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Key Points:
- Arctic change has the potential to impact millions of people through shifts in midlatitude weather, but occurrences are intermittent
- Linkages are a two-step process: Arctic temperatures are favorable in the last decade, but jet stream shifts must allow for a connection
- Sub-seasonal jet stream variability explains part of the scientific uncertainty from low correlations and in model studies

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Resolving Future Arctic/Midlatitude Weather Connections

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Abstract Given ongoing large changes in the Arctic, high-latitude forcing is a new potential driver for sub-seasonal weather impacts at midlatitudes in coming decades. Such linkage research, however, is controversial. Some metrics find supporting evidence and others report no robust correlations. Model studies reach different conclusions. Case studies from particular historical months suggest potential connections. We propose that a difficulty in resolving the science is due to the inherent complexity and intermittent character of atmospheric dynamics, which serves as a variable causal bridge between changes in the Arctic and midlatitude weather. Linkages may be more favorable in one atmospheric jet stream pattern than another. Linkages are a two-step process: thermodynamic forcing, i.e. warm Arctic temperatures and loss of sea ice, is generally favorable in the last decade, but internal atmospheric dynamics, i.e. the jet stream location and strength, must also allow for a connection. Thus, in the last decade only a few possible linkage events are noted into and out of the Arctic; for examples 2006, 2016, and 2018 had warm Arctic Januaries, and 2010 and 2017 had cold eastern North American Decembers. Record large sea-ice-free areas and warm temperatures north of Alaska and over Baffin Bay helped to anchor the long wave atmospheric pattern, which in turn fed cold temperatures into the eastern US. Intra-seasonal and inter-annual intermittency explains low direct Arctic/midlatitude linkage correlations and large variability in model studies. Yet a full understanding is necessary for important future forecasts of increased Arctic/midlatitude interactions impacting millions of people.

1. Introduction

The public has been aware of severe eastern United States storms in the last decade from “snowmageddon” in 2010 to the’bomb cyclone” of 2018. Questions are whether there is a more frequent presence of a menacing “polar vortex” and whether there is a connection to increased temperatures in the Arctic. Kug et al. (2015), Kim et al. (2017), and Cohen et al. (2018) show that severe winter weather including cold spells and heavy snows became more frequent during recent decades in the eastern US. This was during the same times when Arctic warming increase is greatest. The authors acknowledge that this is a statistical link; uncertainties remain in causality. Whatever the trend, early winter eastern US monthly temperatures are primarily characterized by year-to-year variability over the last three and a half decades, with positive and negative excursions in December of 4 ° C in some years (Figure 1, gray bars).

The question arises whether the Arctic has changed enough to have a direct impact on the midlatitude atmosphere. In the recent decade there are regional delays in Arctic autumn sea ice freeze-up. Figure 2 shows the spatial pattern of the 1979–2016 trend of sea ice concentration in November (units are percent per decade). Three regions stand out: the Chukchi Sea northwest of Alaska, Baffin Bay/northern Hudson Bay, and the Barents/Kara Seas north of western Russia, with sea-ice concentration reductions of over 40% over the period of the satellite record. These regions represent new extended periods of open water, increased regional temperatures (Taylor et al., 2018), and reduced vertical stratification in the atmosphere (Jaiser et al., 2012). We concentrate on early winter North American potential connections. The Kara Sea/eastern Asia is also an important linkage region but is not covered here (see Kim et al., 2014; Zhao et al., 2018).

A conceptual diagram for possible early winter Arctic/midlatitude weather linkages is shown in Figure 3. Global climate change and regional Arctic feedbacks are responsible for an Arctic Amplification, that Arctic temperatures are increasing faster than in the rest of the hemisphere (Notz & Stroeve, 2016). The tropospheric jet stream is the pathway or bridge to midlatitude weather events, which in turn is also influenced by internal variability (chaotic atmosphere), tropical and midlatitude oceans, and the stratospheric polar vortex wind pattern (Messori et al., 2018).

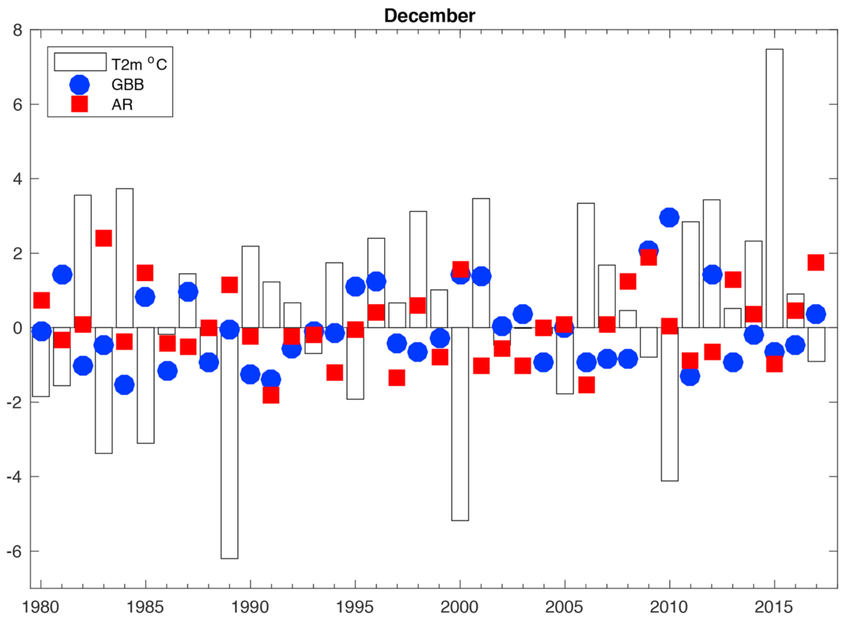

Figure 1. December time series for 2 m surface air temperature anomaly based on NCEP/NCAR reanalysis averaged over an eastern North American domain (30–45°N, 90°W–72°W) (gray bars), and normalized Greenland/Baffin Blocking (GBB) index (solid blue dots) and the normalized Alaskan Ridge (AR) index (solid red dots). The AR index is maximum geopotential height for the teleconnection region (60–75° N, 150–130° W) during cold US winters. GBB is the same type of index for the region (60–75° N, 70–50° W). Units for 2 m surface air temperature are °C, and the AR and GBB indices are normalized by their standard deviations. More details are provided in Overland and Wang (2018).

An important aspect of present Arctic weather linkages research is the failure to achieve consensus between investigators, as noted in a recent workshop (Cohen et al., 2018); even the workshop white paper has the word "possible" in the title. Some metrics applied to historical data find supporting evidence and others report no robust linkages (Barnes & Screen, 2015; Francis, 2017). It is unclear whether current-generation climate models respond too weakly to sea-ice change (Screen et al., 2018). The present review hypothesizes that part of the controversy stems from difficulties in recognizing the inherent intermittency of the underlying atmospheric physics; Arctic/midlatitude weather linkages may be more favorable in one atmospheric pattern than another. We define intermittency as when there is a strong forcing signal, but a response is not manifest in all cases; there is not always a direct cause and effect connection. Increasing understanding is a goal that can be approached through careful data analysis and use of model studies. Data show that recent weather linkages both into and out of the Arctic are event-like, rather than causing shifts in seasonal statistics (Ayarzagüena & Screen, 2016; Overland et al., 2015).

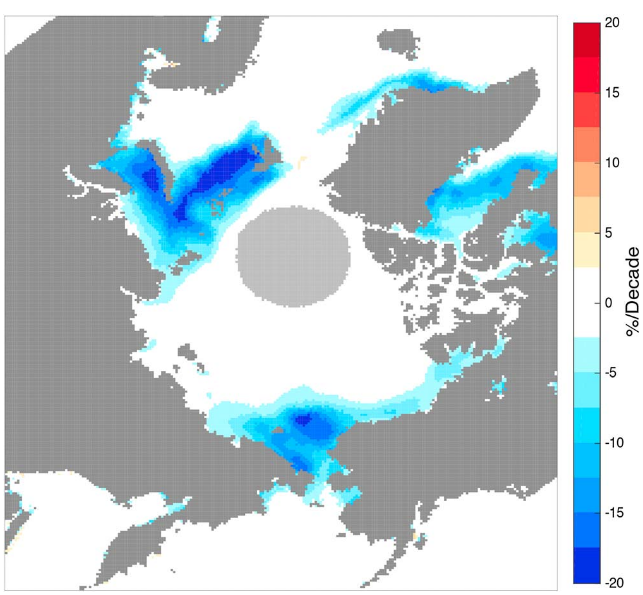

Figure 2. The spatial map of the linear downward trend in November sea ice concentration notes the locations of delay in timing of sea ice freeze up for November, the nominal time of autumn sea ice freeze-up. The Barents/Kara Seas, Chukchi Sea, and Baffin Bay are the regions with largest decline. The Figure shows a linear downward trend of 40% over the satellite observation period (1979–2016). Units are percent per decade. Data from NSIDC.

2. Recent Cold Weather Linkages

Although global warming should overtake current climate conditions in increasing seasonal temperatures during the future (Wallace et al., 2014), there is interest in the paradox that Arctic warming and other changes might impact cold events on the eastern side of both North American and Asian hemispheres, through reinforcing large north/south meanders in the jet stream (Chen et al., 2016; Cohen, Pfeiffer, & Francis, 2018; Sung et al., 2016; Vavrus et al., 2017). The historical distribution of cold months for eastern US Decembers is shown in Figure 1; the previous decade has

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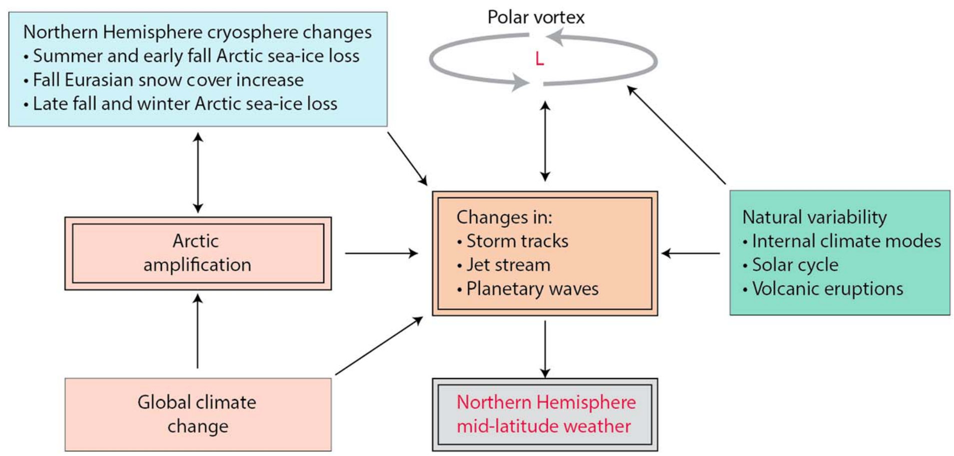

Figure 3. Complexity of linkage pathways from the Arctic to midlatitudes with the jet stream forming the bridge, and subject to internal natural variability. (Figure from Cohen et al., 2014).

mostly warm months with two, rather rare, cold eastern US cold Decembers in 2010 and 2017. Prior to 2010 there is a distribution of both warm and cold months.

A way forward is to assess what atmospheric wind patterns are associated with causing these east coast cold events. Rather than looking a wind fields directly, meteorologists investigate maps of the varying altitude of

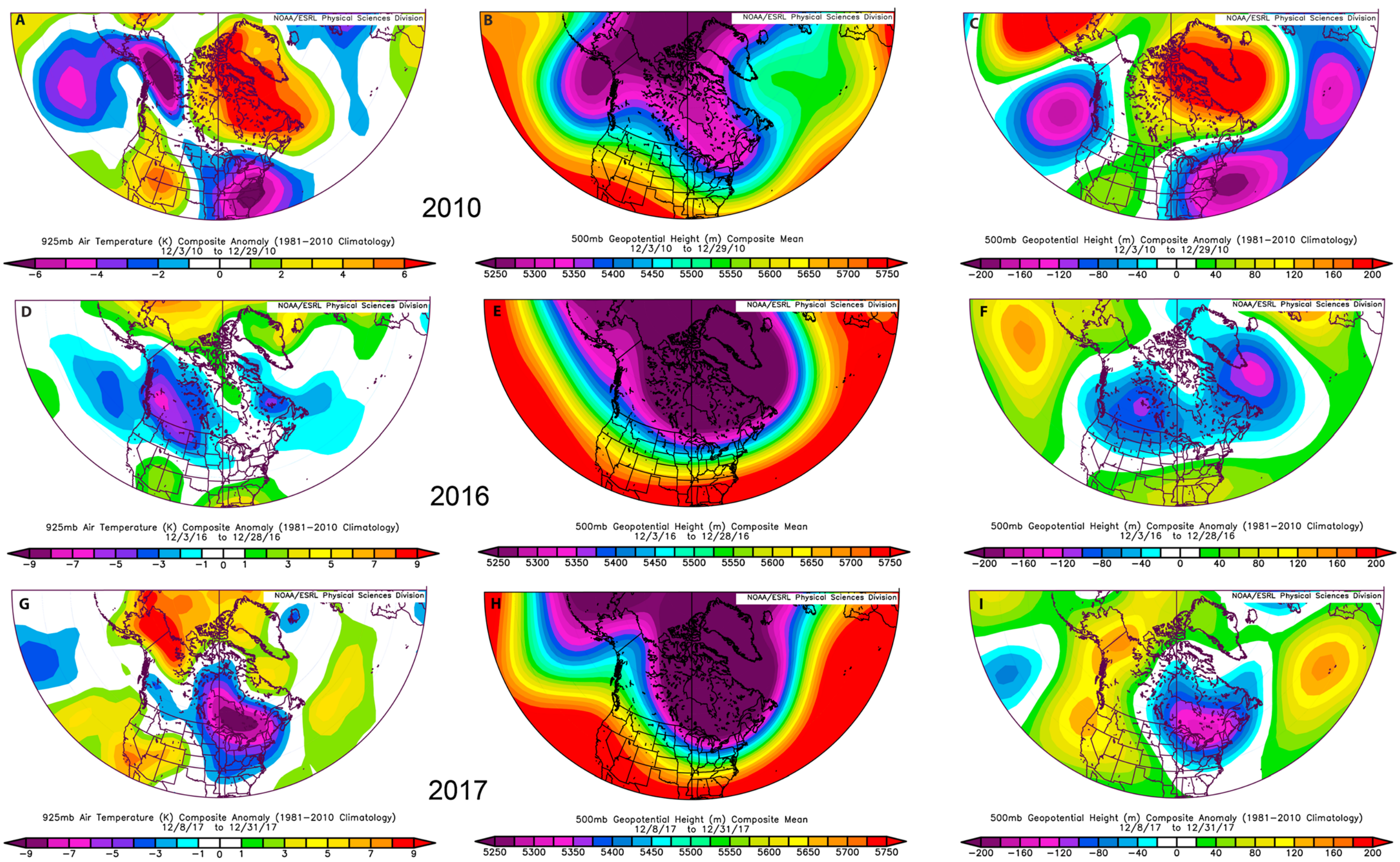

Figure 4. Top Row (A, B, C) 925 hPa temperature anomaly field, 500 hPa geopotential height field and 500 hPa geopotential height anomaly field that represent a Greenland Baffin Blocking (GBB) case for December 2010. Bottom Row (G, H, I) 925 hPa air temperature anomaly field, 500 hPa geopotential height field and geopotential height anomaly field for an Alaskan Ridge case from December 2017. Middle row fields (D, E, F) from December 2016 show a contrary case of Alaskan warm temperatures without an eastern US temperature response. Data from the NOAA/NCAR reanalysis using the NOAA/ESRL online plotting routines.

constant pressure surfaces, known as *geopotential heights*; for example the height of the 500 hPa pressure surface half way up in the atmosphere. Constant contours of geopotential height give the wind direction and horizontal gradients give the magnitude (see Figure 4, center panels). Additionally, warm air is less dense, so a layer of warmer temperatures implies a greater distance between constant pressure surfaces, termed *geopotential thickness*. Examples of the monthly temperature anomalies at the 925 hPa level, not too far above the surface, for December 2010, 2016, and 2017 are shown in left panels of Figures 4A, D, and G. December 2010 and 2017 have cold temperatures over the eastern US, 2010 has warm temperatures west of Greenland, and 2016 and 2017 have warm temperatures over and north of Alaska. The geopotential height pattern in Figure 4B shows a December 2010 wavy jet stream south of Greenland, i.e. follow the blue contours of the direction of strong winds. Figure 4H for 2017 has a wavy geopotential height pattern along the west side of North America. Figure 4E (middle row) for 2016 shows a strong west–east orientation to the wind direction over the northern US and no cold temperature anomalies on the US east coast (Figure 4D). Geopotential height anomaly fields for December 2010 and 2017 (Figure 4C and 4I) highlight the co-locations of the Arctic positive temperature anomalies and associated elevated geopotential heights.

The north–south pattern of opposite signs of temperature anomalies (sometimes called a teleconnection) for 2010, the wavy jet stream location near Greenland, and a positive geopotential thickness anomaly over Baffin Bay related to the warm regional temperature anomaly, has been referred to as Greenland/Baffin Blocking, or GBB (Ballinger et al., 2018; Chen & Luo, 2017; Overland & Wang, 2018). A blocking pattern has a tendency to persist (Nakamura & Huang, 2018). The pattern for December 2017 has been referred to as a ridge (northward movement of the geopotential height field) over northwestern North America with warm Alaskan temperatures, and is known as an Alaskan Ridge pattern, or AR (Kug et al., 2015; Messori et al., 2016; Mills et al., 2016; Overland & Wang, 2018; Xie et al., 2017). (Note the GBB center (Overland & Wang, 2018) is located somewhat to the west of the historical Greenland Blocking Index (GBI) which is centered over Greenland (Hanna et al., 2016)).

Richard Thoman (NWS, personal communication) notes an extreme record (1979–2017) amount open water during autumn 2017 in the Chukchi Sea based on NSIDC passive microwave data. The Chukchi Sea can show autumn surface heat loss of ~200 Wm^{-2} over recent open water regions and given to the atmosphere (Ola Persson & Kevin Wood, personal communications). Ballinger et al. (2018) show a record delay in freeze-up dates (1979–2016) for Baffin Bay in autumn 2010. Also Hanna et al. (2018) show the co-location of high geopotential height (500 hPa) anomalies, based on daily GBI data, with winter low sea-ice anomalies over southern Baffin Bay, Davis Strait and the northern Labrador Sea. Lack of sea ice in both regions (Baffin Bay in 2010 and Chukchi Sea in 2017) imply surface coupling to the Arctic atmosphere as shown by the 925 hPa positive temperature anomalies (Figure 4A and G).

The strength of the GBB and AR patterns in historical December months (blue and red dots) are shown in Figure 1. The cold December 2010 case corresponds to the strongest Greenland/Baffin Blocking (GBB) pattern in the record. The cold December 2017 is a strong AR case, the largest AR index since 2010, and the 3rd largest in the record. Note the many historical cases where east coast US cold monthly events are associated with positive GBB, AR or Both that occur before major Arctic warming: e.g. 1983, 1985, 1989 (Grotjahn et al., 2016; Overland & Wang, 2018; Singh et al., 2016). In 2000, for example, both patterns contributed to cold eastern US temperatures. This is a further indication that Arctic warming can support a wavy jet stream pattern, but is not necessary for its internal development. Despite recent Arctic change since 2007, the December 2010 and 2017 Arctic change/cold eastern US cases remain rather rare, intermittent events. At most, one can say that increased temperatures over sea-ice-delayed regions could contribute to, but not cause, increase geopotential thickness that reinforced the location of the existing wavy geopotential height pattern, and increase the persistence of the eastern US cold event to a monthly time scale (Overland & Wang, 2018).

December 2016 provides a counter example to December 2017. Despite warm Alaskan temperatures (Figure 4D), the strong east–west oriented jet stream across southwestern Canada (Figure 4E) is not conducive for Alaskan warm temperatures to reinforce an AR pattern. Linkages are a two-step process: loss of sea ice and warm Arctic temperatures are generally favorable in the last decade, but the jet stream configuration must also allow for a connection, and this occurs intermittently. December 2016 is an example where the first condition is present, but not the second jet stream configuration.

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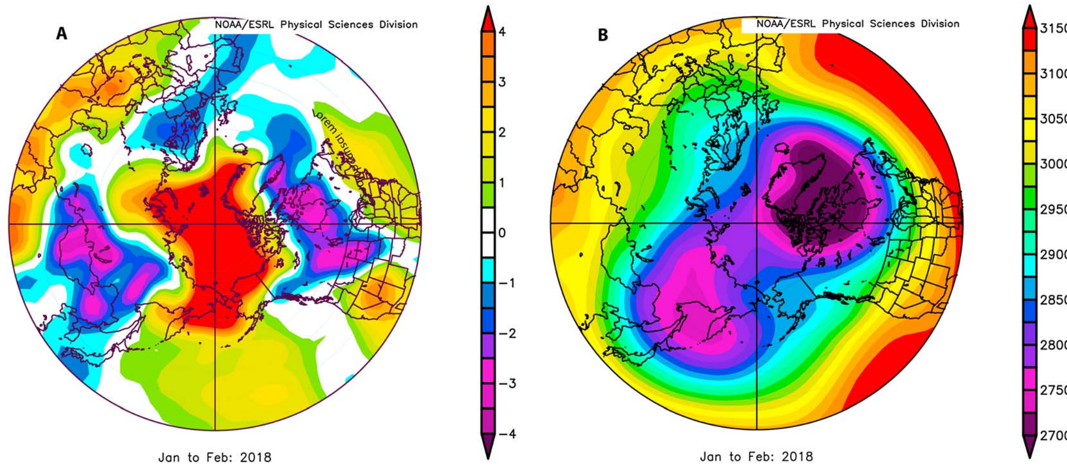

Figure 5. Mean January and February 2018 spatial patterns of (A) near-surface (925 hPa) air temperature anomalies and (B) averaged geopotential height at 700 hPa. Data from the NOAA/NCAR reanalysis using the NOAA/ESRL online plotting routines.

3. Recent Warm Weather Linkages

Subarctic atmospheric circulation and moisture transport led to record Arctic winter temperature maximums in 2006, 2016, and 2018. A major Arctic warming event occurred from late December 2015 to late winter 2016. For January 2016, the Arctic-wide averaged temperature anomaly was 2.0 ° C above the previous record of 3.0 ° C (Kim et al., 2017; Overland & Wang, 2016). This event caught the public's attention with reports of temperatures warming to near the freezing point at the North Pole. A similar extreme Arctic warm event followed in winter 2018. These warm events (Figure 5A) were caused by advection of heat and moisture into the Arctic on Atlantic and Pacific pathways as shown by contour directions of the 700 hPa geopotential height field for January/February 2018 (Figure 5B). Northward advection of temperature and moisture, which increases of downward long wave radiation, delayed sea ice freeze-up along the trajectory, thus providing a positive feedback by Arctic process that helped to maintain the record high temperature events (Binder et al., 2017; Cullather et al., 2016; Hanna et al., 2016; Rinke et al., 2017).

The 2016 and 2018 Arctic warm events, while setting records, are not unique in the Arctic past (Graham et al., 2017, Figure 6). January 1990 and 2006 had similar North Pole warming with a similar atmospheric wind trajectory in the Atlantic sector as in Figure 5B, but without a Pacific contribution. Winter 2016 and 2018 are additional examples where year-to-year and intra-seasonal variability in jet stream meanders (dynamics) combines with Arctic thermodynamic changes to result in new extreme weather events.

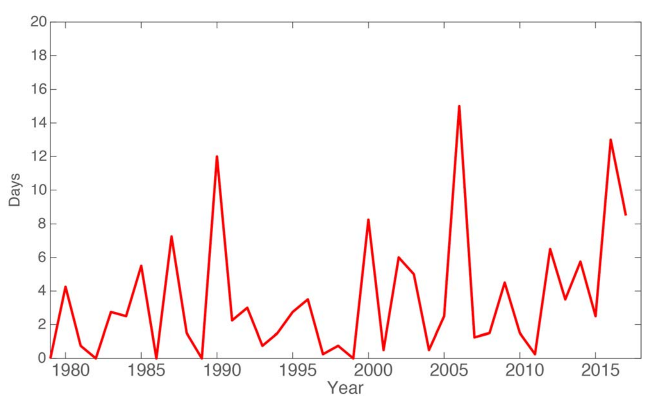

Figure 6. Time series of total time (in days) each winter (DJFM) where the maximum 2 m temperature anywhere within the North Pole domain (80–90° N) exceeded −5 ° C based on ERA interim reanalysis. Figure is modified from Graham et al. (2017).

4. The Road to Intermittency

Organized complexity in the jet stream pattern is largely characterized by nonlinear interactions between atmospheric waves around latitudes in the Northern Hemisphere, irregular transitions between west–east and north–south flows, and the maintenance of atmospheric blocks (Dole, 1986; Franzke et al., 2015; Masato et al., 2008; Sura & Hannachi, 2015; Whittleston et al., 2018; Woollings et al., 2018). Persistence and trigger mechanisms for shifts of atmospheric wave structure are not well understood.

Many modeling experiments have been carried out to determine the atmospheric response to Arctic sea ice loss. There can be (Cohen, Zhang, et al., 2018): different results from different models and within the same model, teleconnection patterns that are underestimated, and linkage results that depend on the meteorological background state in the models. A large range of results from different models to ostensibly the same physical problem suggests intermittency in atmospheric physics (Semmler et al., 2016; Wu & Smith, 2016). The atmospheric response to

Arctic change simulated by models is typically small compared to internal variability, i.e., low signal-to-noise ratio, so that a large number of simulations are required to obtain robust results (Mori et al., 2014). If one considers that the Arctic primarily reinforces existing atmospheric patterns, then results will depend on the meteorological background flow pattern, a different characteristic in each model (Chen et al., 2016; Osborne et al., 2017; Smith et al., 2017). In summary, model results are not inconsistent with observations, that one should expect variability in model response simulations, as in the real world.

5. A Problematic Way Forward

Intermittency in Arctic/midlatitude linkages is shown by the uneven event-scale response in the past decade during rather steady Arctic amplification. Models point both to the difficulty in resolving linkage physics relative to large-scale atmospheric dynamics, and also demonstrate the inherent variability of such events. Recent warm Arctic events and cold midlatitude events show a large role of internal variability and interannual differences in atmospheric jet stream behavior. Thus, part of the controversy in studying Arctic/midlatitude weather linkages stems from the inherent complexity and intermittency in underlying atmospheric physics (Lloyd & Oreskes, 2018).

It is unclear whether scientists will have sufficiently detailed data sets to fully analyze or initialize models to understand such interactions; this leads to an *underdetermined* problem. The problem may be *computationally irreducible* due to nonlinearities and chaotic behavior; it may be necessary to trace the trajectory over time through multiple weather prediction model runs. The ongoing Year of Polar Prediction takes this approach (Semmler et al., 2018).

A solution to controversy in the Arctic/midlatitude weather linkage issue includes coming to grips with a robust intermittency interpretation, rather than direct cause-and-effect hypothesis testing. Explanations for future cold continental and warm central Arctic events, as opposed to overall winter seasonal warming, are needed for communicating potential Arctic change impacts on midlatitude weather to a broader public.

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