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# Amplified Arctic Warming and Mid-Latitude Weather: New Perspectives on Emerging Connections

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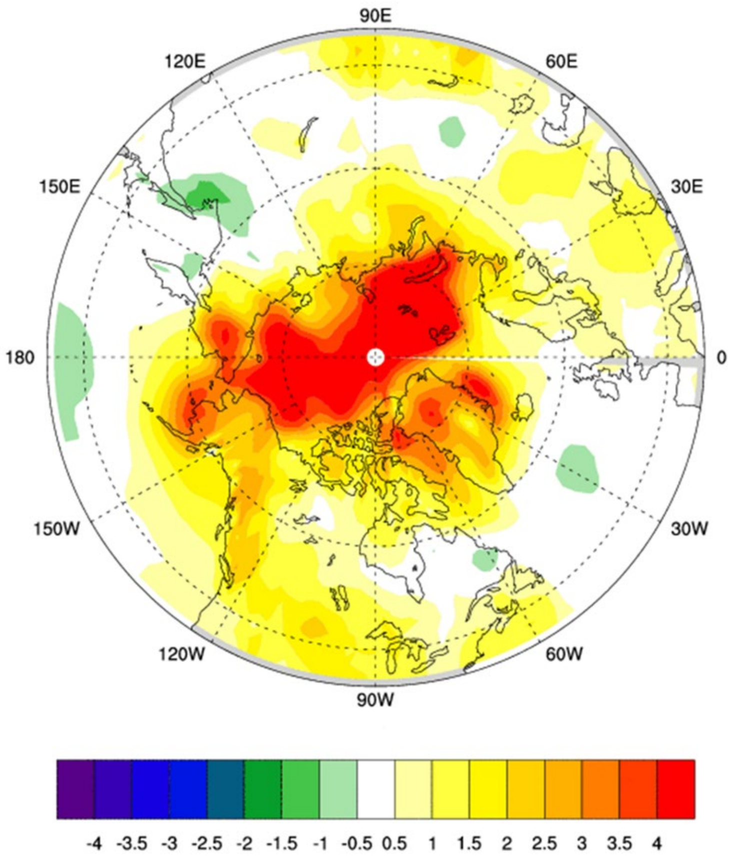
### Abstract

The Arctic is warming and melting at alarming rates. Within the lifetime of a Millennial, the volume of ice floating on the Arctic Ocean has declined by at least half. The pace of Arctic warming is two-to-three times that of the globe; this disparity reached a new record high during 2016. While the Arctic spans only a small fraction of the Earth, it plays a disproportionate and multifaceted role in the climate system. In this article, we offer new perspectives on ways in which the Arctic's rapid warming may influence weather patterns in heavily populated regions (the mid-latitudes) of the northern hemisphere. Research on this topic has evolved almost as rapidly as the snow and ice have diminished, and while much has been learned, many questions remain. The atmosphere is complex, highly variable, and undergoing a multitude of simultaneous changes, many of which have become apparent only recently. These realities present challenges to robust signal detection and to clear attribution of cause-and-effect. In addition to updating the state of this science, we propose an explanation for the varying and intermittent response of mid-latitude circulation to the rapidly warming Arctic.

## Graphical/Visual Abstract and Caption



**An unusually warm Arctic during 2016: a preview of a 2°C warmer world?** Rapid Arctic warming is expected to affect weather patterns around the northern hemisphere, but exactly how, where, and when is a rapidly evolving research topic. This image shows departures from normal of near-surface air temperatures (°C) during 2016. Baseline is 1981-2010; data are from the NCEP/NCAR Reanalysis at http://www.esrl.noaa.gov/psd/.

## Introduction

Extreme weather events have generally occurred more frequently in recent decades (1). The looming question – asked by the media, public, and scientists alike – is which of these increases can be attributed to human-caused climate change, and what are the mechanisms? One possible factor is the rapid and amplified warming of the Arctic. A flurry of new research suggests it is increasing the likelihood of persistent atmospheric patterns that can lead to extreme weather events in temperate latitudes (2), but consensus is still elusive (3).

The recent pace of systemic Arctic change is staggering. For example, about 50% of the summer ice extent and 60% of the volume have disappeared within a generation (4), and the ice cover is now the smallest it has been in at least 1400 years (5). Less obvious but equally worrisome is the expanding surface melt area on the Greenland ice sheet (6), which has increased from a summer-mean of about 35% in the 1980s to 45% since 2010 (M. Tedesco, pers. comm.). Springtime terrestrial snowcover has also declined precipitously (7), which is accelerating the degradation of permafrost over much of the Arctic tundra (8) and exacerbating high-latitude wild fires. These clear signals of anthropogenic climate change both contribute to and result from amplified Arctic warming (AAW), evident as rising near-surface air temperatures in the Arctic exceed those of mid-latitudes by a factor of at least two since the late 1990s (9). Change in the Arctic during 2016 was particularly stark (10). In addition to record-breaking losses of sea ice and spring snow cover, AAW reached a new high value (**Fig. 1**). Records are even more striking for the winter months (Jan.-Mar.) in the Arctic (**Fig. 2**): not only were near-surface temperatures the highest since 1948, but upper-level geopotential heights (not shown) and atmospheric water vapor content broke records, as well. Rising trends in water vapor are notable for their enhancement of the greenhouse effect, clouds, and precipitation.

Positive feedbacks involving ice and snow are primarily responsible for the Arctic's elevated sensitivity to warming (11-13). While AAW is strongest in lower atmospheric layers, the expansion of warmer air raises pressure levels aloft, thereby reducing poleward geopotential height gradients. Because these gradients are a primary factor in driving upper-level zonal (west-east) winds via the thermal wind relationship, reduced speeds are typically found south of the areas with geopotential height increases, which can vary greatly by season and location. This relationship has been noted in recent observations (14) and model-simulated responses to sea-ice loss (15, 16).

It has been hypothesized that weaker upper-level zonal winds and raised atmospheric pressure levels owing to AAW will affect the polar jet stream such that large north-south undulations will increase in amplitude and/or frequency; these larger waves move more slowly eastward (2). Slower wave progression causes more persistent weather regimes that often lead to various types of extreme weather associated with long-lasting conditions (e.g., droughts, cold spells, heat waves, flooding, and snowy winters) (17). Clearly, an understanding of how the recent warming of the globe and associated AAW might affect extreme weather in the region of the Earth where billions of people live is of great economic and societal importance.

Since this hypothesis was proposed in 2012, many researchers have set out to test it using observations, model simulations, or a combination of the two. Despite the plethora of new work, debate still rages on. The intent of this article is to offer fresh perspectives about interactions between AAW and naturally occurring variations in the climate system in hopes of reducing some of the ongoing controversy surrounding the topic of Arctic/mid-latitude linkages; it is not to provide a comprehensive update of recent literature since the assessment in this journal by Barnes and Screen (17). Instead we are presenting our viewpoint, while acknowledging that contrasting viewpoints exist (e.g., 18, 28, 48 and references therein). Specifically, we suggest that seasonally varying AAW can intensify or dampen atmospheric responses to influences from lower latitudes, depending on the proximity of regional AAW to natural variations in the configuration of the jet stream.

## AAW of the recent past

A fundamental relationship in atmospheric dynamics relates the strength of north/south temperature gradients with vertical wind shear and, consequently, westerly wind speeds (19). While AAW clearly reduces gradients and thus weakens upper-level zonal winds (20-23), the hypothesized connection with wavier jet-stream configurations is less clear (24, 25). Some studies, based on both observations and model simulations, have associated AAW with the negative phase of the Arctic Oscillation (AO) (26-31), which tends to exhibit a wavier jet-stream character (32). The linkage is not consistent, however, as AO is often not a good indicator of the hemispheric-wide jet character. Indeed, idealized model simulations demonstrate that the relationship between AAW and the AO is not reliable (33), and various effects on jet-stream position are complex and often competing (34, 35). Evidence is emerging, however, that the upper-level flow has become more meandering in recent decades (26, 27), although the cause(s) is unclear.

Separating the large-scale circulation responses to AAW from those of other natural and/or forced variations in the climate system is challenging The chaotic nature of the atmosphere – together with factors such as natural large-scale fluctuations (e.g., El Niño/La Niña), other concurrent climate changes that can even strengthen jet streams (e.g., enhanced tropical warming), and the only recent emergence of AAW -- create challenges in detecting robust shifts in jet-stream behavior. New theoretical insight into planetary wave dynamics has emerged that supports the existence of an inverse, non-linear relationship between zonal wind speed and jet-stream wave amplitudes (36, 37). Further model simulations of varying complexity have also demonstrated the influence of sea-ice loss on temperate weather patterns (38-41), while other new studies addressing the same question find no robust linkage (42-45). One likely reason for this ongoing dispute is the assumption by some investigators that sea-ice loss can be used as a proxy for AAW in forcing an atmospheric response in model simulations (42, 46), when in fact it accounts for only a fraction of AAW (12, 43). It is not surprising, therefore, that weak responses may result from atmospheric model simulations that are forced only with sea-ice loss (e.g., 43,45).

Another source of discrepancy may arise from inadequate representation of interactions between AAW and influences from lower latitudes. It is becoming clear that the atmosphere's response to AAW is dependent on the basic state of the climate system (47-50), which is the underlying premise of the specific Arctic/lower-latitude interaction we call "It Takes Two to Tango." For example, the regions of substantial losses in sea-ice coverage and strong AAW vary from year to year, which in turn causes different boundary forcing that elicits distinct atmospheric responses (15, 40, 42, 51). The notion of state dependence is that the atmosphere must be "primed" by other factors, which raises interesting questions about relationships between AAW and natural variability in the climate system (48).

Case in point: several new studies have corroborated the connection between sea-ice loss in the Barents/Kara seas, located northeast of Scandinavia, and cold winters in eastern Asia (20, 28, 38, 39, 51-53), while others do not (42, 45). Lower-latitude factors may provide an initial trigger for the ice loss (55-58), and it is likely that local positive feedbacks amplify the effects of those triggers. The proposed linkage mechanism goes like this: In the area of ice loss during summer (owing to some combination of mechanical wind forcing, poleward heat transport, and additional downwelling longwave radiation, 56), additional solar energy is absorbed, and resulting high sea-surface temperatures (SSTs) further warm the lower atmosphere during autumn, which dilates atmospheric layers upward. If a jet-stream ridge forms near eastern Europe, the elevated heights caused by AAW over the Barents/Kara Seas intensify the ridge, which strengthens the surface high-pressure area that forms east of the ridge axis -- in this case, over western Russia. The so-called Siberian high draws cold air southward over Siberia, promoting earlier snowfall and depressing the jet stream southward over central and east Asia. A larger ridge/trough wave results, which according to Rossby theory (19), progresses eastward more slowly and favors more persistent weather conditions. Wave energy from the amplified jet stream then propagates upward into the stratosphere, which can disrupt the polar vortex from its typically quasi-circular path, helping to maintain a wavy jet stream well into the depths of winter (28, 38; sidebar). The two key ingredients in this "two-to-tango" mechanism are 1) a jet-stream ridge, and 2) that the ridge is located near the area of strong AAW. Either of these conditions alone may be insufficient to trigger the chain of events that leads to an amplified jet-stream configuration associated with persistent cold spells in central and east Asia and abnormally warm conditions in northwestern Europe, and other factors may interfere even if both ingredients exist. A schematic illustrating the mechanism can be found in (28).

A similar mechanism has been identified linking anomalous Arctic warming near Alaska with persistently cold winters in eastern North America during 2013/14 and 2014/15 (41, 51). As in the Eurasian connection, two main factors are needed to tango: Pacific-sector (Chukchi/Beaufort Seas) sea-ice loss along with a collocated ridging in the eastern Pacific. In late 2013 the Pacific Decadal Oscillation (PDO) shifted abruptly from a negative to positive phase, resulting in abnormally warm ocean temperatures along the northwest coast of N. America. A positive PDO favors ridging along the N. American west coast (**Fig. 3,** left), consistent with model simulations forced by SST patterns like those prevailing in winter 2013/14 (41, 58, 59). Also occurring that fall/winter were anomalously warm surface temperatures in the Chukchi Sea region associated with a below-normal sea-ice cover, which further dilated upper-level atmospheric heights and intensified ridging in the area (41, 47, 51). Years with a positive PDO and above-normal surface temperatures in the Chukchi Sea region exhibit stronger ridging near Alaska and deeper troughing in eastern N. America (**Fig. 3**, middle) compared with years that exhibit below-normal Chukchi temperatures (**Fig. 3**, right). A schematic illustrating the relationship between the position of a naturally occurring ridge and above-normal Chukchi temperatures is presented in **Fig. 4**. This "Two to Tango" scenario is believed to have exacerbated the observed persistent warmth and drought in the western U.S. along with cold spells in the east during winters of 2013/14 and 2014/15 that were popularized as the Ridiculously Resilient Ridge and Polar Vortex (**Fig. 5**; 60). We submit that neither of these factors alone may have been enough to elicit the extreme jet-stream pattern that dominated for nearly two years, but rather that the regional AAW associated with a reduced ice cover in the Pacific sector of the Arctic helped amplify the existing ridge associated with a positive phase of the PDO. Clearly additional model simulations are needed to test this hypothesis.

New methods and metrics reveal that highly amplified jet-stream conditions appear to be occurring more frequently since the advent of AAW (14, 26, 27, 31), and blocking highs may be occurring more frequently in the North Atlantic (61), perhaps in response to sea-ice loss (62). Other recent studies focused on attribution of summer extreme weather events suggest that continental jet streams tend to split and stagnate under conditions of weak zonal flow (63, 64) and that surface pressure features are weakened as poleward gradients decline (22), both of which favor persistent heat waves and flooding events. New work also reveals changes in the relative importance of the tropics versus AAW in influencing recent shifts in the mid-latitude circulation. Particularly timely are findings that report a robust wintertime relationship between winds and temperature over land, and the loss (advance) of sea ice (Eurasian snow cover), while the correlation with the El Niño/Southern Oscillation Index (ENSO) is absent (65). These findings support previous analysis (66) that suggests the role of AAW has recently become dominant over ENSO in driving winter continental weather patterns. **Figure 6** (from 65) illustrates the relative importance of influences from the Arctic (**Fig. 6b**) versus ENSO (**Fig. 6c**) in explaining recent trends in zonal winds and temperatures over northern-hemisphere continents during winter (**Fig. 6a**). The striking similarity of **Fig. 6b** to observed trends, along with the striking *lack* of similarity between **Figs. 6c** and **6a**, suggests that ENSO's influence is relatively weak.

Model simulations offer conflicting results and raise questions about not only the observational analysis but also the experimental design and/or the ability of some models to capture the full impacts of AAW, as many studies only include effects of shrinking ice cover but exclude impacts of thinning sea ice, heat transport from lower latitudes, varying lower-latitude SST patterns, and/or troposphere-stratosphere coupling (42-46, 67, 68). Disparate conclusions also arise from differences in model formulation, experimental design, and diagnostic techniques.

## AAW of the Future

There is no question that a further accumulation of greenhouse gases will be accompanied by a continuation of downward trends in the coverage of sea ice (69) and spring snow extent (70), upward trends in temperatures and AAW, and losses of land ice and permafrost. These changes are already profound, and their impacts are already conspicuous. Recent observations imply that the climate system is tracking along the "business-as-usual" or worst-case future scenario (RCP 8.5), one set of conditions used to model the Earth's trajectory in coming decades. As the climate system advances farther into uncharted territory, it is widely expected that unforeseen surprises and abrupt events will occur, particularly when it comes to the ecosystem (71).

While there is little uncertainty about *whether* AAW will affect northern hemisphere weather patterns, there is considerable uncertainty as to *how* and *how much*. Many factors – both natural and anthropogenic – affect the jet streams, and these factors vary by region and season. In addition to amplification of Arctic warming, models are consistent in projecting amplified warming in the tropical upper troposphere (18). Unlike AAW, which reduces the poleward temperature/height gradient, this feature will *increase* the equator-to-pole gradient and therefore will constitute a competing effect on the influence of AAW. This "tug of war" has been recently explored further, suggesting that the tropical influence may dominate in the future (26, 72). It should be noted, however, that two jet streams often exist, particularly in winter. The weakened gradient owing to AAW will affect primarily the polar jet stream, which dictates much of the weather in mid-latitudes, while the strengthened gradient owing to upper-level tropical warming will influence primarily the sub-tropical jet. While the two jets are sometimes indistinct, analyses of the atmosphere's response to AAW should focus on the polar jet. A possible example of differing influences by the two jets may have occurred in this past winter of 2015/16: it has been suggested that the low skill of the seasonal weather forecast – based heavily on past patterns during strong El Niños -- may have been due in part to the influence of strong regional AAW and/or a disrupted polar vortex, which were not observed during previous episodes of strong El Niño events (73).

Many new studies using simulations by a variety of models have addressed the mechanisms by which AAW affects future mid-latitude weather. An emerging conclusion is that non-linear effects are critical for realistically simulating Arctic/mid-latitude linkages (48), and that these effects may not be captured sufficiently by models. For example, without a coupled ocean (15, 16), realistic stratosphere (74), and sea-ice thickness distribution (23), only a muted influence is simulated (42, 44, 45). Other new work finds that AAW must extend throughout the troposphere for it to have a significant influence on the large-scale circulation, indicating that boundary-layer processes must be accurately represented (43, 46). Highly non-linear blocking events are simulated reasonably well by only a few of the CMIP5-generation models (75), and their association with AAW is also model-dependent (72, 76).

A variety of profound changes in the climate system is expected as greenhouse gas concentrations continue to exceed values not seen on Earth for millions of years (77). Understanding exactly how these changes will influence jet streams is a societally critical and rapidly evolving research topic, as changes in the types, locations, frequency, and severity of extreme weather events will have major impacts on economies, ecosystems, and political stability. Progress in this line of research has been steady, but more work is needed to design model experiments that incorporate the full signal of AAW (not only sea-ice variability), identify appropriate metrics, develop methods to attribute responses to causal forcing, and improve model simulations of certain non-linear processes that affect projections of large-scale atmospheric shifts.

## Figures and Captions

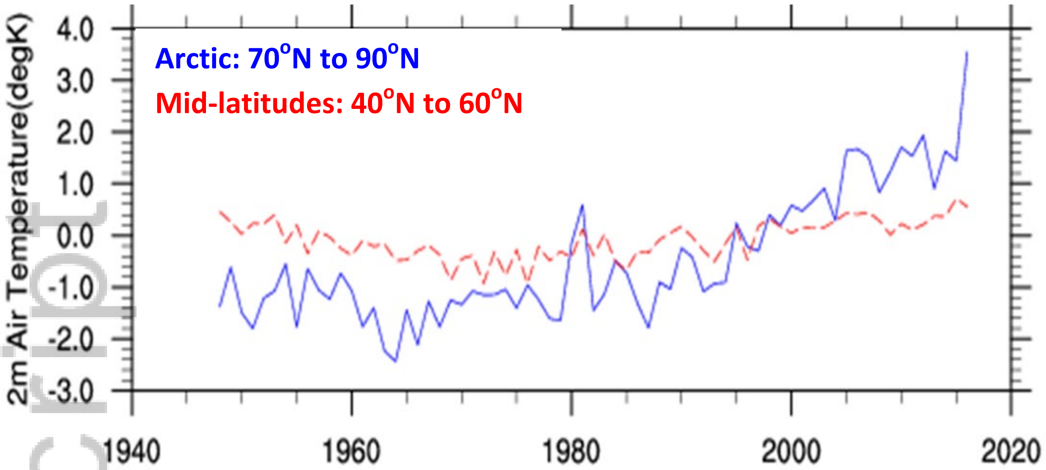


**Figure 1:** Near-surface air temperature departures from normal (relative to 1981-2010) during January-December in the mid-latitude zone (red dashed; 40°N to 60°N) and the Arctic (blue; 70°N to 90°N) from 1948 to 2016. Data obtained from the NCEP/NCAR Reanalysis at http://www.esrl.noaa.gov/psd/.

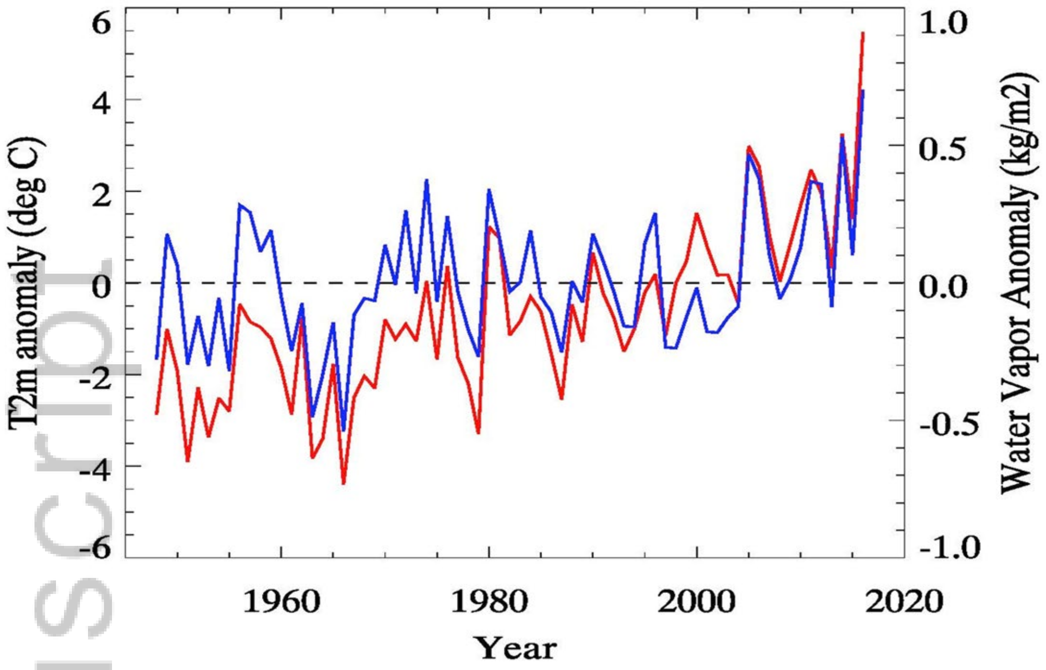


**Figure 2:** Red: Winter (JFM) near-surface air temperature anomalies (relative to 1980-2010) in the Arctic (70°N to 90°N) from 2010 to 2016. Blue: same but for atmospheric water vapor. Data obtained from the NCEP/NCAR Reanalysis at http://www.esrl.noaa.gov/psd/.

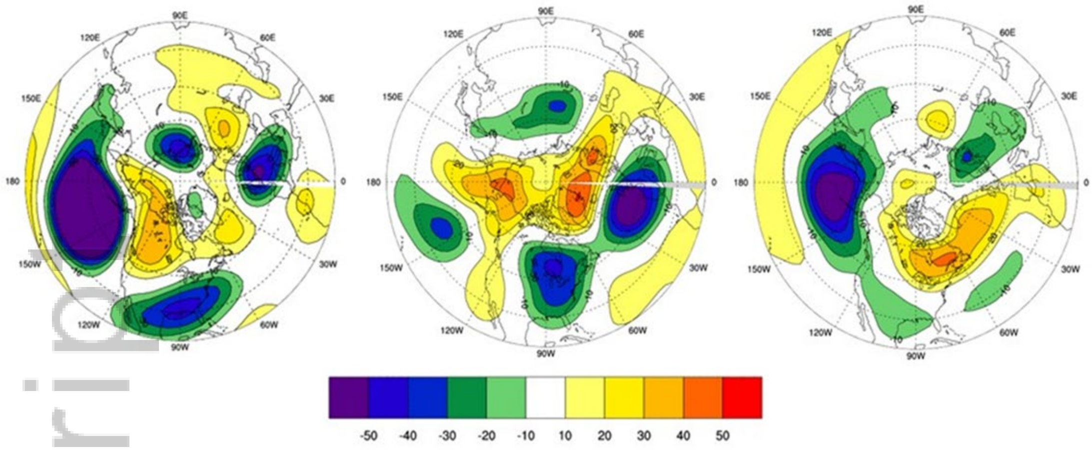


**Figure 3:** Composited 500 hPa heights (m) during JFM for (left) positive-minus-negative phases of the PDO (1983, 1984, 1986, 1987, 1988, 2003, 2015 minus 1989 1991, 2000, 2008, 2009, 2011, 2012), (middle) anomalously warm surface temperatures in the Chukchi Sea region during a positive PDO (1994, 1996, 2003, 2010, 2014), and (right) same as middle but for anomalously cold Chukchi temperatures (1987, 1988, 1998, 2000). Chukchi Sea region defined as in (51). Data obtained from the NCEP/NCAR Reanalysis at http://www.esrl.noaa.gov/psd/.

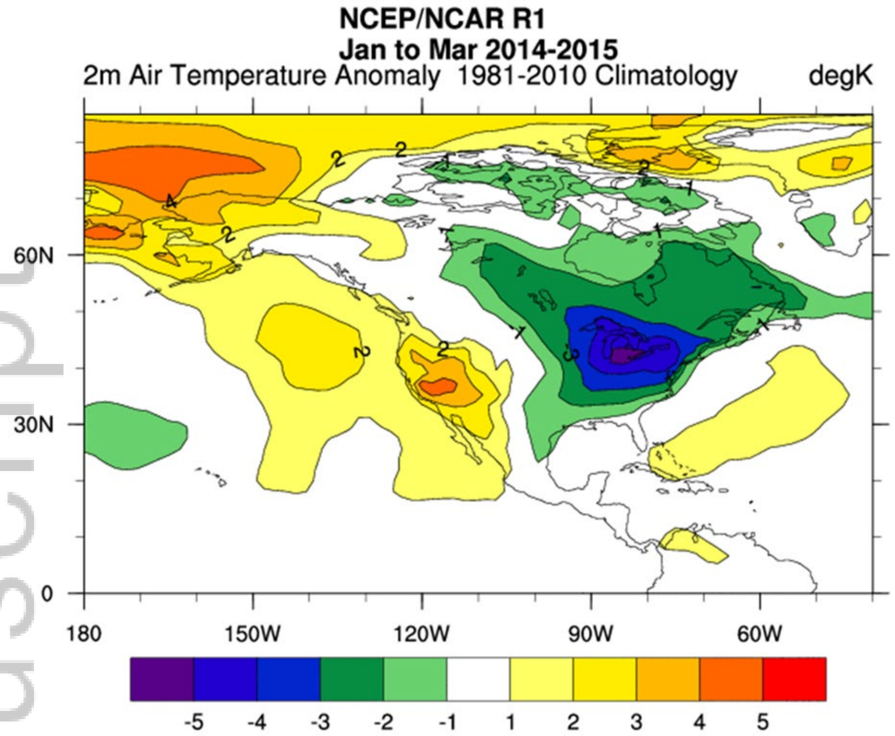


**Figure 5:** Near-surface air temperature anomalies for JFM during winters of 2014 and 2015. Data obtained from the NCEP/NCAR Reanalysis at http://www.esrl.noaa.gov/psd/.

**a** Trend Zonal Wind/Temp DJF 88/89-14/15

**b** Regress SIE&SAI and Zonal Wind/Temp DJF 88/89-14/15

**c** Regress ENSO and Zonal Wind/Temp DJF 88/89-14/15

## Sidebar title: **Polar Vortex: Bridge between AAW and severe mid-latitude winter weather.**

The polar vortex (PV) is a deep low-pressure center in the upper atmosphere (between ~10-50 km) that sits near the North Pole during winter and is encircled by a fast river of westerly wind known as a jet (1). It is strongly coupled with surface weather (2, 3). The PV forms during fall, at which time the vertical propagation of either wave energy or wave drag can accelerate or decelerate the mean flow (4) and consequently precondition the PV for the following winter (5).

Diminished Arctic sea ice in the Barents/Kara Seas and/or extensive Eurasian snow cover during fall may favour changes in the planetary waves that constructively interfere to weaken the PV (6). These Arctic influences appear to promote an atmospheric pattern that features troughing (low upper-level heights) over East Asia along with ridging (high heights) near the Urals (7). This amplified wave configuration favors strong vertical propagation of wave energy from the troposphere into the stratosphere (6).

Enhanced upward wave propagation tends to disrupt the PV, which creates circulation anomalies that appear first in the stratosphere then subsequently propagate downward in winter, creating a "memory mechanism" that prolongs the initial forcing by sea-ice loss and expansive snow cover. These circulation anomalies take the form of ridging and/or blocking in high latitudes along with a weaker and south-shifted polar jet stream. Surface high-pressure over the Arctic tends to increase, and the wavier jet transports mild air northward, further warming the Arctic. Over mid-latitude continents, meanwhile, persistent cold spells are favored along with a greater likelihood of snowstorms in the population centers of the NH mid-latitudes.

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## Conclusion

The Arctic continues on its rapid trajectory of melting and warming, punctuated by new records during 2016. The influences of these changes on the Arctic itself and on regions well beyond its borders are only now coming into focus. Ecosystems are shifting as sea ice allows light to penetrate oceans that were previously nearly dark, infrastructure is crumbling as permafrost decays, sea-level rise is accelerating as Arctic glaciers and the Greenland ice sheet recede, and various living things are shifting their territories and seasonal migrations in response to disrupted habitats. Some of these changes were expected, but in many cases the pace has come as a surprise. More surprises and abrupt shifts are virtually certain. Understanding the effects of physical Arctic change on weather patterns in temperate latitudes presents a substantial challenge, especially as other aspects of the climate system undergo natural fluctuations and human-induced alterations. Recent studies of these processes are parting the clouds of uncertainty, but there is still much to learn in terms of the mechanisms linking AAW with lower-latitude factors, all of which influence jet streams and weather patterns.

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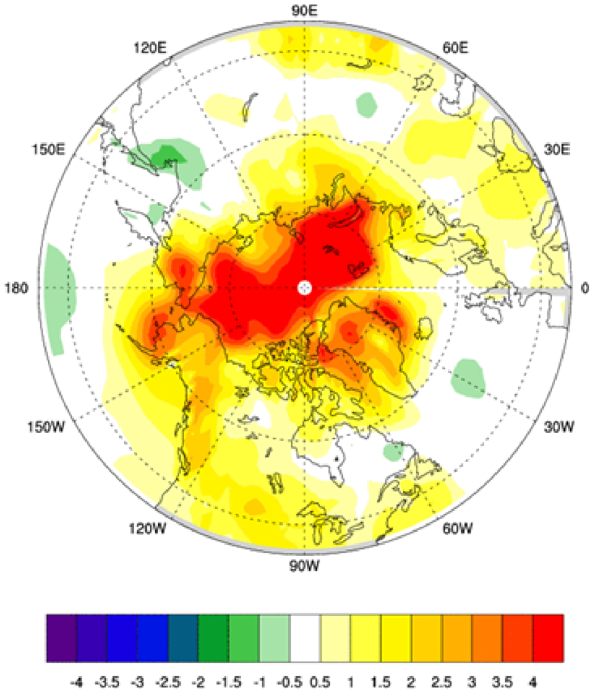

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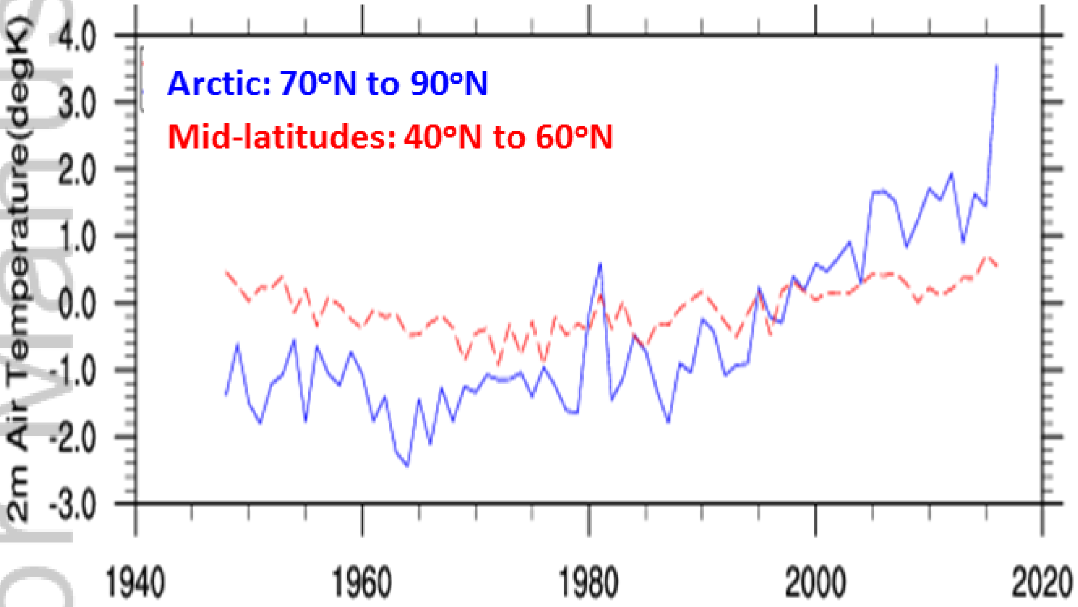

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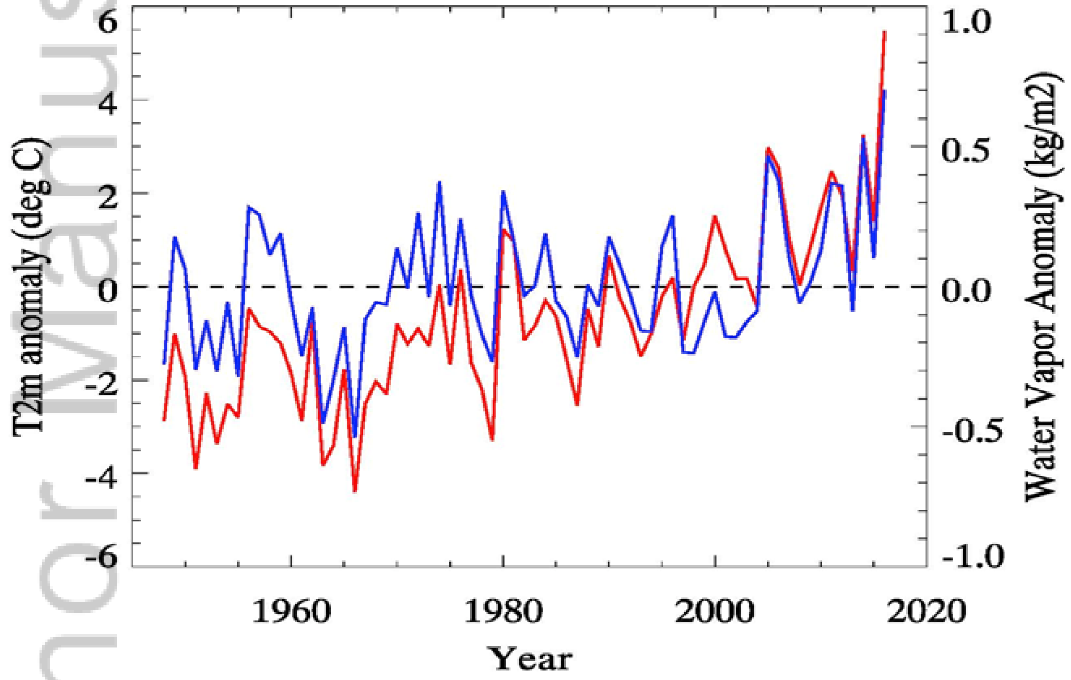

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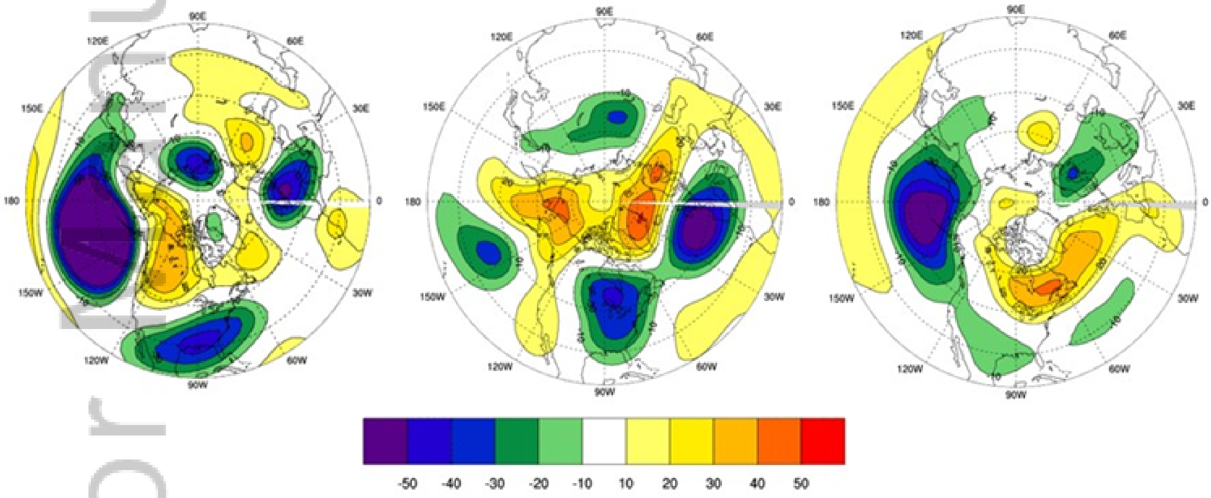

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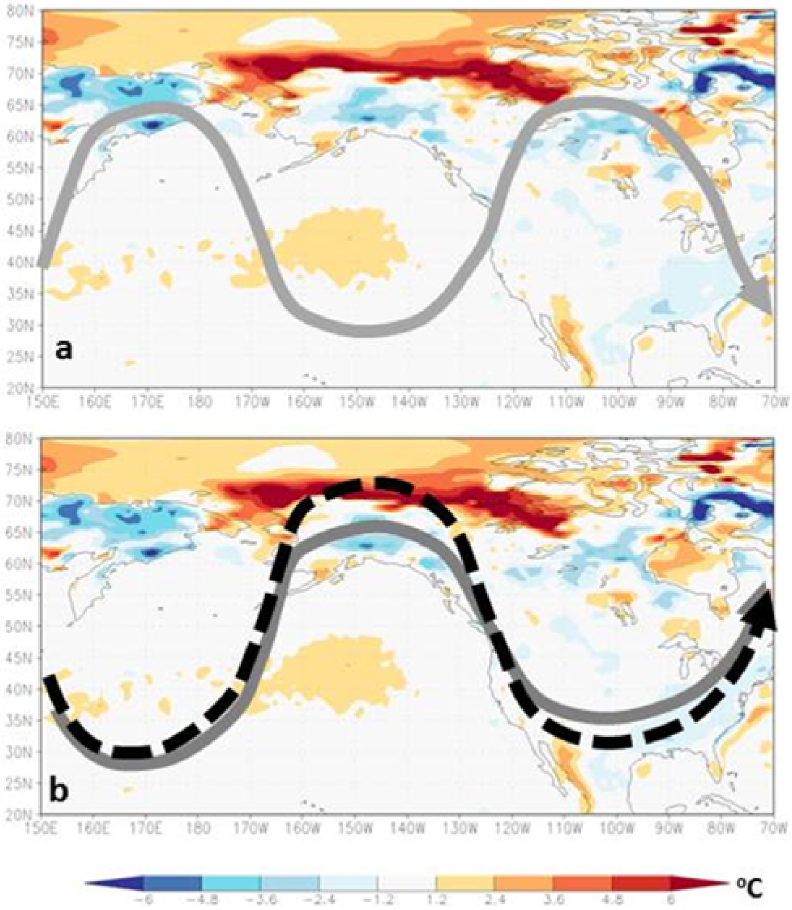

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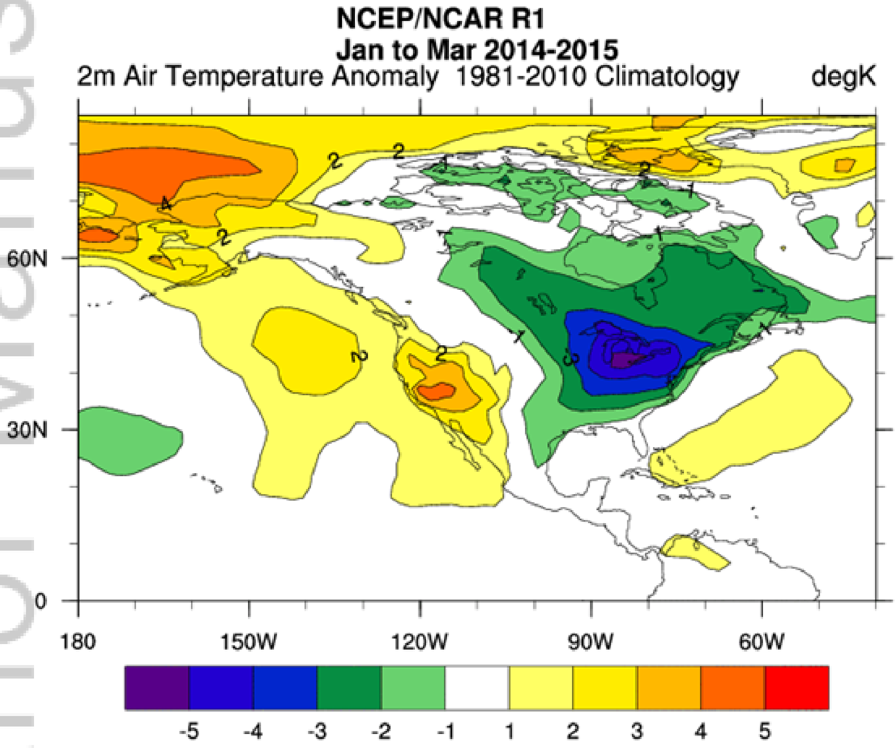

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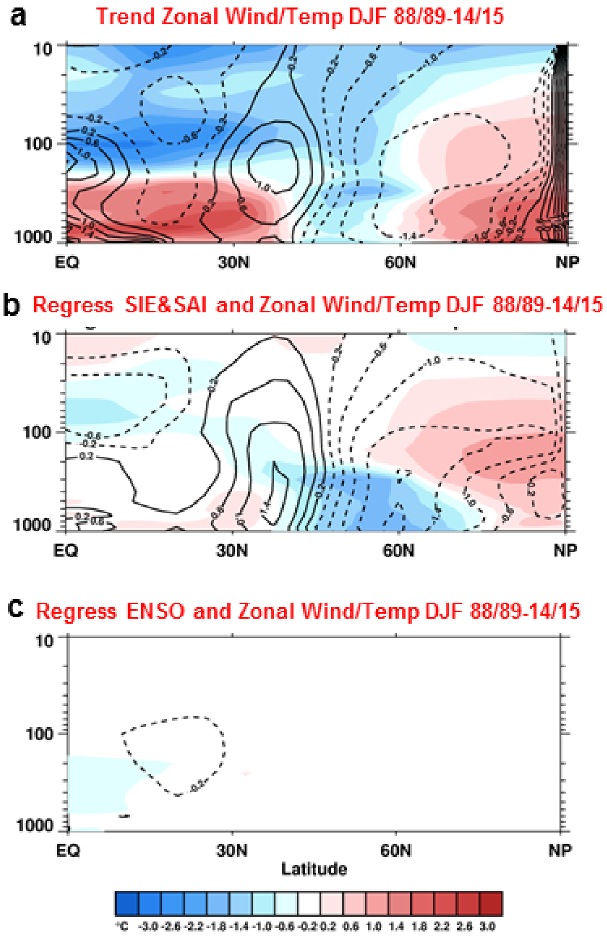

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