model studies, Bengtsson et al. (2004) suggests that anomalous surface heat flux over the sea ice-free areas promoted warm air advection and further sea-ice loss. Large changes in ocean heat content and northward circulation in the broader North Atlantic were evident (Dickson 2002). In this light the proximate cause of the ETCW can be interpreted as essentially a time-extended random climate excursion initiated by anomalous southerly/meridional winds over the northern North Atlantic that was amplified by coupled Arctic ocean–atmosphere–sea-ice processes.

### Arctic amplification at the beginning of the 21st century

The Arctic is the Earth's fastest warming region at the beginning of the 21st century (Fig. 4) as anticipated by climate models as early as Manabe & Stouffer (1980). The annual temperature anomaly north of 60° N in the Arctic relative to a 1971–2000 mean climatology exceeds 1.0° C; regions of the northeastern Barents, Kara, East Siberian and Chukchi seas, and adjacent coast regions exceed 2° C. Arctic temperature anomalies are at least double those at most lower latitudes and, unlike the ETCW, extend Arctic-wide.

Arctic amplification can have multiple causes (Bekryaev et al. 2010; Miller et al. 2010; Serreze & Barry 2011). While amplification is most traditionally associated with local loss of sea ice and an ice-albedo feedback, polar amplification is also a necessity of poleward heat transport (Langen & Alexeev 2007; Graverson & Wang 2009; Döscher et al. 2010). Amplification would occur even on an aqua planet (no land or sea ice) or without an ice albedo feedback. However, the main mechanism of recent Arctic amplification is loss of summer sea ice and related increases in autumn temperatures (Chapman & Walsh 2007; Screen & Simmonds 2010; Inoue & Hori 2011). Rather than just an ice albedo feedback that would be most active in summer in response to *insolation*, recent years show evidence of a late summer early autumn positive *ice insulation* feedback due to additional ocean heat storage in newly sea ice-free areas (Serreze et al. 2008; Jackson et al. 2010). Sea-ice insulation refers to isolating the relatively warm Arctic Ocean from the colder



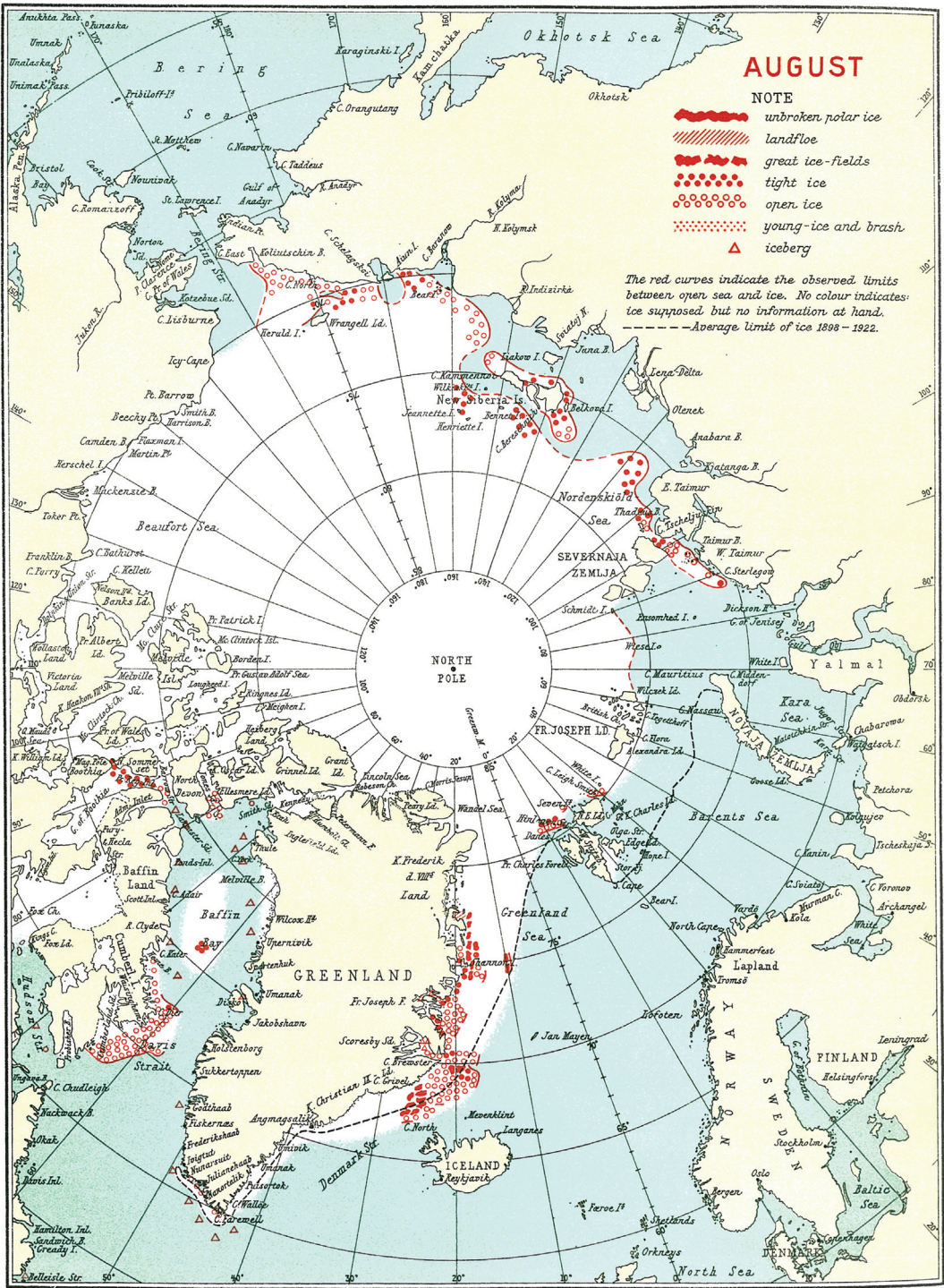
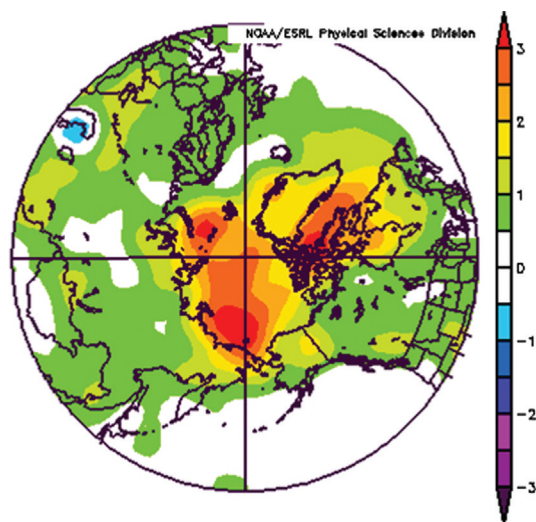


Fig. 3 Sea-ice extent in August 1938 (Thomsen 1939). Note the lack of sea ice just north of Svalbard and in the Kara Sea.

atmosphere as autumn and winter approach. For example, Fig. 5 shows a reduction in sea-ice concentration for October 2009 relative to climatology, representative of recent autumnal conditions, with negative anomalies of

50% in the northern Chukchi, Laptev and Kara seas. Although not discussed in this article, terrestrial feedbacks are important on multi-decadal time scales associated with movement of the tree line, the irreversible loss of

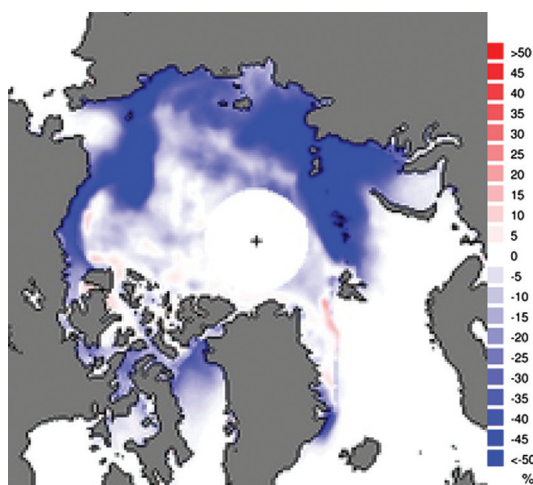




**Fig. 4** Near-surface air temperature anomaly multi-year composites ( $^{\circ}\text{C}$ ) for 2001–10. Anomalies are relative to the 1971–2000 mean and show a strong Arctic amplification of recent temperature trends. Data are from the reanalysis data of the National Centers for Environmental Prediction and the National Center for Atmospheric Research through the National Oceanic and Atmospheric Administration Earth Systems Research Laboratory, generated online at <http://www.esrl.noaa.gov/psd/>.

permafrost and the shift from tundra to shrubs as annual mean temperatures cross  $0^{\circ}\text{C}$  (Callaghan et al. 2010).

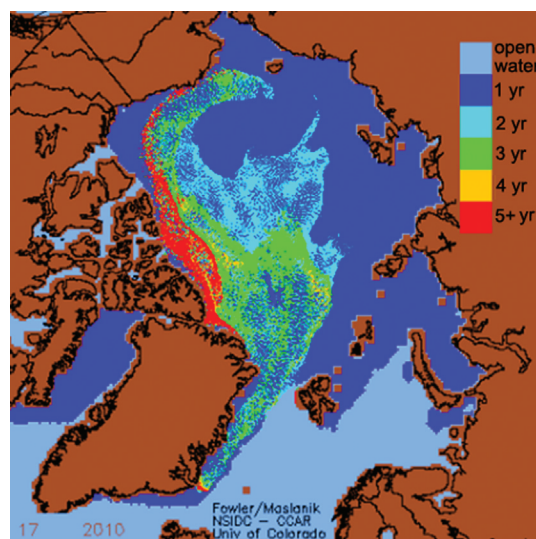
Change in the multiple characteristics of Arctic sea ice contributes to amplification mechanisms. There has been an increase in the rate of trans-polar drift and sea-ice mobility. For example, the Nansen expedition on the



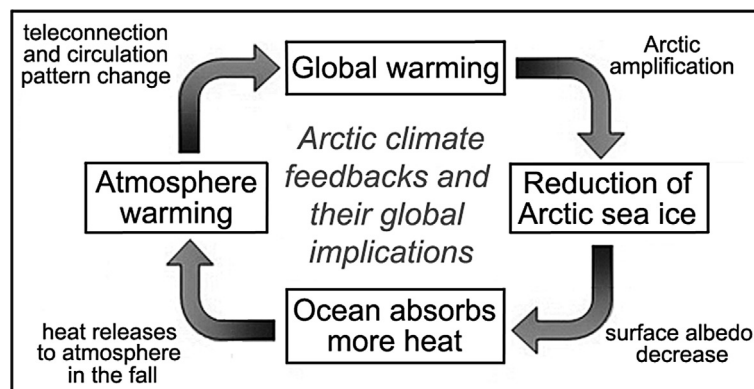
**Fig. 5** Sea-ice concentration anomalies in percent for October 2009 showing major relative decreases in sea ice in the northern Chukchi, Laptev and Kara seas. The figure is based on microwave signatures and was obtained online from the National Snow and Ice Data Center at [http://nsidc.org/data/seaice\\_index/archives/index.html](http://nsidc.org/data/seaice_index/archives/index.html).

*Fram* took over three years to drift across the Arctic at the end of the 19th century, whereas during the Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES) experiment (2005–10) the *Tara* drifted along a similar track in a little more than a year. Sea ice in this region does not reside in the Arctic long enough to thicken as it once did. Indeed, sea ice in the Arctic has thinned by a mean of 0.7 m and the amount of multi-year sea ice decreased by 42% from 2004 through 2008 (Kwok et al. 2009; Kwok & Untersteiner 2011). Figure 6 shows a plot of sea-ice age for spring 2010, calculated from satellite estimates of sea-ice drift. Note the small amount of 5+ year sea ice remaining along the Canadian coast and in the southern Beaufort Sea. As a consequence, seasonal ice is becoming the dominant sea-ice type in the Arctic, both in terms of area coverage and volume (e.g., Barber et al. 2009).

Hypothesized recent Arctic amplification feedbacks are summarized in Fig. 7. Also see Stroeve et al. (2011). Increases in Arctic atmospheric temperatures in all seasons except summer and advection of atmospheric and ocean heat and moisture further into the central Arctic are associated with increased sea ice-free Arctic Ocean areas, especially in the Chukchi Sea, Siberian coastal waters and the north-eastern Barents Sea (Comiso et al. 2008; Giles et al. 2008; Zhang et al. 2008; Wang et al. 2009; Woodgate et al. 2010). An increase in sea ice-free area allows an increase in absorbed heat in the upper ocean, the near-surface temperature maximum (NSTM) (Jackson et al. 2010).



**Fig. 6** Sea-ice age (represented by different colours for different years) for the end of April 2010 showing the small extent of sea ice older than three years. Provided by J. Maslanik as an update to Maslanik et al. (2008).



**Fig. 7** A representation of the current and future Arctic climate feedbacks. Starting at the top, warming and changes in atmospheric circulation lead to loss of summer sea ice and increased storage of heat in the newly sea ice-free ocean areas. This ocean heat is returned to the lower troposphere in the following autumn, increasing the geopotential height of constant pressure surfaces and thus impacting local and far field winds through teleconnections.

Ocean transport processes are also important in maintaining Arctic Ocean heat anomalies (Sumata & Shimada 2007; Woodgate et al. 2010). Return of locally stored ocean heat to the atmosphere occurs the following autumn (Deser et al. 2010; Screen & Simmonds 2010; Kumar et al. 2010). This additional heat from the ocean does not remain at the surface but can penetrate above 850 mb in the Arctic troposphere (Schweiger et al. 2008; Serreze et al. 2008). Increased storm genesis over newly ice-free areas enhances vertical heat transport (Inoue & Hori 2011). A major indicator of Arctic change is this new observed storm genesis in previously sea ice-covered areas. Warmer air is less dense and forms a layer of increased geopotential thickness, which in turn influences Arctic wind fields. The sense of the anomalous geopotential height gradients opposes the westerlies of the polar vortex and favours meridional flow, i.e., weak or negative Arctic Oscillation fields (Overland & Wang 2010).

Figure 7 closes the Arctic amplification feedbacks loop between atmospheric temperature increases, sea-ice processes, ocean heat storage and modified wind fields. Historically, regions of open ocean and newly formed thin ice grew sea ice at a rapid rate, a strong negative radiative feedback which tended to overwhelm other Arctic processes. Arctic changes observed in recent years, however, are likely due to an underappreciated connectivity in multiple atmosphere–sea-ice–ocean processes. Changes observed both recently and during the ETCW in the Atlantic sector, and in numerous climate modelling studies (DeWeaver & Bitz 2006; Parkinson et al. 2006; Holland et al. 2008), support the hypothesis that the Arctic is sensitive to external forcing due to multiple positive feedbacks associated with internal amplification

as sea ice is lost. While hypothesized, the current magnitude of Arctic changes as a result of underlying coupled Arctic amplification mechanisms was not fully recognized even a few years ago (Symon et al. 2005) but underlies key finding number 2 of the Arctic Monitoring and Assessment Programme's Arctic new assessment report (AMAP 2011).

### Sub-Arctic connectivity in winter 2009/10 and December 2010: warm Arctic—cold continents

China and eastern Asia, the eastern United States and Europe experienced unusually cold and snowy conditions during winter 2009/10, especially in December and February (Seager et al. 2010; Hori et al. 2011). Washington, D.C., set a record for winter snow accumulation. Record low temperatures were observed throughout northern Europe. Severe winter weather contributed to a number of deaths, widespread transportation disruptions, power failures and loss of work productivity. These conditions were atypical in recent experience and were simultaneously felt in many regions of the Northern Hemisphere. Other regions (west Greenland and Bering Strait) experience warm temperature anomalies. A warm Arctic—cold continent pattern represents a paradox of recent global warming: there is not a uniform pattern of temperature increases (Cattiaux et al. 2010; L'Heureux et al. 2010). Petoukhov & Semenov (2010) note that sea-ice reduction in the Barents and Kara seas may result in continental-scale winter cooling with more than three times increased probability of cold winter extremes over large areas, including Europe.

The nature of large-scale meteorological conditions for winter 2009/10 can be shown by contrasting it to the



climatological December lower tropospheric atmospheric circulation represented by the pattern of geopotential heights at 850 mb (Fig. 8a). The climatological pattern consists of low geopotential heights over the Arctic forming the polar vortex. Regions of strong north–south geopotential gradients represent strong westerly winds bringing storms into western Europe and British Columbia, Canada. This polar vortex tends to isolate the Arctic region from storms penetrating from mid-latitudes and likewise limits the movement of cold Arctic air toward the south, except over the continents in eastern Asia and central North America. Angular momentum (relative vorticity) helps to stabilize the polar vortex. The unusual weather conditions of December 2009 resulted from a near reversal of this climatological pattern in the geopotential height field (Fig. 8b). Geopotential height maxima are seen over the central Arctic, with lower heights in eastern Asia and the north-western Pacific, and extending from eastern Canada across Europe to western Russia.

This contrast is highlighted in the anomaly field of the 850 mb geopotential height for December 2009 (Fig. 8c), with exceptionally high values at sub-Arctic latitudes in Siberia and western North America, and extending from Davis Strait to the Barents Sea north of Norway. Winter 2009/10 was also influenced by a moderate El Niño with lower than normal geopotential heights over the northern North Pacific (Bond & Harrison 2006; Seager et al. 2010). Following the contour streamlines around low centres of the observed height field in Fig. 8b, one can see implied atmospheric flow from the Arctic Beaufort Sea linked south-eastward into the southeastern USA. The west wind maximum in Europe is well to the south of its more normal location which allowed cold air masses to be established over northern Europe. Northerly winds are observed over eastern Asia bringing cold Siberian air into mid-latitudes. Such major change in the normal December atmospheric circulation is summarized by the negative anomalies in the magnitude of the zonal (eastward) wind component (Fig. 8d). The reduction in the magnitude of the westerly winds across the Atlantic which normally bring warm moist air into Europe, that is, a blocking pattern is especially clear. The large anomalies in the December 850 mb geopotential height field (Fig. 8c) tend to mirror the temperature anomaly field in the lower Arctic troposphere (Fig. 8e). The entire Arctic is warm with maximums in the Chukchi Sea/northern Alaska and from the Barents Sea to Baffin Bay.

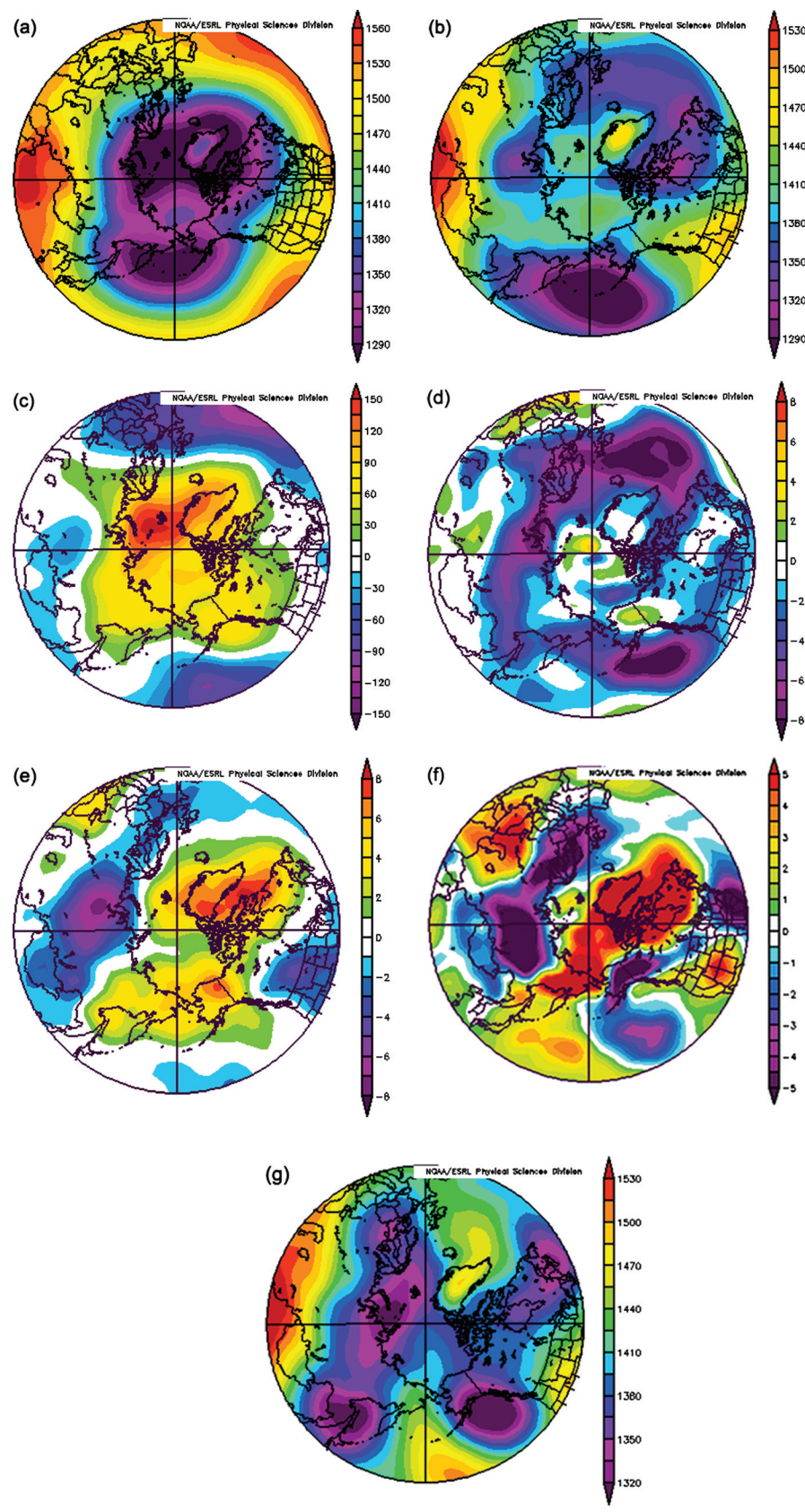
The degree that the winter of 2009/10 atmospheric circulation is unusual is estimated from the historical records of two similar climate indices: the NAO and the Arctic Oscillation (AO). The NAO has a more Atlantic–Arctic focus and a longer historical time series

derived from meteorological station records, whereas the AO time series is defined as the principal component of the Northern Hemisphere sea-level pressure field (20° N–90° N). Positive values of both indices represent strong zonal flow conditions. The winter average NAO value for December 2009–February 2010 was  $-5.1$ , the lowest recorded value since records began in 1865 (NAO index data provided by the Climate Analysis Section, National Center for Atmospheric Research, Boulder, USA, accessed online at <http://www.cgd.ucar.edu/cas/jhurrell/indices.html>). The unusually negative AO value of  $-3.4$  in December 2009 represents weakened or interrupted zonal flow (AO values are obtained from the National Weather Service Climate Prediction Center, accessed online at [http://www.cpc.noaa.gov/products/precip/CWlink/daily\\_ao\\_index/ao\\_index.html](http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html)). The AO in January and February was also negative ( $-2.6$  and  $-4.3$ , respectively). The December and February AO are the most negative recorded values since 1950s, and the only other similar negative AO month occurred in January 1978 ( $-3.8$ ).

Winter 2010/11 began with a similar warm Arctic–cold continent pattern from December through mid-January (Fig. 8f). The December 2010 850 mb geopotential height pattern with a negative NAO (Fig. 8g) has some similarities to December 2009 (Fig. 8b) with modestly high geopotential heights over the central–North American side of the Arctic but with extensive strong meridional flow patterns located throughout the sub-Arctic.

Attribution for the cold mid-latitude winter is difficult given the largely chaotic nature of atmospheric circulation. Since 2002, warmer lower tropospheric temperatures are associated with thin sea ice in marginal Arctic seas (Fig. 5) preceding the autumn period (Schweiger et al. 2008; Serreze et al. 2008). Model studies (Singarayer et al. 2006; Sokolova et al. 2007; Seierstad & Bader 2008; Honda et al. 2009) show a relation between years with minimum sea-ice cover and the negative phase of the AO (weaker zonal wind), although regional details are complicated by storm track and atmospheric long-wave/low frequency dynamic processes. They further suggest that the regions of high and low geopotential heights form a pattern of atmospheric teleconnections with length scales between relative high and low centres of 700–1000 km (Francis et al. 2009). The Arctic 850 mb temperature anomalies and geopotential height fields in December 2009 and 2010 (Fig. 8b, g), may have partially contributed to the resultant meridional hemispheric wind pattern.

A fair question is: compared to December 2009 and 2010, what was the atmospheric influence from lack of





sea ice in December 2007 and 2008, years when the NAO/AO did not show extreme negative values. The December 2008 850 mb temperature anomaly field also shows a warm Arctic—cold continent pattern (Fig. 9a) with local maximums over the Chukchi and Barents seas, the regions of major sea-ice loss and a temperature minimum over central Canada. The 850 mb geopotential height field (Fig. 9b) shows the impact of the anomalous temperatures north of Alaska with a distortion of the polar vortex from zonal flow resulting in a meander with north-west meridional winds over northern Canada feeding into the cold temperature region. South-eastern Canada was particularly cold in winter 2008. In December 2007, the extensive warm anomalous Arctic temperatures (not shown) perhaps impact the 850 mb geopotential height field in the central Arctic with a local maximum (Fig. 10), separating the polar vortex into two nearly independent cells (Kumar et al. 2010).

In our first look at the impact of warmer autumn air temperatures on Arctic wind fields through the thermal wind mechanism before winter 2009/10 we concluded that it would be nearly impossible to detect mid-latitude influences directly with observations and that the only approach was through teleconnection studies in models (Overland & Wang 2010). After the winters of 2009/10 and 2010/11, and looking at the case from December 2008, we can conclude there is an impact of increased temperatures on the polar vortex, favouring a more meridional flow pattern. However, the impact will often be too regional to project significantly onto the broad NAO/AO indices. Even in the December 2009 case the large chaotic nature of atmospheric circulation and multiple processes (stratospheric, snow, El Niño–Southern Oscillation) involved mask a clear and unique attribution (Wang & Chen 2010). The higher geopotential heights over sea ice-free regions can induce a meander in the zonal flow, but how this perturbation couples with the downstream flow is different for each case.

Several previous studies suggested that global warming would result in an increase in the positive AO and that

the fingerprint would be through a persistent positive sign of the major climate pattern (Palmer 1999). This claim was based in part on the positive AO in the early 1990s and weak positive results from modelling (Feldstein 2002; Gillett et al 2003). In contrast, our study looks a different mechanism: increased geopotential thickness and a thermal wind effect which favours a weakening of the vortex and a resulting meridional flow pattern (e.g., Seierstad & Bader 2008; Budikova 2009).

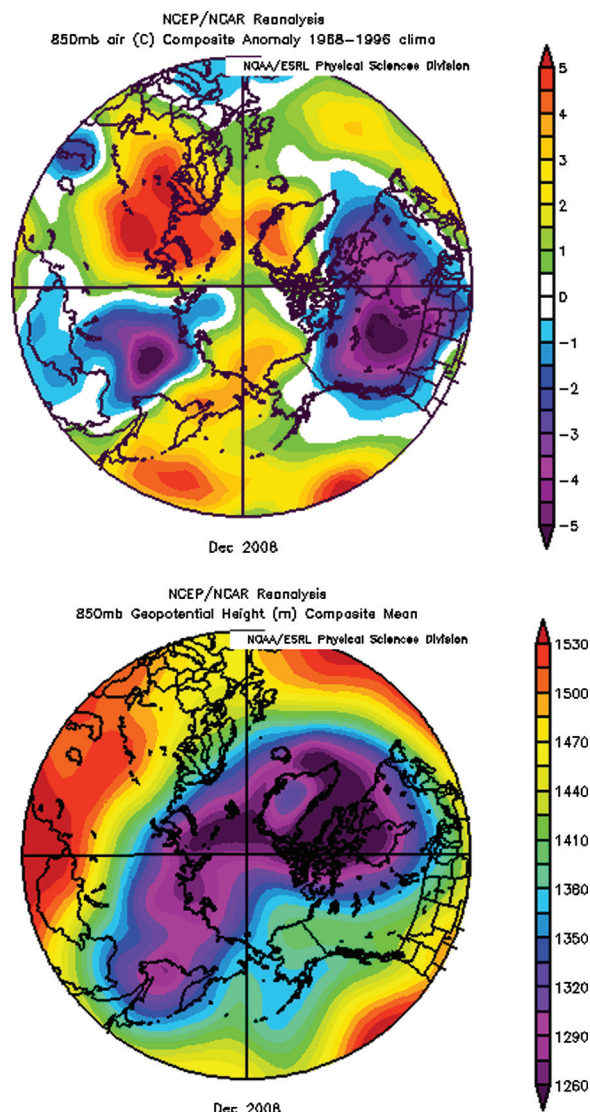
With regard to February 2010, maximum heights in the 850 mb geopotential height field appear over the northern Kara Sea and Iceland, the normal centre of the Icelandic Low (Fig. 11a). Lower heights are seen east of China with strong gradients and therefore northerly winds west of this region. The 850 mb temperature anomalies (Fig. 11b) show that the temperature support for anomalous wind fields over the central Arctic is no longer present this late into winter, but the figure still highlights a warm Arctic—cold continent temperature anomaly pattern (Cohen et al. 2010).

The case study of meteorological conditions of December 2009 and 2010, and the extreme nature of these circulation events based on negative NAO/AO values inspire an important question. Is the observed severe mid-latitude weather in two adjacent years simply due to an extreme in chaotic processes alone, or do they included a partial but important Arctic forcing and connection due to recent changing conditions? The answer lies in continued case studies of the interactions of Arctic change with intrinsic variability of the NAO and Pacific North American patterns. It would be intriguing if the interactions of an increasing negative amplitude of the AO with the El Niño–Southern Oscillation, such as the winter of 2009/10, became a more pronounced feature in the future.

## Future

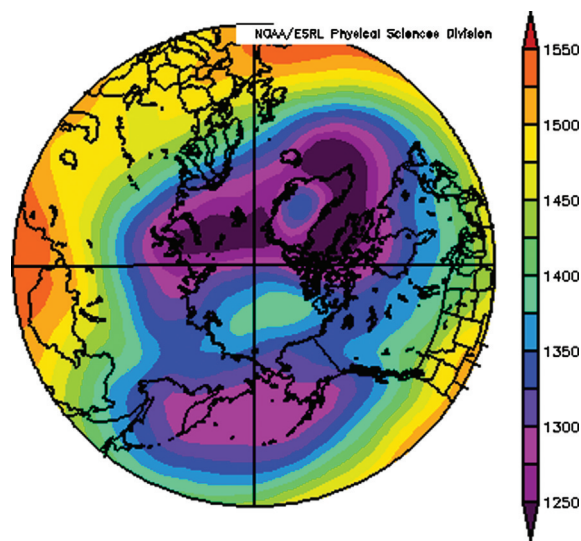
The eight ensemble members of the NCAR CCSM3 model of future sea-ice extent show a major reduction in

**Fig. 8** (a) The climatological 850 mb geopotential height field for December 1968–1996. Low heights over the Arctic are representative of the polar vortex of westerly winds. (b) Similar to (a) but for the observed 850 mb geopotential height field in December 2009. Note the near reversal of the pattern with the highest heights now residing over the Arctic. Air streamlines follow the height contours, showing a connection between the Beaufort Sea region and the eastern United States and that the westerly flow into Europe is strongly displaced to the south. The normal region of the Icelandic Low now actually shows a near maximum. (c) Similar to (b) but showing the anomaly field for the December 850 geopotential height. Heights are displaced upward compared to normal conditions throughout the Arctic. (d) Anomalous zonal wind component for December 2009. The extensive regions of negative values (blue/purple) show the reduction in the normally strong westerly winds in the polar vortex, a major atypical pattern. (e) Temperature anomalies at 850 mb for December 2009. Note the regions of relatively warmer lower tropospheric temperatures around regions of the seasonal ice zones in the Chukchi Sea, north of Svalbard and in Baffin Bay. Note the similarity of the pattern shape to the 850 mb anomalous geopotential height field in (c). (f) A warm Arctic—cold continent pattern for December 2010. (g) The observed 850 mb geopotential height field in December 2010. Data are from the reanalysis data of the National Centers for Environmental Prediction and the National Center for Atmospheric Research through the National Oceanic and Atmospheric Administration Earth Systems Research Laboratory, generated online at <http://www.esrl.noaa.gov/psd/>.



**Fig. 9** (a) Air temperature anomalies at 850 mb for December 2008. Note the warm anomalies over the Chukchi and Barents seas and colder temperatures over Canada. (b) Similar to (a) only for the 850 mb geopotential height field. Note the distortion of the polar vortex with north-west winds over northern Canada. Data are from the reanalysis data of the National Centers for Environmental Prediction and the National Center for Atmospheric Research through the National Oceanic and Atmospheric Administration Earth Systems Research Laboratory, generated online at <http://www.esrl.noaa.gov/psd/>.

summer sea-ice extent by mid-century (Holland et al. 2008). Of the models in the CMIP3 archive of 25 models used by the Intergovernmental Panel on Climate Change for its fourth assessment, the NCAR model was one of the best in simulating sea ice (Overland et al. 2011). Like the observed 2007 sea-ice reduction event, the CCSM3 results suggest the possibility, but nearly random nature, of both increasing and decreasing large year-to-year shifts



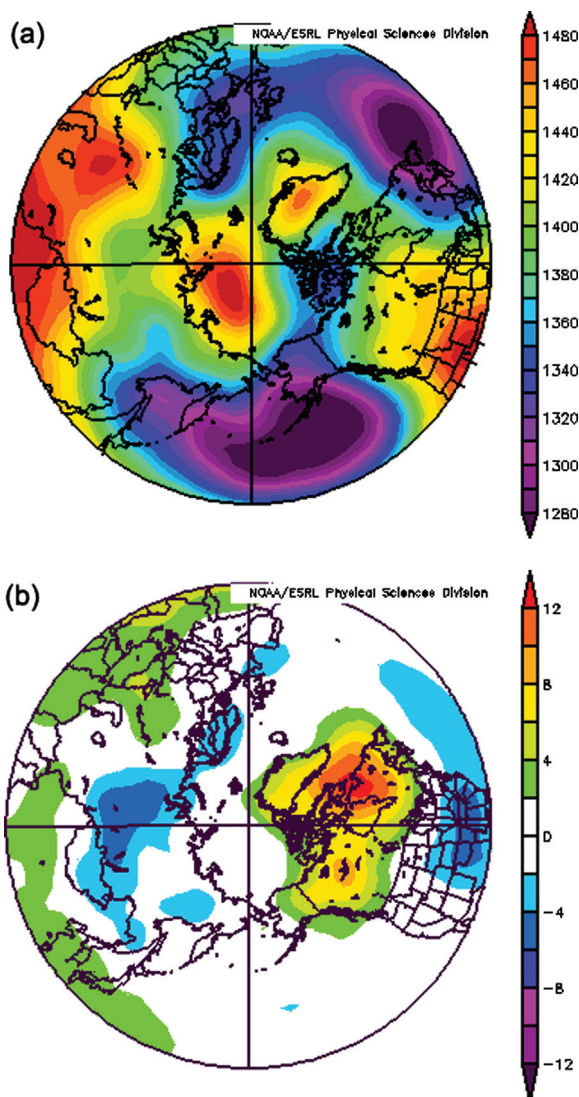
**Fig. 10** The 850 mb geopotential height field for December 2007. Data are from the reanalysis data of the National Centers for Environmental Prediction and the National Center for Atmospheric Research through the National Oceanic and Atmospheric Administration Earth Systems Research Laboratory, generated online at <http://www.esrl.noaa.gov/psd/>.

in sea-ice extent in addition to a downward sea-ice trend over the next four decades. In theory, loss of sea ice favours increased meridional flow patterns and increased connectivity between Arctic climate and sub-Arctic weather. This is also shown by Deser et al. (2010). We therefore conclude that the frequency of occurrence of the global climate change paradox of an autumnal warm Arctic—cold continents weather pattern should increase over the coming decades. But one does not expect this to be a universal feature in every year as it is one mechanism among multiple competing processes, as December 2007 illustrates.

## Summary

Arctic amplification is a consequence of the atmospheric general circulation on the planet, enhanced locally by sea-ice and land processes. Ice albedo feedback (*insolation*) is well known, but a main feature in recent years is the change in upper ocean heat storage in newly sea ice-free ocean areas, the sea-ice *insulation* feedback. The release of this stored heat to the atmosphere affects tropospheric wind fields which in turn impacts atmospheric and oceanic advection of heat and thus the distribution of sea ice. Direct observations of such changes were made on recent cruises of the Japanese research vessel *Marai* (Inoue & Hori 2011). The sensitivity of one-way shifts in Arctic climate to multiple amplification processes may be greater than previously recognized (Miller et al. 2010; AMAP





**Fig. 11** (a) The 850 mb geopotential height field for February 2010. Again note the anomalous height maxima over the Arctic, the southward displacement of streamline into Europe and the northerly streamline into eastern Asia. Again the Icelandic Low location has a high. (b) The 850 mb temperature anomaly field for February 2010. While the temperature anomalies are now absent over the central Arctic Ocean, there is still the general warm Arctic—cold continents pattern. Data are from the reanalysis data of the National Centers for Environmental Prediction and the National Center for Atmospheric Research through the National Oceanic and Atmospheric Administration Earth Systems Research Laboratory, generated online at <http://www.esrl.noaa.gov/psd/>.

2011; Serreze & Barry 2011). This amplification can be driven by internal or external forcing or both, as observed during the ETCW and in the previous decade.

Increased atmospheric temperatures over loss of sea-ice areas, creates a meander in the polar vortex flow which will have different downstream effects in different

years. Given a continuing trend for increased temperatures and thinner sea ice in the Arctic, modelling results and the data from recent late autumns, December 2008, 2009 and 2010, suggest that the frequency of an autumn warm Arctic—cold continents climate pattern will increase, but because of competing processes, such as changes in Arctic stratospheric flow and the chaotic nature of atmospheric circulation in the sub-Arctic including blocking events, it will not be clearly manifest in the same way in every year.

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