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A difficult Arctic science issue: Midlatitude weather linkages

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ABSTRACT

There is at present unresolved uncertainty whether Arctic amplification (increased air temperatures and loss of sea ice) impacts the location and intensities of recent major weather events in midlatitudes. There are three major impediments. The first is the null hypothesis where the shortness of time series since major amplification (~15 years) is dominated by the variance of the physical process in the attribution calculation. This makes it impossible to robustly distinguish the influence of Arctic forcing of regional circulation from random events. The second is the large chaotic jet stream variability at midlatitudes producing a small Arctic forcing signal-to-noise ratio. Third, there are other potential external forcings of hemispheric circulation, such as teleconnections driven by tropical and midlatitude sea surface temperature anomalies. It is, however, important to note and understand recent emerging case studies. There is evidence for a causal connection of Barents-Kara sea ice loss, a stronger Siberian High, and cold air outbreaks into eastern Asia. Recent cold air penetrating into the southeastern United States was related to a shift in the long-wave atmospheric wind pattern and reinforced by warmer temperatures west of Greenland. Arctic Linkages is a major research challenge that benefits from an international focus on the topic.

1. Introduction

There is at present unresolved uncertainty whether recent Arctic amplification (increased air temperatures and loss of sea ice) impacts the location and intensities of recent major weather events in midlatitudes, the Arctic/midlatitude linkage question (hereafter Linkages). Scientific opinions differ on whether recent extreme weather, including the cold eastern U.S. winters of 2009/10, 2010/11, January 2014, and winter 2015, were merely random events or if there were contributions from recent global or Arctic climate change (e.g. Jaiser et al., 2012; Tang et al., 2013; Wallace et al., 2014; Lee et al., 2015; Trenberth et al., 2015). Much has been made in popular culture of the "Polar Vortex" influencing cold events in midlatitudes. Sixty percent of the public in the northeastern United States believe that Arctic warming will impact their weather (Hamilton and Lemcke-Stampone, 2014). Thus, there is more than scientific curiosity in delineating the extent of understanding for potential future Linkages in terms of extended range forecasting (Jung et al., 2014, 2015).

Reviews of Linkage science are provided by Vilma (2014), Walsh (2014), the National Academy of Sciences (2014), Cohen et al. (2014), Barnes and Screen (2015), and Overland et al. (2015), and there are over 50 individual peer reviewed studies in the last three years. The current state of research depends much on correlation, modeling, case studies, and physical reasoning. Differences that lead to apparent controversy often revolve around different analysis methodologies, time and spatial averaging, and analysis variables, and zonal mean versus regional viewpoints. Different model studies, and even multiple runs of the same model, can both suggest and reject Linkage pathways. Single, repeatable, parsimonious causal pathways for Linkages are difficult to confirm. There are, however, papers that discuss the direct influence of dynamic processes on Linkages (e.g. Jaiser et al., 2012; Handorf et al., 2015). All six reviews state that progress depends on further understanding of the dynamics underlying potential atmospheric circulation response to Arctic Amplification [increases in Arctic temperatures due to a number of feedback processes including loss of snow and sea ice and associated land-ocean-atmosphere heat fluxes, ocean and land heat storage, and changes in wind and current patterns (Duarte et al., 2012; Jeffries et al., 2013)]. The driver of this interest is potential improvement of weekly to seasonal predictability of severe winters in midlatitudes driven by future trends in Arctic conditions. Uncertainty remains an unavoidable limitation, however, mostly induced by large, random chaotic variability of midlatitude circulation resulting in small signal-to-noise ratios for

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potential Arctic forcing.

A step forward in understanding is that the occurrence of quasi-stationary weather events may be mostly random, carried by the atmospheric dynamics, while the amplitude of events can be influenced and reinforced by a regional Arctic thermodynamic Linkage contribution (Shepherd, 2014; Overland and Wang, 2015). Further, Linkages may be *conditional* on which state is predominant in the large-scale weather pattern, a nonlinear effect, such as whether the atmospheric circulation at any given time is primarily zonal or wavy, what is the location and intensity of ridge-trough pressure systems, or is the atmospheric state represented by the negative or positive Arctic Oscillation (AO).

The range of controversy on Linkages provides relevant scientific questions (National Academy of Sciences, 2014; Barnes and Screen, 2015). Does one consider recent extremes as part of the preexisting climatology? Is the known Arctic amplification important additional information for the Linkages issue, and how do we incorporate this information? How do we interpret the lack of consistent one-to-one correspondence of cause and effect in data and models? How do we broadly communicate this uncertainty?

2. The null hypothesis

A null hypothesis refers to a default proposition that there is no relationship between two phenomena. In the significance testing of Fisher, a Frequentist approach, a null hypothesis is rejected on the basis of data, given that it is significantly unlikely that the null hypothesis is true. The null hypothesis itself is never accepted or proved. The test for the mean value of a data set to be different from a population mean is given by the *t*-test, with the t-statistic:

$$t = \frac{\overline{x} - \mu}{s/\sqrt{n}}$$

$\overline{x}$ is the sample mean, μ is the population mean, s is the sample standard deviation, and n is the sample size. The null hypothesis is rejected if the *t*-statistic is greater than a p-value of a random distribution for a given significance level, usually 5%. The significance level is the chance of a Type I error, accepting a false hypothesis. The value of s represents the variability of the time series under investigation and the *t*-statistic increases as s decreases. The *t*-statistic increases with n with a reduced rate based on the square root dependence; it increases by a factor of more than two as n increases from 10 to 50. It is often recommended that the *t*-test be used for $n > 30$, as the statistical inference becomes less sensitive to n and more sensitive to s (Kar and Ramalingam, 2013). Using this test is not viable for Linkages, as Arctic Amplification is dominant only in the last 15 years (Jeffries et al., 2013; Lindsay and Schweiger, 2015).

Discussion of the "no change" null hypothesis for Linkages under short time series brings us to consider an alternate hypothesis: that we have additional information of changes in global and Arctic forcing in the last decade. Indeed, on the planetary level, global warming is "unequivocal" and "very likely" caused by human activities (Trenberth, 2011). Arctic Amplification is beyond doubt. Perhaps a default hypothesis is one of change. In Bayesian statistics, this additional information is thought of as adding a prior. Thus, not being able to reject the no-change null hypothesis may be too conservative on the Linkage issue. Accepting prior information elevates the science issue to a risk-avoidance approach for global change impacts.

A Bayesian view emphasizes that changes in probability statements about the world are introduced mathematically and philosophically as we acquire more evidence (Silver, 2012). Occurrence of Arctic Amplification over the previous decade and in projections for the future provide increased forcing that potentially could have an impact on atmospheric circulation (Walsh, 2014; Barnes et al., 2014). Variability of atmospheric circulation within the previous decade, however, does not provide statistical proof that recent atmospheric extremes are different from random. The Bayesian issue is that we still do not know how to physically interpret these recent extremes; are they part of the climatology or samples of newly forced conditions by known Arctic or equatorial changes buried in noise (Jaiser et al., 2012; Palmer, 2014)?

Some of the controversy over Linkages results from individual scientist's approach to null hypothesis versus risk avoidance. Viewpoints contrast the evolution of random weather features versus a potential shift in the externally driven probability of occurrence (Otto et al., 2012). We take up this issue in the next section.

3. Events versus climatology

Cohen et al. (2014) and Kug et al. (2015) both show winter cooling trends over eastern North America and central-eastern Asia since 1999 (Fig. 1). Such trends are not seen over longer periods. Nakamura et al. (2015) show a correlation between loss of sea ice and negative temperature anomalies at the same eastern continental locations. While these maps show significant correlations and are suggestive of causation by the Arctic, they are not conclusive as the sample period is short, as noted in the previous section, and other forcings may be active. There is, however, little support for seasonal average midlatitude cooling trends in temperature or increases in extreme events over hemispheric or large geographic regions in data, as shown by Screen and Simmonds (2013), Barnes (2013), Perlwitz et al. (2015), Horton et al. (2015), and Screen et al. (2015). These results suggest that if Linkages exist they are regional in extent and episodic; i.e., they do not show regular linear trends.

There is emerging evidence of physical mechanisms for Linkages based on limited case studies in north-central Asia. A series of studies, performed with different analyses based on observations and model experiments, provides evidence of a potential linkage between regional loss of sea ice in the Barents-Kara Seas and the tendency for wave trains that lead to cold surges in central Asia and stormy regimes along the east coast of Asia (Kim et al., 2014). Over the last decade, cold-air outbreaks in winter have occurred more frequently over East Asia, and they are stronger and last longer than in the 1990s during negative phases of the AO (Kug et al., 2015; Overland et al., 2015). During recent autumns through winters that have anomalously high Arctic temperatures, resulting from new sea ice loss in the Kara Sea and extending eastward along the Siberian coast, north-south temperature gradients are lessened, which in turn reduce the westerly wind component (Outten and Esau, 2012) and strengthen the Siberian High (Takaya and Nakamura, 2005; Takano et al., 2008; Jeong et al., 2011; Inoue et al., 2012; Son et al., 2012). In data (Wu et al., 2013) and a numerical experiments (Honda et al., 2009; Mori et al., 2014; Kug et al., 2015), sea ice loss in the Barents-Kara Seas leads to an increase in northerly wind cold-air outbreak events in north central and east Asia (Hori et al., 2011). Woo et al. (2012) showed that the cold surge is stronger and longer under the negative AO. Such connections are complex, however, involving a chain of causality and multiple interacting time scales. Loss and thinning of sea ice is on a seasonal scale, enhancement of the Siberian high is on a weekly-to-monthly scale, and multiple cold surges are on the synoptic scale (<weekly).

Potential Linkages in North America are even more speculative. Several authors note major negative AO events in recent years (e.g. Cattiaux et al., 2010; L'Heureux et al., 2010; Santo et al., 2013) and their connection to warm atmospheric conditions west of

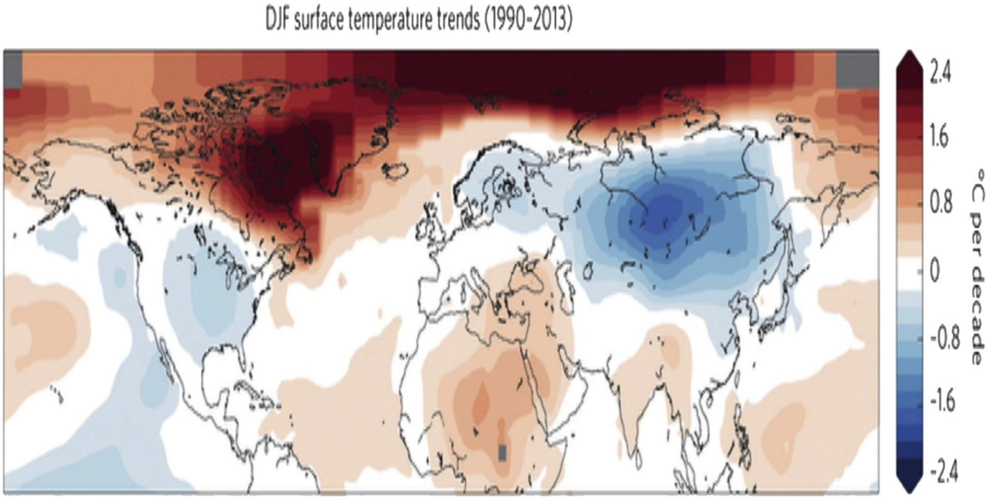

Fig. 1. Linear trend (°C per 10 years) in December–February (DJF) mean surface air temperatures from 1990/91 to 2013/14. Shading interval every 0.2 °C per 10 years. Figure from Cohen et al. (2014) and data from http://data.giss.nasa.gov/gistemp.

Greenland. We note in five recent early winters, 2009/10 through 2013/14, there were three Decembers and three Januaries when the negative AO was −1.0 or less:

(http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml).

The similarity of the meteorological fields for North America during these recent Decembers and Januaries allows compositing of four early winters when the negative AO was −1.0 or less in at least one of the two months (2009/10, 2010/11, 2012/13, and 2013/14). The composite 500–1000 hPa geopotential thickness anomaly field has major positive values and warm temperatures over Baffin Bay and Davis Strait (Fig. 2a). Composite December–January geopotential height and anomaly fields had a high over Greenland and a broad trough of lower heights over Hudson Bay and extending eastward across the Atlantic south of Greenland. Such a height field configuration gives a cool temperatures (lower thickness values) and northerly meridional wind component anomaly over central Canada and into the U.S. [Fig. 2(a) (b)]. The direct impact of positive low-level temperature anomalies over Baffin and Hudson Bay and a southerly wind component northeast of Hudson Bay that advects warmer air into the Davis Strait/Baffin Bay region reinforce the positive geopotential thickness anomaly with downstream impacts on midlatitude cold air outbreaks over eastern North America (Overland and Wang, 2015). Fig. 2 shows reinforcement of a negative anomaly by cold air advection over central North America.

4. Conditional dependence

Regional mechanisms for eastern Asia and North America in the previous section can be summarized by Fig. 3 that shows a chain of connections to parse potential Linkages (from Overland et al., 2015). The length of the chain itself suggests difficulties in connecting causality. The top link is well documented Arctic Amplification, that Arctic temperatures are increasing faster than at midlatitudes. The second link connects increased temperatures to changes in wind through changes in geopotential height field. The last two links state that large-amplitude planetary waves in the jet stream tend to progress more slowly, which favors persistent weather events (Francis and Vavrus, 2012, 2015). The dotted link in the middle of the chain, based on regional dynamics, represents the largest uncertainty in the Arctic/midlatitude causal Linkage.

With regard to large-scale climate variations, Trenberth (2011) and Shepherd (2014) note that thermodynamic aspects of change (temperature, water vapor, sea ice) tend to be robust, while dynamic aspects are not so robust. For atmospheric circulation, chaotic internal variability often dominates over multiple sources of external forcing. Such logic can also apply to Arctic forced Linkages. Linkages can be *conditionally* dependent based on different atmospheric circulation regimes. Essentially, the chaotic part of circulation variability can be carried by the dynamics depending on which circulation regime is present, and regional thermodynamics can reinforce the particular pattern. For example, positive AO would have strong midlatitude westerlies, where air masses would not have sufficient time to be modified by regional thermodynamic forcing. The more meridional circulation of a negative AO and slow eastward propagation for ridge-trough systems would increase interaction times. This conditional dependence fits the case studies in the previous section; different years have different large-scale atmospheric circulation regimes, in line with the year-to-year and within seasonal variability in observations.

Internal variability of the midlatitude atmospheric circulation variability is large. The recent decade does not show a trend in the mean AO value but does show an increase in December variance with extremes of both signs (Overland and Wang, 2015). Model studies can show either an Arctic/midlatitude Linkage or no effect based on different ensemble members of the same initial runs (Orsolini et al., 2012). Mori et al. (2014) make use of 100 ensemble members to obtain robust conclusions relative to energetic internal fluctuations in the atmospheric circulation. On year-to-year timescales, the upper-tropospheric jet over the Atlantic can vary in location by up to 10° latitude (Woolings et al., 2014; Hall et al., 2014). Any potential linkage of Arctic forcing to the long-wave atmospheric circulation would represent a small signal in background variability (Sokolova et al., 2007; Strey et al., 2010; Balmaseda et al., 2010; Hopsch et al., 2012; Liu et al., 2012; Rinke et al., 2013; Tang et al., 2013). Screen et al. (2014) concluded that it would take 50 years or more for the forced signal in the large-scale winds to be distinguishable from internal variability. Fig. 4, taken from Nakamura et al. (2015), shows the distribution of an AO index for model cases with diminished sea ice and a control run; while the distribution is skewed toward negative AO for the diminished sea ice cases, there are many individual events of both

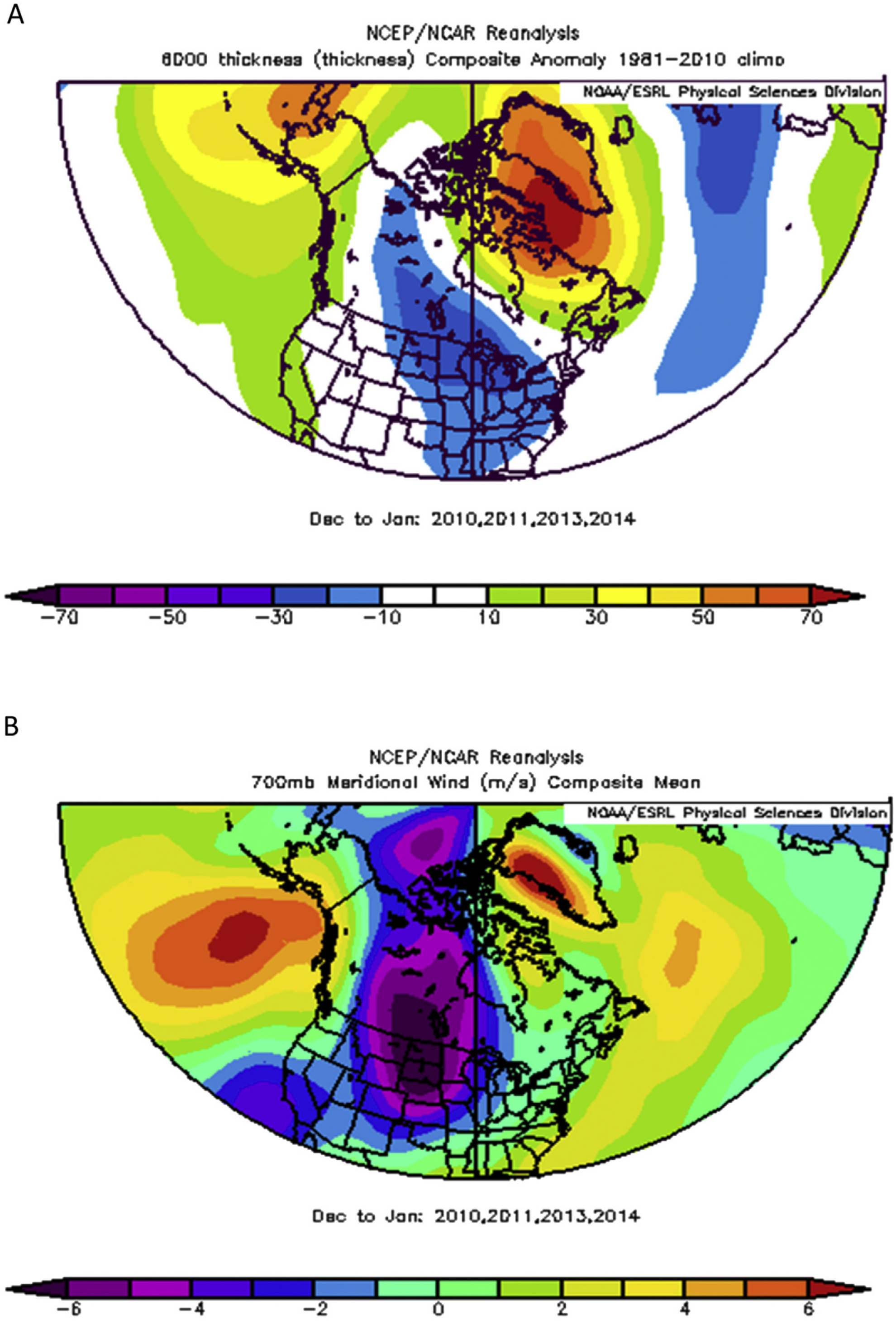

Fig. 2. (a). Composite 1000–500-hPa geopotential thickness (m) for December–January 2009/10, 2010/11, 2012/13, 2013/14; (b) Meridional 700-hPa wind component (m/s) for the same months; blue shading indicates winds from the north reaching into the southeastern United States. Data are from NCEP–NCAR reanalysis through the NOAA/ESRL website.

signs for both the sea ice and control run. Given the large chaotic internal variability of midlatitude atmospheric circulation and with most changes in the Arctic taking place after 2005, it is questionable whether linear trend analyses of multi-decadal time series, or positive or negative results from models, are definitive in proving or disproving recent potential Linkages.

A further issue is that tropical and midlatitude teleconnections may help initiate subarctic temperature and height anomalies. Ding et al. (2014) suggest that the recent rapid warming of northeastern Canada and Greenland has a tropical component. The re-emergence in winter 2014/15 of the positive Pacific Decadal Oscillation with positive SST anomalies in the northeastern North Pacific contributed to shifting the North American ridge-trough alignment eastward toward the Atlantic. Perlwitz et al. (2015) also indicate the importance of tropical and North Pacific connections. Sato et al. (2014) note an influence of the Gulf Stream on the Barents Sea ice

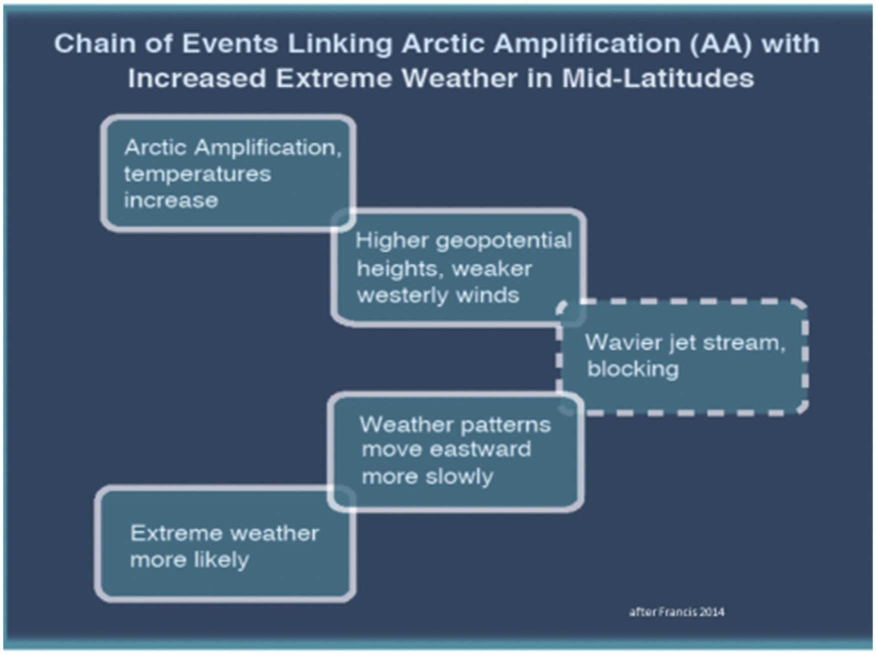

Fig. 3. Hypothesized steps linking Arctic amplification with extreme weather events in Northern Hemisphere midlatitudes. Figure from Overland et al. (2015).

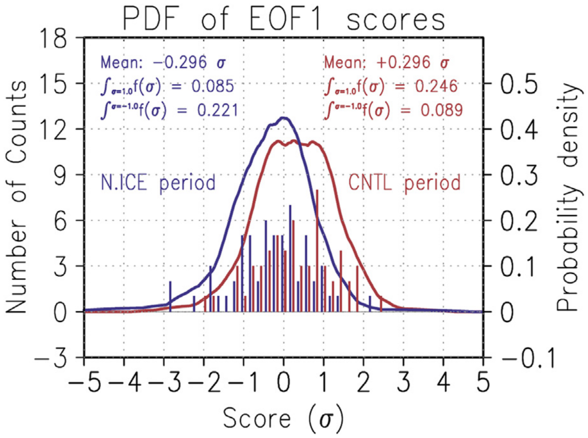

Fig. 4. Histogram of the EOF1 score from the combined EOF (0.2σ bins); red and blue bars indicate the CNTL and N.ICE periods, respectively. The horizontal axis shows scores for the center of each bin. The vertical axis on the left-hand side indicates the number of counts for each bin. Lines indicate the probability density function (PDF) estimated from the EOF1 score for the CNTL (red) and N.ICE (blue) periods, respectively. The vertical axis on the right-hand side indicates probability density. The mean score and the integral of the PDF above (below) 1.0σ (−1.0σ) are shown in the panel in the colors corresponding to CNTL and N.ICE (red and blue, respectively). Figure from Nakamura et al. (2015).

retreat and Eurasian coldness during early winter. Such connections are not incompatible with the conditional dependence hypothesis, where large-scale patterns from teleconnection dynamics are reinforced locally by thermodynamics.

5. An example of Bayes theorem

Bayes theorem can be used to potentially contrast the contribution from increasing Arctic forcing versus the large noise component from midlatitude chaotic flow in assessing whether the Arctic may have an influence on midlatitude weather. A prior probability (X) is taken from the fact that the Arctic has changed in the last decade and will continue to change through multiple Arctic amplification processes (Jeffries et al., 2013). Arctic temperatures are increasing two or more times greater than mid-continent values. Maximum increases are regional over reduced sea ice areas of Baffin Bay, Barents-Kara Seas, and north of eastern Siberia. For an estimate of X we have the large change in the fraction of open water area for the Arctic Ocean at the end of summer two decades ago (~0.0), at present (~0.4), and an increase to ~0.9 over the next decades as a surrogate for overall Arctic amplification (Zhang and Knutson, 2013; Overland et al., 2014). Increase in open water area is a direct heat source that is given to the atmosphere in autumn and early winter, and affects the geopotential height field throughout the troposphere (Walsh, 2014). Although loss of sea ice and related heat storage and sea-air fluxes is not the only process that is active, other indices such as reduced meridional temperature gradients or modification of the jet stream are more difficult to quantify.

Major organized climate patterns identified by the Empirical Orthogonal Function (EOF 1–3) loading patterns represent less than 50% of total variability, with the AO representing about 23% of the variance of sea level pressure at 20–90°N (Overland et al., 2008). The probability of observing a linkage, conditional that the linkage is true (Y), can be represented by the fraction of variability of the large-scale circulation associated with the AO; thus Y can be set with a low value of ~0.2. Wu et al. (2013) also noted that the leading pattern of winter daily 850-hPa wind variability over northern Eurasia accounts for 18% of the total anomalous kinetic energy, and is associated with negative surface temperature anomalies over the mid-to high latitudes of Asia and loss of sea ice. Finally, the condition of seeing a change in midlatitude circulation, given that the linkage hypothesis is false (Z), is taken as the fraction of unaccounted noise variance of the circulation (~0.5).

From Bayes theorem:

$$\frac{XY}{XY + Z(1 - X)}$$

gives a posteriori probability of a Linkage contribution of 0.21 at present and increases to 0.78 in roughly three decades. Such a calculation suggests, based on reasonably selected, large and small but inexactly known values of *X*, *Y*, and *Z*, that midlatitude noise dominates the Linkage hypothesis at present, but one should see the emergence of evidence for an Arctic Linkage from the noise in the future due to the shift in *X* before mid-century. Such a result is consistent with the current lack of clear statistical significance in recent studies given in Section 3. Even in the future, Linkages will represent a small part of northern hemispheric atmospheric circulation variability.

6. Summary

Contrasting a Bayesian versus Frequentist (null hypothesis) approach to the scientific method of interpretation of recently observed events highlights recent controversy on Linkages. Impacts from the Siberian High on cold temperatures in eastern Asia, and increased geopotential thickness west of Greenland with severe weather in the central and eastern U.S., suggest possible mechanisms for Linkages. However, data length is too short to robustly attribute these case studies to external Arctic forcing rather than a chaotic view of high latitude atmospheric circulation, such as atmospheric blocking events or hemispheric teleconnections (Barnes, 2013; Ding et al., 2014; Francis and Vavrus, 2015; Screen et al., 2015). There is little support for seasonal Linkage impacts over large midlatitude regions, other than those associated with global warming (Wallace et al., 2014; Perlwitz et al., 2015; Screen et al., 2015). Yet the null hypothesis of no Arctic influence is also not proven. It does not seem unreasonable to include information on recent Arctic change as prior information in addressing the Linkage issue.

Conditional dependency can be considered a conceptual model to account for some of the observed variability in Linkages. Thus, if there is an Arctic influence on midlatitude cold events, it is episodic and regional. The main difficulties is that Arctic Linkages remain buried in internal chaotic variability where the connections can be nonlinear, based on conditional dependence and midlatitude and tropical teleconnections, as well as direct Arctic forcing. While Linkage mechanisms do exist, it is important not to overstate their potential causality relative to chaotic variability and other forcings, especially to a broad audience (Barnes and Screen, 2015). If we focus on the goal of improving weekly to seasonal forecasts, one should consider a possible emergence of an Arctic change impact on midlatitude weather as an important research challenge. Progress can be made through international cooperation as prioritized by the new first International Arctic Science Council (IASC) goal: Assessing and understanding rapid Arctic climate change and connections to the global climate system.

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