Is the Melting Arctic Changing Mid-latitude Weather?

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The Arctic is an integral part of Earth's climate system and has undergone unprecedented changes within the past decades. In the winter half of the year with no or little solar radiation reaching the surface, there is a net cooling of the Arctic by infrared energy lost to space. This loss is balanced by transfer of energy from lower latitudes via atmospheric winds and ocean currents. With a resulting winter north-south temperature difference on a rotating earth, winds are created that flow primarily west to east across mid-latitudes and the sub-Arctic [30-60°N]. This counter-clockwise wind pattern in the upper atmosphere [if you could look down on the earth from above the pole], is traditionally called the polar vortex. Much has been made in popular culture of the "Polar Vortex" in the last few years, with emphasis more on the mid-level atmosphere and, perhaps less correctly based on the American Meteorological Society glossary, on the variation in the shape of the wind pattern influencing cold events in mid-latitudes. To clarify what we are talking about look at the mid-level atmospheric weather map in Figure 1 from December 2015; this figure has lines and colors representing atmospheric fields of data at a particular time, overlying a northern hemisphere map with the north pole in the center, North America to the left, and Europe toward the bottom. Weather tends to follow the direction of winds at around 5.5 km above sea level at the pressure level of 500 hPa, halfway up in the atmosphere based on pressure. Contours in Figure 1 give the varying height of this 500 hPa pressure surface. Because of the force balance between sloping pressure surfaces and the rotation of the earth [Coriolis force] winds follow the direction of these contours and speeds are proportional to the inverse distance between the contours; in Figure 1 we see tight packing of contours and thus strong winds from the west over northeastern North America and across the North Atlantic. The entire somewhat circular pattern of wind flow can be termed the polar vortex and the regions of strong winds at this altitude are at the lower part of the jet stream. In

Figure 1 air temperature at the 850 hPa level, or around 1.5 km above sea level, are also shown by colors. Note that the cold air [blues and purples] are bounded on the south by the polar vortex; regions of cold air are mostly contained within the Arctic. Interest in the polar vortex in recent winters has been when the southern edge of the vortex takes a more north-south wavy pattern allowing cold air regions to penetrate further south into the mid-latitudes.

Changes in Arctic climate variables are substantial. The average annual surface air temperature anomaly over land north of 60°N for 2015 was the highest in the observational record since the beginning of the 20th Century, representing a 2.9°C increase. Since 1980 this increase is at a rate more than double of the northern hemisphere average, and this relative increase is referred to as Arctic Amplification. While Arctic changes are driven by warming of the ocean and atmosphere, they are also manifested in loss of sea ice, glaciers, snow cover in spring, permafrost, and shifts in the ecology of the Arctic. Arctic sea ice has exhibited an unprecedented decline over the past three decades with a loss of 2/3 of the sea ice volume. There have been comparable rapid decreases in snow cover during May and June. This amplification of climate change in the Arctic occurs for two main reasons.[1] First is the feedback loop that gets underway as temperatures rise and snow and ice melt. The less snow and ice on the ground or ocean during the Arctic's long summer days, the more sunlight the ocean and land absorb. The more they absorb, the warmer they get, and the more ice and snow melt. Second, while the Arctic is warming, its temperature is still lower than in the sub-tropics. Radiational loss of heat from the top of the atmosphere is less in the Arctic. Based on over 20 climate models developed for the International Panel on Climate Change [IPCC] Assessment Report, future winter season (NDJFM) surface temperatures are projected to rise in the Arctic [60-90°N] by 4.0°C at 2040 relative to the end of the previous century (1981-2000). [2] The corresponding 2040 increase for the Northern Hemisphere is 1.8°C. As anthropogenic CO2 increases mostly remain in the atmosphere, carbon loading of the previous two decades and projected for the next two decades lock in this Arctic temperature increase. However, a modest amount of carbon mitigation can have an impact in reducing temperature increases in the second half of the century.

A major question arises from combining the information in the previous two paragraphs: do the changes in Arctic conditions have the potential to modify the shape of the polar vortex and thus impact the weather at mid-latitudes? This question is referred to as Arctic/mid-latitude weather Linkages. A wavier jet stream has the potential to bring cold air southward in some regions and warm air northward in other regions. There is a paradox that overall global warming and related Arctic amplification of positive temperatures could induce such cold air events through changes in wind patterns. As evidence of the increased public awareness of this topic, Hamilton and Lemcke-Stampone[3] reported that a majority (60%) of surveyed members of the public now accepts that there is a connection between Arctic warming and mid-latitude weather. Is such acceptance justified? There is more than just public and scientific curiosity in delineating the extent of understanding for potential future Linkages. Can continued Arctic amplification provide an additional tool for extended range weather forecasting in mid-latitudes?

Scientific opinions differ on whether recent extreme weather, including the cold eastern U.S. winters of 2009/10, 2010/11, January 2014, and winter/spring 2015, were merely random events or if there were discernible contributions from recent global or Arctic climate change.[4,5,6] Different atmospheric model studies both suggest and reject support for such Linkages. Even given this controversy in the atmospheric community, national and international agencies—such as the World Meteorological Organization's Polar Prediction Program (PPP) and U.S. CLIVAR (Climate and Ocean: Variability, Predictability and Change)—have prioritized the research and forecasting challenge. Previous reviews state that progress depends on further understanding of the fundamental dynamics of atmospheric circulation features. The following article lays out the current state of the science.

Given the complexity of the atmospheric physics and the importance of the Linkage topic, it is not unreasonable to say that we are in a pre-consensus period and that we should expect diversity, disagreements, and fragmentation of the scientific community. There are two major impediments to scientific progress to provide a definitive answer to Linkages. The first is the large chaotic jet stream variability at mid-latitudes. While north-south temperature differences provide the energy for jet stream winds, strictly west to east flowing winds are not stable on a rotating earth; instabilities cause north-south meanders in the wind pattern and eventually the development of weather systems [high and low pressure centers, regions of rain, snow, etc.]. Since the initiation of such instability is not predictable, meteorologists refer to atmospheric winds as chaotic, random, or based on *internal* variability of the atmospheric flow. When such wavy atmospheric features begin to be established, modern weather forecasting models can project their general evolution out to about a week's forecast, based on the equations of fluid motion. Internal variability is contrast to *forced* variability. Sea surface temperatures (SST) in the tropics and mid-latitude oceans, or warmer than previous conditions in newly sea-ice-free regions, can influence atmospheric temperatures. Warmer air is less dense so that increased temperatures can change the height of constant pressure surfaces and thus influence the wind circulation, as noted in the first paragraph. As these ocean and land conditions can persist, they can be considered as somewhat an external forcing [having a longer time scale] to the more rapidly evolving weather conditions displayed in Figure 1. Because the atmosphere can support waves, the influence of external forcing does not need to remain local but can act at a distance, referred to a teleconnections. As the energy associated with internal variability of mid-latitude weather systems is larger than the contribution of external forcing from potential changes in the Arctic, detection and attribution of an Arctic influence is limited by a small signal-to-noise ratio. This impediment is compounded by the shortness of time series since major Arctic amplification (~15 years) that further makes it impossible to robustly distinguish the influence of Arctic forcing from random events. The second impediment is that there are other potential external forcings of mid-latitude atmospheric circulation driven by tropical and mid-latitude sea surface temperature anomalies.

A goal for extending the time horizon of weather forecasts on a probabilistic basis is to increase Arctic weather data and improve understanding of multiple external forcings and related teleconnections. However, there is at present irresolvable uncertainty whether Arctic Amplification clearly impacts the location and intensities of recent major weather events in mid-latitudes. Major changes in the Arctic are observable and will increase over the next decades. The question remains, how large or small or consistent from case to case will be an impact on weather at mid-latitude from forcing in the Arctic, and can such an impact be recognized?

A recent paper[7] addresses the Linkage issue with the questions: Can it? Has it? Will it? Model evidence strongly suggests that near-surface Arctic warming and sea ice loss can modify the mid-latitude jet stream. Complications arise, however, when one asks how the circulation responds to Arctic warming. The major issues with *Has it?* are the short observational record since Arctic Amplification began and that variability of the mid-latitude wind circulation is substantial. For example, the jet stream position over the Atlantic can vary by up to 10 degrees latitude from year to year based on internal atmospheric variability. There is some emerging evidence from case studies for causal mechanisms for Linkages in Asia between sea ice loss in the Barents-Kara Seas and cold temperatures in eastern Asia. There were also recent cold air episodes penetrating the southeastern United States that were related to shifts in the atmospheric wind pattern over the Pacific and reinforced by warmer temperatures west of Greenland. Some climate models (e.g., the CMIP5 collection used for future projections in the recent IPCC Assessment Report) have difficulty resolving regional atmospheric dynamics important to Linkage mechanisms as a result of poor spatial resolution and lack of detailed Arctic physics such as clouds and sea ice. Different confidence in model projections among scientists result in a wide response to the *Will it?* question.

From a range of model results, there is little support for future seasonal average mid-latitude cooling trends in temperature or increases in the number of extreme weather events over hemispheric or large geographic regions, as shown by Screen et al.[8], Perlwitz et al.[9], and Horton et al.[10] Any future cold event occurs against a background of global and Arctic temperature increases.[4] Results suggest that if Arctic weather Linkages exist they are regional in extent and episodic, even within seasons.[11]

There is evidence for increased variability in December atmospheric wind patterns over the last decade.[12] While limited and quite possibly simply caused by internal atmospheric dynamics, this information about current Arctic atmospheric conditions is different than studies that suggest less weather variability in the future. The Arctic Oscillation (AO) is a single number index used to represent time series of Northern Hemispheric atmospheric wind circulation that implies periods in its positive phase with a strong west-east [called zonal] direction to the wind flow, and a more north-south meander (wavy) wind pattern in its negative phase (Figure 2). During the last five years (2009/10–2013/14), December and January have exhibited twice the expected number of negative AO events, based on the number of cases that meet or exceed 1.0 standard deviation, as well as several large positive AO months. A recent increase in December AO standard deviation based on nine year running means is statistically significant. But time series remain too short to provide definitive proof for or against Linkages.[7,11]

There is emerging evidence of physical mechanisms for Linkages based on case studies in north-central Asia.[13] A series of studies performed with different analyses using observations and model experiments provides evidence of a potential Linkage between regional loss of sea ice in the Barents-Kara Seas north of Eurasia and a tendency that leads to cold temperatures and stormy conditions along eastern Asia. Over the last decade, cold-air episodes in winter have occurred more frequently over east Asia, and they are stronger and last longer during negative phases of the AO than in the 1990s. The chain of causality is complex and is summarized by the conceptual view in Figure 3. The forcing starts with sea ice loss and warmer temperatures in the Kara Sea during recent autumns through winters. Locally warmer Arctic temperatures reduce north-south atmospheric temperature gradients that in turn reduces the strength of the westerly wind. The high pressure region over Siberia is strengthened and cold-air can collect on the east side of this enhanced Siberian High. This cold air can then propagate to Japan, Korea, or China as suggested by the three blue arrows in Figure 3. Such connections are complex, however, involving multiple interacting time scales; loss and thinning of sea ice is on a monthly scale, and multiple cold air movements into eastern Asia are on a weekly scale.

Potential Linkage mechanisms in North America are more speculative. Here, rather than the Arctic initiating mid-latitude weather, it may reinforce specific wind patterns, specifically a wavier jet stream. Internal instabilities in the atmosphere influence the wind pattern over the North Pacific and contribute to whether the downstream wind pattern over North America is primarily zonal or wavy [referred to as a large amplitude ridge-trough pattern in the pressure field]. In addition tropical and mid-latitude sea surface temperature have teleconnections to changes in the mid-latitude atmosphere.[14] Consider the recent December cases (Fig. 2) with large AO of both signs since 2006; weather maps are shown in Figure 4.[12] For reference Figure 4A shows the heights of the historical December mean 700-hPa pressure level (with contours given by colors), with higher heights along the US west coast (yellow) and lower heights in northeastern Canada (blue); winds follow the contours with a bit of a wavy pattern in the historical average for December. Also shown are the composite height *anomaly* patterns for the three recent major negative AO (-AO) events (2009, 2010, 2012) and three positive AO (+AO) events (2006, 2011, 2013) in Figs. 4B and 4C. The magnitudes of the *negative* height anomalies (blue) for +AO cases are centered near Greenland (Fig. 4C); the anomaly pattern can be considered to strengthen the north-south difference in the height of the pressure surface and therefore strengthen the winds from the west of the climatological North American circulation pattern. The *positive* geopotential height anomalies for -AO cases cover a substantial region centered west of Greenland (Fig. 4B), collocated with the minimum height center of the climatology. These positive height anomalies in the -AO cases help cancel the low height center in the climatology, which in turn diverts the height field and the winds into a more wavy pattern. For example in the December 2012 –AO case (Fig. 4D), the north-south wind components at the 850 hPa pressure level reveal a wavy pattern with blue showing the location of winds from the north and red showing winds from the south.

Do changes in near surface Arctic conditions influence the height fields in the –AO cases? The positive low level temperature anomaly fields for the –AO minus the +AO cases over Baffin and Hudson Bay (Fig. 4E), are consistent with the higher heights in the –AO cases west of Greenland (Fig. 4B); these low-level warm temperatures increase the vertical distance between different pressure levels in the atmosphere, which in turn modify wind patterns. With regard to large-scale climate variations, Trenberth et al.[15] notes that thermodynamic forced aspects of change (temperature, water vapor, and sea ice) tend to be robust, i.e. show sustained impacts, while dynamic aspects of atmospheric wind circulation appear to be mostly random and chaotic. Such logic also applies to Arctic-forced Linkages; thermodynamic processes in the Arctic can reinforce a wavy wind pattern. Thus, with two possible Northern Hemispheric wind patterns, zonal and wavy, one does not necessarily develop the same mid-latitude weather Linkage response from similar Arctic forcing. The appearance of Arctic Linkages can be said to be *state dependent* based on the random variability of which large-scale atmospheric wind pattern is dominant at any given time.

Model studies can show either an Arctic/mid-latitude Linkage or no effect, based on computer runs with similar initial conditions.[16] Screen et al.[17] concluded that it would take 50 years for the forced signal from the Arctic to be clearly seen in the large-scale winds, distinguishable from internal variability. Even rather well-accepted climate models can have difficulties capturing some of the regional atmospheric dynamics associated with Linkages. In a recent comparison of results from two models and two data sets that assimilate observations into spatial fields, models compare poorly with observations near 60° W longitude[18], which is the critical region for potential Arctic Linkages to eastern North America. It is questionable whether results from models are yet definitive in proving or disproving recent potential Linkages.

It is not unreasonable to include information on recent Arctic change such as sea ice loss and changes in atmospheric variability, as prior information in addressing the potential for contributions to, but not to dominate, future extreme weather over the next few decades. Beyond that time horizon mid-latitude weather impacts depend on future CO2 emission scenarios, and it is projected that continued global increases in temperature will dominate[4].

If we focus on the goal of improving extended-range forecasts, one should consider an emergence of a contribution of Arctic change forcing on mid-latitude weather as an important research challenge. This goal will require increasing Arctic observations and data assimilation, and improving Arctic-specific physics in models. There is a major need to increase the limited observations in Arctic regions to help initialize weather forecast models. The doubling of Arctic Amplification over the next decades provides an incentive for improving extended range weather forecasts (weeks to months), despite the controversy about mechanisms for Arctic/mid-latitude weather Linkages.

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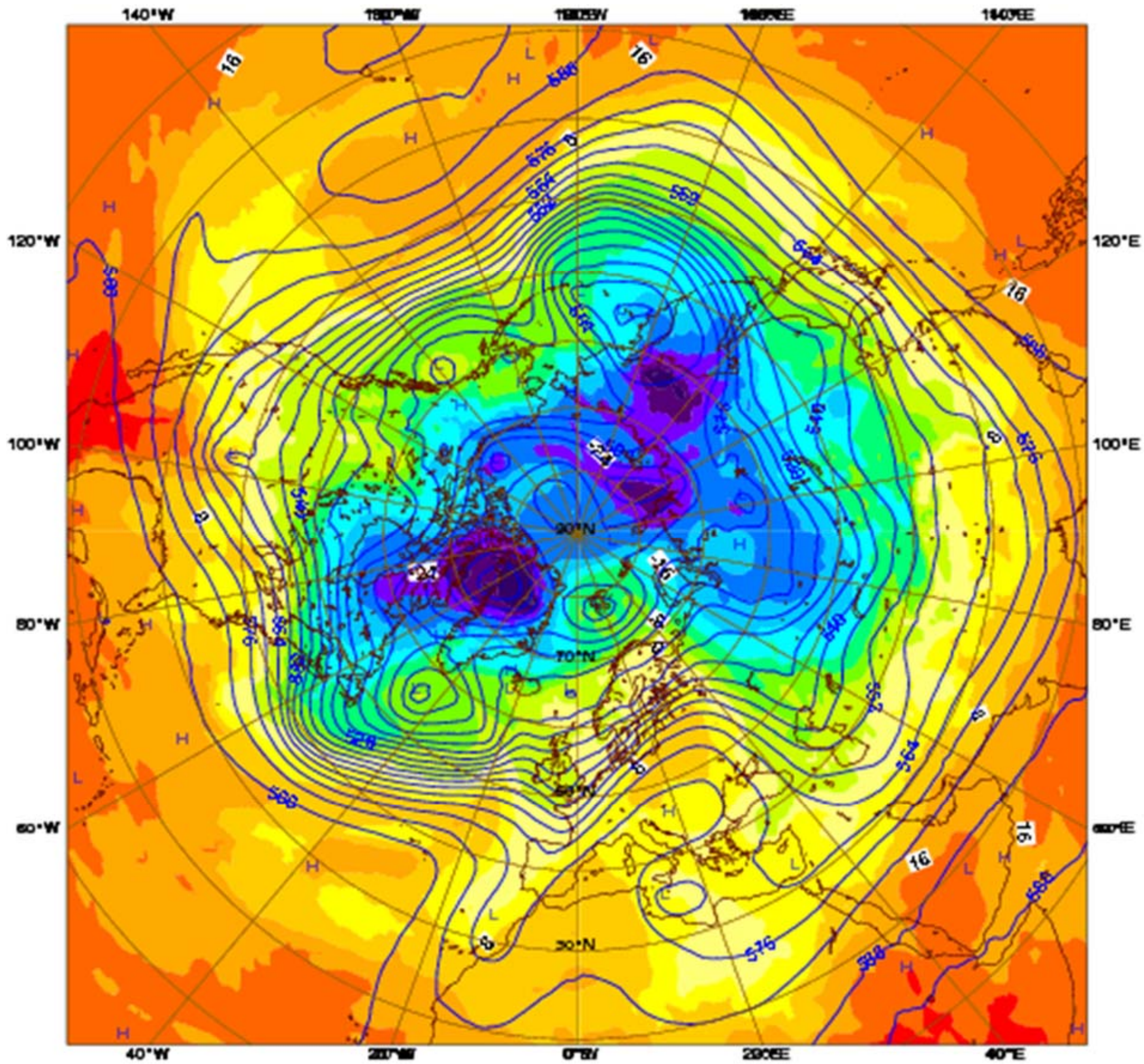

Figure 1 Weather map for 21 December 2015. Continental outlines are provided with North America to the left and Europe in the center bottom. Line contours are the geopotential height of the 500 hPa pressure surface at about 5.5 km above sea level; contours provide the direction to the wind and the contour separation is inversely proportional to wind speed (close contours have greater speeds). Colors proved contours of temperature at the 850 hPa altitude level with colder temperatures in blue and purple. From ECMWF.

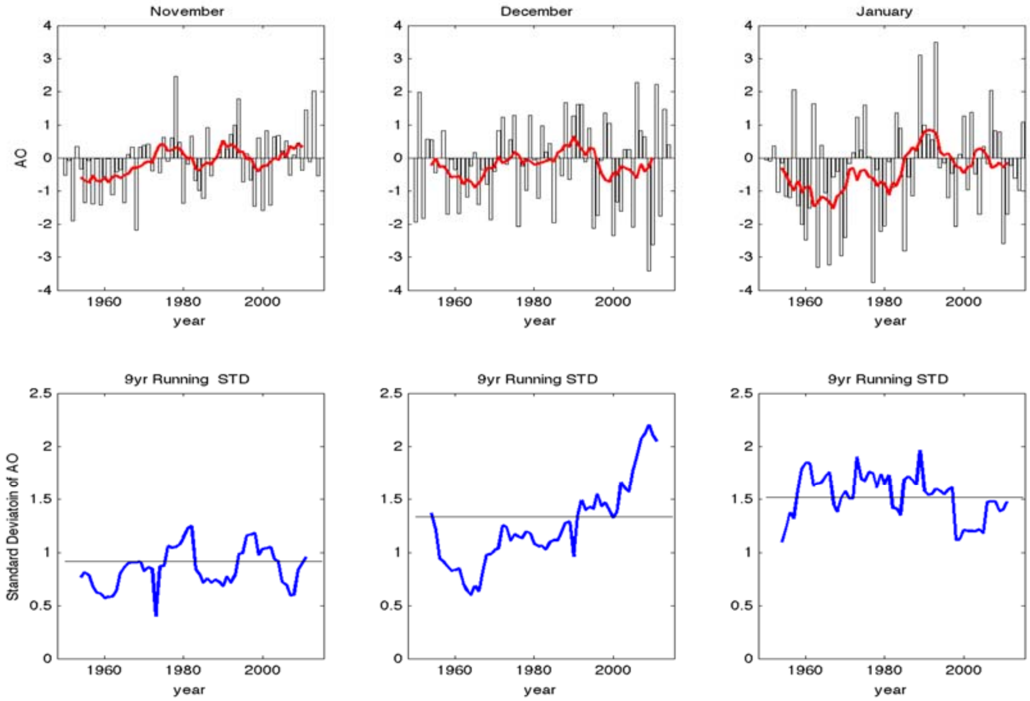

Figure 2. (top) November, December, and January monthly Arctic Oscillation (AO) index values and 9-yr running mean (red), and (bottom) running standard deviation (SD, blue)[12]. The horizontal line is the mean for the record. The AO index gives a rough indication whether Northern Hemispheric wind patterns are more straight west to east (positive AO) or more wavy (minus AO). The data are from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml.

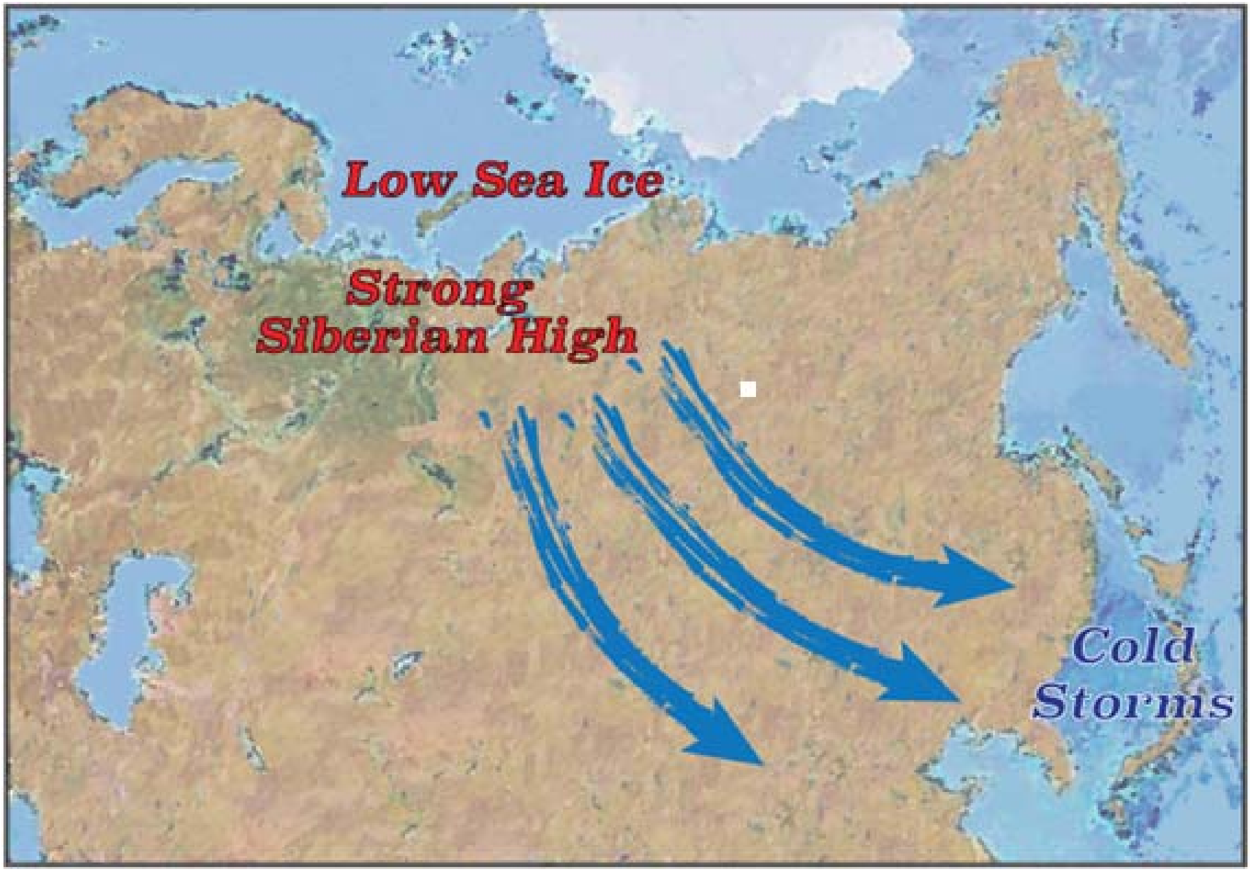

Figure 3. Conceptual model of potential Linkage between loss of sea ice north of western Siberia and movement of cold air into eastern Asia. Loss of sea ice is associated with warmer local temperatures, which in turn reduce the north-south temperature gradient. This reduction in gradient works against the speed of the jet stream, which allows for the strengthening of the Siberian high pressure region. With a stronger Siberian High, cold air weather systems (Blue lines) can form east of the High and propagate into Japan, Korea, or China. This conceptual model is based on observations and model studies from a number of journal articles.[13]

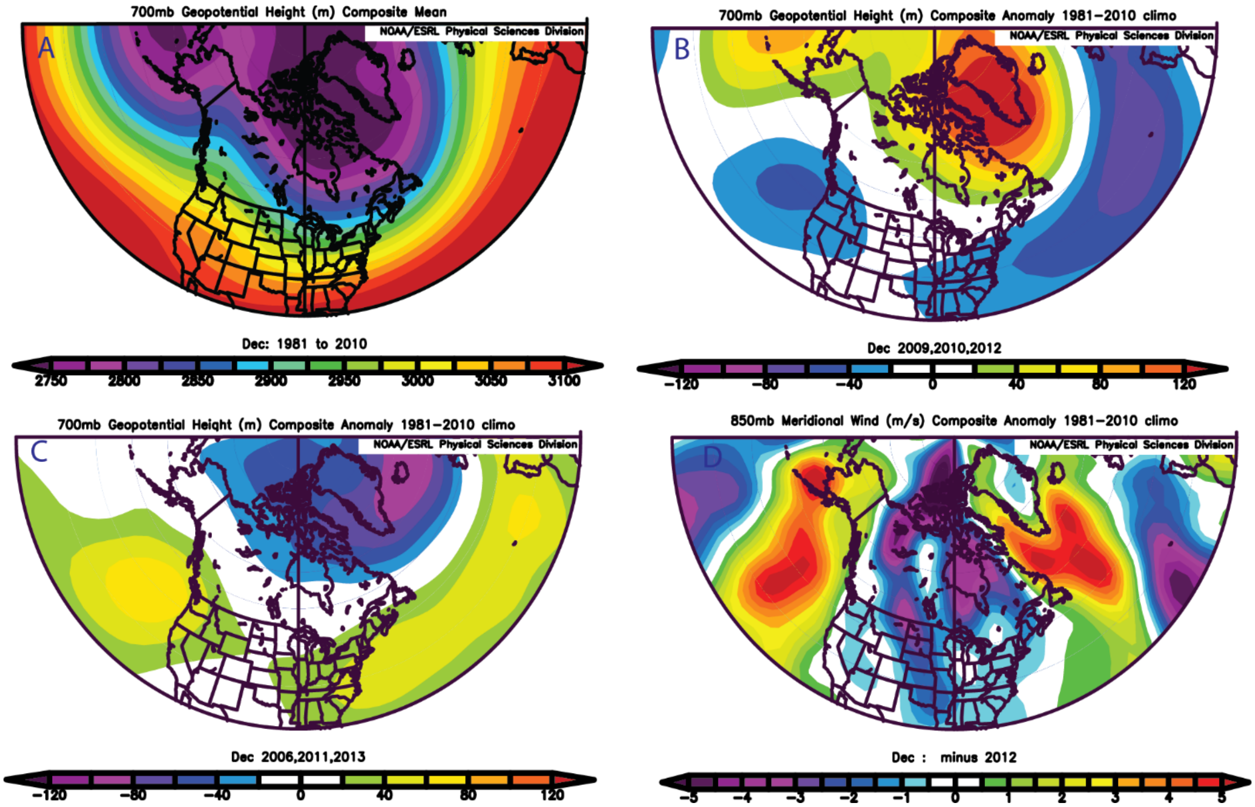

Figure 4. A) December climatic mean of geopotential heights for the 700 hPa pressure surface over North America. Lower heights are to the north providing for primarily winds from the west. (B &C) Composite of height anomalies for three months of recent -AO (Dec. 2009, 2010 and 2012) and +AO (Dec. 2006, 2011, 2013). (D) Meridional (north-south) wind component at the 850 hPa showing a "wavy" pattern for Dec 2012;[12] blue regions are winds from the north. Potential Linkages in North America are dependent on the state of the jet stream, whether the winds are strong flowing from west to east (zonal) or take a wavy pattern. Which pattern develops over North America depends in part on the upstream conditions over the North Pacific and whether these patterns are influenced by mid-latitude and tropical sea surface temperatures. The more stationary wavy pattern allows the air mass to be further modified by Arctic conditions west of Greenland. Thus, the same Arctic forcing does not necessarily produce the same impacts every year or even with a winter season.

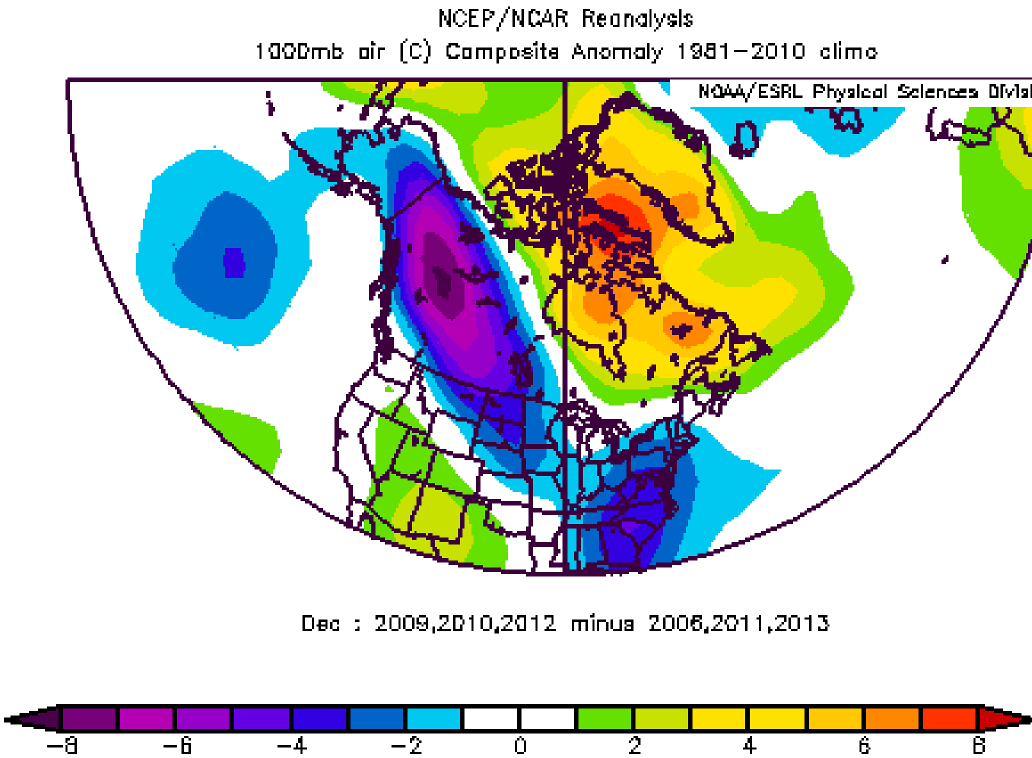

Figure 4E. Near-surface air temperature anomalies for three recent Decembers when the Arctic Oscillation index was negative, favoring a wavy jet steam pattern, relative to three Decembers when the winds were more zonal.[12] Positive temperature anomalies west of Greenland help to reinforce the wavy wind pattern. A resultant northerly wind component is associated with cold air anomalies in central Canada and southeastern U. S.