Communicating Arctic-midlatitude weather and ecosystem connections: direct observations and sources of intermittency

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Abstract

There is controversy over the extent that Arctic change can influence midlatitude extreme weather and vis-à-vis. Part of the uncertainty is due to the intermittency of the connection through the jet stream and polar vortex that leads to different emphases when communicating research. Although statistical studies and model results often show weak or non-existent connections, we can provide two observational examples. Three interactive physical processes are involved through atmospheric dynamics: (a) internal atmospheric jet stream/polar vortex processes that add to the persistence of a wavy jet stream; (b) warm and humid air transport into an existing longwave atmospheric pattern; and (c) local thermodynamic surface forcing, often associated with loss of sea ice. All three atmospheric processes were active in two recent studies: winter 2016 in the Barents Sea and winter 2018 in the Bering/Chukchi Sea. Both impacted sea ice loss and the entire marine ecosystem food chain, and resulted in downstream cold air transport into midlatitudes. Societal anticipation is necessary to respond to a repeat of such events. Both the North American and eastern Asia examples show a causal connection from atmospheric and ocean physics through ecosystem disruption to human impacts. Thus global warming influences can be more than a local heating response, but follow a chain of events involving disruption of the jet stream.

1. Introduction

An investigation of Arctic/midlatitude connections began over a decade ago with a discussion of warm Arctic/cold continents patterns in monthly data (Overland and Wang 2010, Cohen et al 2013). A key point was the connection between Arctic temperature change and atmospheric dynamics through increases in geopotential thickness. Soon there were contrary articles that direct global warming was a larger cause for local midlatitude changes (Wallace et al 2014). The issue is of broad interest because of the remote forcing and potential impacts on millions of people, and as interesting, but not so straightforward, dynamics. There have been over one hundred papers on the topic, both pro and con (Cohen et al 2020), and multiple international workshops. The controversy continues with papers on both sides of whether Arctic temperature amplification is associated with a wavier jet stream (Blackport and Screen 2020, Alizadeh and Lin 2021). What is to be made of the continuing controversy over the connection of Arctic change to midlatitude weather events? Here we lay out an approach to the issue, noting what is known and proposing a conceptual model. Literature reviews on Arctic/midlatitude weather connections are found in Cohen et al (2020), Blackport and Screen (2020), and Overland et al (2021), and references therein.

2. Conceptual model based on ten years of community research

These are points that are generally made about Arctic/midlatitude weather connections:

- Greenhouse gases are increasing as an overall climate forcing.
- There is a multiple decade increase in seasonal Arctic and midlatitude temperatures; cold air coming south is not as cold as it used to be. The
There is large natural variability in with-season and interannual variability in the jet stream and stratospheric polar vortex locations and magnitudes. Large-scale atmospheric circulation indices such as the Arctic Oscillation show little long-term changes.

Harsh winter still exists. The polar vortex occasionally brings colder than usual air to Europe, Asia and North America. Historically, there is often a direct connection between waviness and weather extremes. It is uncertain whether rapid Arctic warming has led to a wavier jet stream in recent decades.

Many models fail to demonstrate a major linkage. It is possible that the models are not getting it right, but this should give pause regarding connections.

Sea-ice freeze-up is being delayed into December in marginal Arctic seas providing regional positive tropospheric air temperature anomalies and increases in geopotential thickness.

More open water areas in the Barents Sea is a moisture source for snow in Europe.

Societal and ecological changes are occurring in the subarctic and midlatitudes, the causes of which require further investigation.

Several takeaways are apparent from this listing. Even if there were an Arctic/midlatitude weather connection, it would be intermittent; this point leads to community controversy. If a wavy, cold air event sets up over a month or less, the axis and amplitude of cold and warm extreme events simultaneously in adjacent regions may progress in longitude, so that a seasonal average will show little or no climatological impact. There is not necessarily a major shift in atmospheric circulation due to global change, but wind patterns have a large range of natural variability. What can be happen is that Arctic changes such as sea-ice loss/more open water areas provide precursor conditions that combine with the natural range of atmospheric circulation to result in reinforcement of Arctic and midlatitude impacts on a limited event basis. That impacts do not require circulation deviations to be much beyond their normal extremes, combined with new thermodynamic Arctic Amplification (temperature increases, sea ice loss, permafrost thaw), suggests a reason for potential Arctic connections to occasional single midlatitude weather events (Overland et al 2021).

In pursuing intermittent Arctic reinforced weather events, one can make an argument based on process studies, in contrast to statistical/correlation approaches. Three Arctic processes are involved in feeding back to longwave atmospheric patterns: (a) internal atmospheric blocking processes that add to the persistence of the wavy jet stream pattern; (b) northward warm air advection into an existing longwave ridge; and (c) local thermodynamic surface forcing, often associated with loss of sea ice. The basis for these three regional factors comes from a qualitative interpretation of the geopotential height tendency equation in pressure coordinates (from Overland and Wang 2015), a modified version of equation (6.14) from Holton (1979):

$$\chi \propto \frac{1}{f_0} \mathbf{V}_g \cdot \nabla \left( \frac{1}{f_0} \nabla^2 \Phi + f \right) + \frac{f_0^2}{\sigma} \frac{\partial}{\partial p} \left[ \mathbf{V}_g \cdot \nabla \left( \frac{\partial \Phi}{\partial p} \right) \right] + \frac{f_0^2 R_d}{\sigma c_p} \frac{\partial}{\partial p} \left( \frac{\partial Q/\partial t}{p} \right)$$

(A) \hspace{1cm} (B) \hspace{1cm} (C)

where $\chi = \partial \Phi / \partial t$ is defined as the geopotential tendency, and the static-stability parameter $\sigma$ is defined as $\sigma = -\langle \alpha / \theta \rangle (\partial \theta / \partial p)$, $\theta$ is potential temperature, $\alpha$ is specific volume, $\Phi$ denotes the geopotential height, $f(f_0)$ is the Coriolis parameter (at 45°), $\mathbf{V}_g$ is the geostrophic wind, $R_d$ is the gas constant for dry air, $c_p$ is the specific heat at constant pressure, and $Q$ is the external heating. Geopotential heights rise and fall proportional to negative and positive absolute vorticity advection (term A), vertical variation of geopotential thickness (heat) advection (term B), and low-level diabatic heating (term C). Tying midlatitude weather regimes primarily to internal atmospheric variability of the regional jet stream, which can be modulated by Arctic forcing, provides physical insight into linkage theory. The next sections show two observation-based examples of Arctic/midlatitude weather connections for the Chukchi and Barents Seas, regions of delayed sea-ice freeze-up, and downstream weather impacts.

3. Bering/Chukchi Seas case study

Cold weather characterized the winter of 2017–18 in North America. At the same time the Bering/Chukchi Seas experienced anomalously low sea-ice extent during winter. The jet stream deviated from zonal patterns northward into sea-ice-free areas north of the Bering Strait. Downstream, southward jet stream pathways formed over central and eastern North
America, allowing cold air to spread south. This large anomalous jet meander during winter 2017–18 drives warm moist air north and cold air towards midlatitudes (figure 1(a)). These contrasting anomalous cold and warm areas were seen in the upper air (figure 1(b)); note the wavy jet stream (5200 m geopotential height contour in figure 1(b)), as the jet flows along the constant geopotential height contours. The 2018 poleward jet intrusion was unprecedented (Tachibana et al. 2019).

In relation to processes in equation (1), the event began with an advection of low potential vorticity (PV) at 330 K from 4 to 7 November 2017 (figure 2). This was followed by relatively warm surface temperatures and horizontal warm/moist air advection influencing the jet meander. A vertical-meridional section of air temperature, specific humidity, and northward and upward wind covered the Bering/Chukchi region in winter 2017–18 is based on the Japan Meteorological Agency JRA-55 Reanalysis product (figure 3(a)). The moist warm anomaly propagated poleward and upward over the region. Anomalous upward surface heat flux supported atmospheric warming (figure 3(b)). The increase in geopotential thickness throughout the lower troposphere results in increases of tropospheric geostrophic heights due to increased mean temperatures. Anomalous northward wind stress allowed warm water to penetrate across the Bering Strait into the Chukchi Sea, favorable for maintaining a sea-ice-free Chukchi Sea. Horizontal atmospheric heat transport was intermittent, occurring during southerly winds. Vertical heat transport from the ocean north of Bering Strait was continuous during fall and early winter, as the ocean was a major heat reservoir. Both thermodynamic process and mechanical northward advection of sea ice due to the northward wind stress maintain low ice conditions; warm Arctic air temperature anomalies were, thus, sustainable. These atmosphere-sea ice-ocean feedback processes promoted tropospheric warming (Cohen et al. 2018) that was responsible for helping to maintain the jet meander. Atmospheric numerical experiments under a sea-ice-free condition in the Chukchi Sea successfully simulated a cold North America (Tachibana et al. 2019).

At a process level, we examined the Chukchi regional co-variability of daily surface air temperature (SAT) and sea ice concentration (SIC) anomalies (figure 4(a)), along with area-averaged surface turbulent heat fluxes and downward longwave radiation (DLR) during this event (figure 4(b)), based on the Japan Meteorological Agency JRA-55 Reanalysis. Here, the region is defined north of Bering Strait by 70°–80° N, 160°–210° E. Open water was present through 20 December (figure 4(a)) and vertical heat transport from the ocean north of Bering Strait was continuous before that date (figure 4(b)).

Figure 1. Anomalous jet meander, cold winter in Asia and America in winter 2017–18. (a) Three month mean air temperature (contour) and standardized temperature anomaly (shaded) at 2 m between 15 November 2017 and 15 February 2018. The anomalies were divided by their standard deviations and the data were linearly de-trended. The contour interval is 1 °C. Hatching areas recorded the highest or lowest temperature of the three-month means since 1981. (b) As in (a) but for geopotential height (contour) and temperature anomaly (shaded) at 500 hPa. The unit of height is meters, and its contour interval is 50 m. Reproduced from Tachibana et al. (2019). CC BY 4.0.
Figure 2. Evolution of daily-mean potential vorticity (PV) at 330 K in the Northern Hemisphere for the period of extreme Arctic amplification that occurred during 4–7 November 2017 (a)–(d). For better visualization, only areas with PV over 5 PV units (PVU) are shaded (1 PVU $= 10^{-6}$ km$^2$ kg$^{-1}$ s$^{-1}$).

Horizontal atmospheric heat transport was intermittent, occurring during southerly winds as noted in temperatures (figure 4(a) red) and DLR flux (figure 4(b) green). Both thermodynamic process and mechanical northward advection of sea ice and warm water due to the northward wind stress maintained early winter low ice conditions.

The risk of ecosystem reorganization due to delayed sea ice growth and warmer temperatures in some years is high for the Bering Sea as the system favors cold waters (Britt et al 2019, Duffy-Anderson et al 2019). While we have shown the atmospheric conditions for winter 2017–18, a similar atmospheric southerly jet stream-extreme sea ice minimum was also experienced during winter 2018–19 (Jones et al 2020, Overland 2020, figures 2 and 3). The extreme atmospheric and sea ice phenomena that occurred for these two consecutive years affected the ecosystem. Both years had Alaskan ecosystem/societal impacts and downwind North American cold events. In a more typical year a Bering Sea ocean bottom layer cold pool is established from increased upper ocean stratification due to the southward advance of sea ice and surface melt. The preferred prey for the large pollock fishery, large zooplankton (euphasiids), is favored by an extensive cold pool, and due to lack of sea ice the cold pool was missing in 2018 and 2019 during extreme sea-ice-free conditions (Stabeno and Bell 2019, Eisner et al 2020). The entire food chain was impacted. Ice-dependent seals lost their platform for resting and breeding. Walrus, rather than feeding from ice floes, were forced to haul out on
land creating additional food stress on the animals (figure 5). There were seabird die-offs, disrupted marine mammal hunts, flooding of coastal villages due to longer ocean wave fetch, and warm-water driven toxic algae blooms (Sheffield 2020). Although data is for 2019, fish stocks were affected; walleye pollock and Pacific cod together comprised 36% of the fishery biomass in the northern Bering Sea (Nielsen 2021) compared to 2% of the northern biomass in a more normal year of 2010. More recently, 2020 and 2021 had more typical sea ice extents; the jet stream was located to the south allowing northeast winds to grow the ice extent across the Bering Sea. The next decade may hold environmental shocks similar to 2018 and 2019 as the occurrence of sea-ice loss in 2018 and 2019 is earlier than projected by climate models (Wang et al 2018, Thoman et al 2020).

The story of Alaska and the rest of North America is for such extremes in some years but not others. The life history of most subarctic species depend on several strong year class recruitments out of a decade to maintain their populations. An increase in the frequency of rare events could affect their stability and the communities who are dependent both locally (marine mammal hunting) and distant (commercial pollock fishery). Cold downstream weather events from Alaskan enhancement of the jets stream meanders are aimed at the large population centers of central and eastern United State and Canada.

4. Barents Sea/Eurasia case study

We further investigate winter 2015–16 in the Barents Sea and underlying physical mechanisms, followed by an exceptional cold spell in East Asia during late January 2016 (Tyrlis et al 2019, Overland et al 2021). PV fields initiate the event, and a daily evolution of anomalies in air temperature, turbulent heat fluxes, sea-ice concentrations, and DLR fluxes that contributed to the amplification of the Arctic warm atmospheric temperature anomaly are presented. High Arctic SATs exceeded 0 °C in early January 2016 based on the operational analysis from the European Centre for Medium-Range Weather Forecasts (Binder et al 2017). This was 25 °C above the winter climatological mean, with a record high daily temperature since 1950. A large reduction in the Arctic sea-ice extent occurred in the middle of the cold season (Cullather et al 2016, Kim et al 2017). A cold wave brought record low temperatures and snowfall to many parts of southeast and central Asia during January (Wang et al 2017).

Initially, a lobe of low PV of less than 5 PVU on the 330 K isentropic surface, at approximately 300 hPa advected into the Arctic (figure 6(a)) and
Figure 4. Time-series of anomalies in (a) surface air temperature (SAT; red) and sea-ice concentration (SIC; blue, %); (b) turbulent heat flux (THF; red) and downward longwave radiation (DLR; green) from November 2017 to February 2018 over Chukchi Seas (70°–80° N, 160°–210° E). Note that positive DLR is directed downward. The analysis is based on the variables from Japan Meteorological Agency JRA-55 reanalysis (www.jra.kishou.go.jp/JRA-55).

Figure 5. Walrus haul out onto land in the Chukchi Sea in a sea-ice diminished year. Credit: Corey Accardo, NOAA/NMFS.
Evolution of daily-mean potential vorticity (PV) at 330 K for the period of extreme Arctic amplification that occurred during late December 2015 (a)–(d). For better visualization, only areas with PV over 5 PV units (PVU) are shaded (1 PVU = 10⁻⁶ km² kg⁻¹ s⁻¹). Data are from the Japan Meteorological Agency JRA-55 reanalysis (www.jra.kishou.go.jp/JRA-55/). Reproduced from Overland et al (2021). © The Author(s). Published by IOP Publishing Ltd. CC BY 4.0.

high PV developed and amplified over the North Atlantic. PV reached its minimum value during 29–31 December 2015, the (figures 6(b)–(d)). A precursor to this Barents Sea event was thus internal atmospheric variability from vorticity advection (term A). High PV developed to the south producing a gradual reversal of the PV gradient, indicating a cyclonic wave-breaking event, a typical indicator of blocking formation.

After the initiation of abrupt warming by the intrusion of a low-PV airmass, a warm Arctic/cold continent pattern appeared for the first 10 days of January 2016 (figure 7(a)). For the next 10 days, warm temperature anomalies over the Barents/Kara Seas became relatively weaker. At the same time, a cold temperature anomaly appeared in East Asia (figure 7(b)), which further amplified during the last 10 days of January 2016, accompanied by prolonged cold spells over China and south Asian countries (figure 7(c)). On a weekly scale, the regional cold SAT anomalies coinciding with the warm Arctic shifted eastward (figures 7(a)–(c)). Notably, during the evolution of this Barents/midlatitude weather linkage, a stationary high geopotential height anomaly persisted for nearly a month over the Ural Mountains region, a Ural blocking event (figures 7(d)–(f)) (Takaya and Nakamura 2005, He et al 2020). This synoptic-scale analysis supports the hypothesis that Ural blocking plays a role in Eurasia and East Asia cold events; an observed increased tendency of Ural blocking occurrence shows a high association with enhanced anticyclone activity (Zhang et al 2012 and figure 2(g) therein). Identification of physical causes linking enhanced anticyclone activity to persistent
Ural blocking and downstream cold air impacts are key to understanding the nature of Arctic-Asian mid-latitude linkages (He et al. 2020).

At a process level, area-averaged turbulent heat fluxes and DLR during this event are shown in figure 8(b), as well as co-variability of daily SAT and SIC anomalies (figure 8(a)), based on the Japan Meteorological Agency JRA-55 Reanalysis. Here, the region is defined by 76°–83° N, 20°–80° E. The local temperature variation leads SIC variation by 1 or 2 days (figure 8(a)) with SAT increasing abruptly on 28–29 December 2015 (figure 8(a)), coincident with the PV analysis in figures 6(a) and (b); this was an intrusion of a low-PV airmass from lower latitudes (Kim et al. 2017). The DLR anomaly in figure 8(b) is strongly correlated with the SAT anomaly in figure 8(a) \( r = 0.92 \). The anomalies in turbulent heat flux and SIC are not correlated on daily time scales. Turbulent heat flux exhibits an anti-correlation with DLR \( r = -0.69 \); DLR slightly leads the turbulent heat flux. There was an active role of warm and moist air advection (term B) in driving atmospheric warming and sea-ice melt (Sorokina et al. 2016, Zhong et al. 2018). We note several warm-air intrusion events by the DLR anomaly with less than a 10 days repetition (figure 8(b)). Sea ice was well below normal during winter of 2015–16 (figure 8(a)). By integrating from 20 December 2015 to 10 February 2016 the turbulent heat flux anomaly is positive (upward), contributing to atmospheric temperature increases due to sea-ice loss (term C), while warm-air advection is episodic (figure 8(b)).

The Barents Sea has a connection between atmospheric circulation, sea-ice loss, warming atmospheric and sea temperatures, and ecosystem impacts. The Barents Sea has reached a 'tipping point' (Lind et al. 2018). Loss of sea ice has shifted the Barents Sea from acting as a buffer between the Atlantic and Arctic oceans to something closer to an arm of the Atlantic. The changes in the Barents Sea have occurred earlier than in the Bering Sea with a trend starting in 2000 with year-to-year variability, but the shift is currently nearly complete after 2015. There was a transition from a cold, fresh, and stratified Arctic to a warm and well-mixed Atlantic-dominated region, with impacts on marine mammal and commercial fisheries habitat (Lone et al. 2019).
Figure 8. Time-series of anomalies in (a) surface air temperature (SAT; red) and sea-ice concentration (SIC; blue); (b) turbulent heat flux (THF; red) and downward longwave radiation (DLR; green) from 20 December 2015 to 10 February 2016 over Barents/Kara Seas (76°–83° N, 20°–80° E). Note that positive DLR is directed downward. The analysis is based on the variables downloaded from Japan Meteorological Agency JRA-55 reanalysis (www.jra.kishou.go.jp/JRA-55/). Reproduced from Overland et al (2021). © The Author(s). Published by IOP Publishing Ltd. CC BY 4.0.

5. Conclusion

The extent of knowledge is so vast, and the entrance by which the knowledge of things gets into our understanding so narrow, that the whole time of our life is not enough to acquaint us with all those things.

John Locke

What can be said about the state of the science for Arctic/midlatitude weather connections and how can this be communicated? The connection is not present every year due to a more zonal versus wavy jet stream predominance, and there are multiple atmospheric processes involved. On a seasonal basis there appears to be little impact. Explanations for a broad audience would prefer a clear statement and to be due to a single cause, but this is not part of the present situation after ten years of investigation.

What is clear that Arctic/midlatitude interaction is a historical on-going feature, regardless of whether increased open water areas due to sea-ice loss has a major impact. A major controlling factor for classic late-winter cold-air outbreaks into midlatitudes is the linkage to the occurrence of stratospheric polar vortex disruptions and displacements over the continents (Overland and Wang 2019, Kretschmer et al 2020). A recent example of a strong southerly migration of the polar vortex/jet stream were the cold temperatures and snow over Texas USA during mid-February 2021. Due to poor weather and loss of power, there was loss of 80 lives with this event. The cold temperatures for mid-February showed a strong west-east character, in contrast to the wavy, more blocking type pattern for the Bering Sea case study.

Because of their dynamics, atmospheric circulation features, such as blocking over limited areas, vortex displacements, and impacts from sudden stratospheric warmings, are a topic for increased research
relevant to extended range forecasting. When this pattern sets up, persistent cold spells and heavy snow events can typically affect central and eastern North America, including the densely populated corridor from Boston to New York City and as far south as Washington, D.C., or set up a chain of cold events east of the Ural mountains moving across eastern Asia (Overland et al 2021).

Extended weather events can have an impact on the sustainability of subarctic marine species through retarding individual year classes based on their life history. While several extreme warm/sea-ice loss years in a decade are a normal occurrence, an increase in their number could have a negative survival impact on commercial fisheries, ice-dependent seal and walrus, and subsistence for coastal communities.

The Bering/Chukchi and Barents Seas examples in sections 3 and 4 do show direct reinforcement of the atmospheric pattern by heat fluxes from newly open water areas, along with other processes: large-scale atmospheric jet stream preconditioning, warm and cold air advection, and downstream weather impacts. Such clearly defined events are rather rare (see Overland et al 2021, figure 10). Thus, all authors on this topic are somewhat correct: there are examples of singular connected events, but at present they do not have a large seasonal or multi-year impact.

We cannot exclude that the disruption of the jet stream and polar vortex are interacting with global warming and thermodynamic changes in the Arctic and subarctic with the potential for intermittent extreme events, affecting ecosystems and people both in local villages and the larger population. Not least are we witnessing multiple weather events of the type noted here and extreme heat in Siberia, Finland, Pacific Northwest and California. These outlier events exceed what one would expect if it were only a 1 ◦C–2 ◦C local global warming impact. Such outliers likely include non-linear additional interactions between the thermodynamic/moisture elements of climate system and the jet stream/polar vortex.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://jra.kishou.go.jp/JRA-55/index_en.html.

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The data that support the findings of this study are openly available: Data are available from Japan Meteorological Agency JRA-55 reanalysis (https://jra.kishou.go.jp/JRA-55/index_en.html) also see Harada et al (2016).

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