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ARCTIC CHANGE AND POSSIBLE INFLUENCE ON MID-LATITUDE CLIMATE AND WEATHER:

A US CLIVAR White Paper

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EXECUTIVE SUMMARY

The Arctic has warmed more than twice as fast as the global average since the mid 20th century, a phenomenon known as Arctic amplification (AA). These profound changes to the Arctic system have coincided with a period of ostensibly more frequent events of extreme weather across the Northern Hemisphere (NH) mid-latitudes, including extreme heat and rainfall events and recent severe winters. Though winter temperatures have generally warmed since 1960 over mid-to-high latitudes, the acceleration in the rate of warming at high-latitudes, relative to the rest of the NH, started approximately in 1990. Trends since 1990 show cooling over the NH continents, especially in Northern Eurasia.

The possible link between Arctic change and mid-latitude climate and weather has spurred a rush of new observational and modeling studies. A number of workshops held during 2013–2014 have helped frame the problem and have called for continuing and enhancing efforts for improving our understanding of Arctic-mid-latitude linkages and its attribution to the occurrence of extreme climate and weather events. Although these workshops have outlined some of the major challenges and provided broad recommendations, further efforts are needed to synthesize the diversified research results to identify where community consensus and gaps exist.

Building upon findings and recommendations of the previous workshops, the US CLIVAR Working Group on Arctic Change and Possible Influence on Mid-latitude Climate and Weather convened an international workshop at Georgetown University in Washington, DC, on February 1–3, 2017. Experts in the fields of atmosphere, ocean, and cryosphere sciences assembled to assess the rapidly evolving state of understanding, identify consensus on knowledge and gaps in research, and develop specific actions to accelerate progress within the research community. With more than 100 participants, the workshop was the largest and most comprehensive gathering of climate scientists to address the topic to date. In this white paper, we synthesize and discuss outcomes from this workshop and activities involving many of the working group members.

Workshop findings

Rapid Arctic change – Emergence of new forcing (external and internal) of atmospheric circulation: Rapid Arctic change is evident in the observations and is simulated and projected by global climate models. AA has been attributed to sea ice and snow decline (regionally and seasonally varying). However this cannot explain why AA is greatest in winter and weakest in summer. It was argued at the workshop that other factors can also greatly contribute to AA including: increased downwelling longwave radiation from greenhouse gases (including greater water vapor concentrations from local and remote sources); increasing ocean heat content, due to local and remote processes; regional and hemispheric atmospheric circulation changes; increased poleward heat transport in the atmosphere and ocean; and cloud radiative forcing. In particular, there is emerging observational evidence that an enhanced poleward transport of sensible and latent heat plays a very important role in the AA of the recent decades, and that this enhancement is mostly fueled by changes in the atmospheric circulation. We concluded that our understanding of AA is incomplete, especially the relative contributions from the different radiative, thermodynamic, and dynamic processes.

Arctic mid-latitude linkages – Focusing on seasonal and regional linkages and addressing sources of inconsistency and uncertainty among studies: The topic of Arctic mid-latitude linkages is controversial and was vigorously debated at the workshop. However, we concluded that rapid Arctic change is contributing to changes in mid-latitude climate and weather, as well as the occurrence of extreme events. But how significant the contribution is and what mechanisms are responsible are less well understood. Based on the synthesis efforts of observational and modeling studies, we identified a list of proposed physical processes or mechanisms that may play important roles in linking Arctic change to mid-latitude climate and weather. The list, ordered from high to low confidence, includes: increasing geopotential thickness over the polar cap; weakening of the thermal wind; modulating stratosphere-troposphere coupling; exciting anomalous planetary waves or stationary Rossby wave trains in winter and modulating transient synoptic waves in summer; altering storm tracks and behavior of blockings; and increasing frequency of occurrence of summer wave resonance. The pathway considered most robust is the propagation of planetary/ Rossby waves excited by the diminished Barents-Kara sea ice, contributing to a northwestward expansion and intensification of the Siberian high leading to cold Eurasian winters.

Opportunities and recommendations—An important goal of the workshop was achieved: to hasten progress towards consensus understanding and identification of knowledge gaps. Based on the workshop findings, we identify specific opportunities to utilize observations and models, particularly a combination of them, to enable and accelerate progress in determining the mechanisms of rapid Arctic change and its mid-latitude linkages.

Observations: Due to the remoteness and harsh environmental conditions of the Arctic, *in situ* observational time series are highly limited spatially and temporally in the region.

Six recommendations to expand approaches using observational datasets and analyses of Arctic change and mid-latitude linkages include:

1. Synthesize new Arctic observations;
2. Create physically-based sea ice–ocean surface forcing datasets;
3. Systematically employ proven and new metrics;
4. Analyze paleoclimate data and new longer observational datasets;
5. Utilize new observational analysis methods that extend beyond correlative relationships; and
6. Consider both established and new theories of atmospheric and oceanic dynamics to interpret and guide observational and modeling studies.

Model experiments: We acknowledge that models provide the primary tool for gaining a mechanistic understanding of variability and change in the Arctic and at mid-latitudes. Coordinated modeling studies should include approaches using a hierarchy of models from conceptual, simple component, or coupled models to complex atmospheric climate models or fully coupled Earth system models. We further recommend to force dynamical models with consistent boundary forcings.

Three recommendations to advance modeling and synthesis understanding of Arctic change and mid-latitude linkages include:

1. Establish a Modeling Task Force to plan protocols, forcing, and output parameters for coordinated modeling experiments (Polar Amplification Model Intercomparison Project; PAMIP);
2. Furnish experiment datasets to the community through open access (via Earth System Grid); and
3. Promote analysis within the community of the coordinated modeling experiments to understand mechanisms for AA and to further understand pathways for Arctic mid-latitude linkages.

1 The character and mechanisms of Arctic Amplification

In light of recent scientific advances, the community should quantify the relative importance of processes that give rise to rapid Arctic warming and determine in what measure each process modulates how Arctic warming influences mid-latitude weather and climate variability.

The Arctic has warmed more than twice as fast as the global average since the mid 20th century (e.g., Blunden and Arndt 2012), a phenomenon referred to as Arctic Amplification (AA). In particular, AA was further enhanced during 1998–2012, showing a warming rate more than six times the global average (Huang et al. 2017). The high sensitivity of the Arctic climate change has been known for some time (Manabe and Wetherald 1975). Beginning with this early paper and reiterated recently, the high sensitivity of the Arctic climate to external forcing has been largely attributed to the reduction in the Arctic surface albedo. Our understanding of the mechanisms contributing to the enhanced Arctic warming, however, has significantly evolved in the last couple of decades, finding that other mechanisms may be more important, thus altering the currently accepted chain of causality.

Observed Arctic changes

For brevity, we limit the discussion of recent Arctic climate changes to surface temperature and sea ice, even though there are other notable changes (e.g., Greenland Ice Sheet and permafrost degradation). Figure 1a shows Arctic averaged surface air temperature (SAT) trends between 1981–2014. Arctic warming is evident in these datasets, with strongest warming during fall and weakest during summer. The vertical distribution of Arctic temperature trends, as reconstructed by reanalyses, shows warming that extends throughout the troposphere but strongest near the surface (Figure 1b–e).

Arctic climate change manifests visibly in the declining perennial sea ice cover (Kwok et al. 2009; Lang et al. 2017), which has intensified over the last few decades, resulting in a record minimum sea ice extent in September 2007 and a new record in 2012 (Figure 2; e.g., Comiso et al. 2008; Zhang et al. 2008). Seasonally, sea ice decline is most prominent over

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the western Arctic Ocean in summer and over the Nordic/Barents/Kara seas in winter (Figure 2). Additionally, the time between the spring melt and the fall freeze-up increased by roughly 5–11 days per decade. This lengthening of the sea ice-free season has been shown to influence the interactions between the Arctic atmosphere and surface (Stroeve et al. 2014).

Despite robust observed signals of AA, our knowledge of the mechanisms contributing to AA and their seasonal dependence remains incomplete. At the workshop, we agreed that the nature of AA, including its magnitude and mechanisms, likely influences the temporal and spatial character of Arctic and mid-latitude climate and weather linkages.

Arctic amplification mechanisms

The mechanisms of AA can be divided into two groups: local forcing and remote forcing. The local forcing group includes radiative forcing (from both greenhouse gases and cloudiness), sea ice-albedo feedback, lapse rate feedback, and surface turbulent heat fluxes from the Arctic Ocean. The conventional viewpoint places local forcing mechanisms as the trigger in the causal chain leading to AA (Manabe and Wetherald 1975). Mechanisms in the remote forcing group represent newer research, including forcing from the mid-latitudes and tropics, which are subsequently amplified by various feedback processes.

It can often be challenging to distinguish between the local and remote forcing. For example, an increase in Arctic clouds and atmospheric water vapor could result from a local forcing if cloud properties change in response to reduced sea ice cover. Alternatively, remote forcing can alter clouds through a change in moisture transport from lower latitudes. In either case, any increase in Arctic heating will be magnified owing to a variety of positive feedbacks involving ice, snow, and particular characteristics of the Arctic atmosphere.

Perhaps the best-known sensitivity in the Arctic is the sea ice albedo feedback (Perovich et al. 2008), owing its existence to the stark difference in albedo between open water and snow-covered sea ice surfaces (cf. ~7% with ~80% reflectance, respectively). The sea ice albedo feedback links the disappearance of sea ice to Arctic lower tropospheric warming and the subsequent melting of sea ice, and it has become common practice to conflate the two on climatological time scales (Screen and Simmonds 2010). However, modeling studies indicate that AA can occur in the absence of the sea ice albedo feedback (Alexeev et al. 2005), even though changes in sea ice have certainly altered the Arctic surface energy budget (Pistone et al. 2014). Recent research has forced us to question the role of sea ice albedo feedback in the causal chain driving AA. One outcome of the workshop was the need to disentangle the contributions of local and remote forcing on AA as a way to better guide scientific efforts on the issue of Arctic and mid-latitude linkages.

Surface turbulent fluxes of sensible and latent heat represent an important medium of transferring local forcing due to increasingly exposed warm ocean water into a mechanism for AA. Declining sea ice cover and extent (Figure 2) have enabled enhanced air-sea energy exchanges in recent years (Figure 3; Boisvert et al. 2015; Taylor et al. 2018).

Regional and seasonal variations in surface turbulent flux trends (Figure 3, top panels) may be important characteristics of AA and potential Arctic and mid-latitude linkages (Honda

2009; Peings and Magnusdottir 2014; Feldstein and Lee 2014; Cohen et al. 2014; Kim et al. 2014). The largest increases in surface turbulent heat fluxes from the ocean to the atmosphere are found in the Chukchi and Kara seas. It is important to note that not all trends are positive. For instance, over the Bering Sea, Barents Sea, and the waters surrounding Greenland, both sensible (not shown) and latent heat flux trends are from the atmosphere into the ocean (negative in Figure 3 top left panel). However, over most of the Arctic, sensible and latent heat flux trends are small. An additional mechanism is that anomalous warmth in the lower atmosphere and surface are maintained longer into the early winter season, which supports larger geopotential thickness values (Figure 1, right) that, in turn, reduce poleward gradients and ultimately feed back into wind fields.

An equal, or possibly more important, sensitivity relates to the role of clouds in the surface energy budget. Arctic clouds warm the surface via enhanced downwelling longwave radiation for much of the year, except during June and July when the shortwave cloud radiative effect dominates, cooling the surface (Kay and L'Ecuyer 2013). The shortwave cloud effect is further complicated by the seasonal evolution of surface albedo. During summer, for instance, the surface albedo decreases owing to increased open ocean areas and melt pond fraction (Intrieri et al. 2002). The surface energy budget in climate models is also very sensitive to clouds. For example, small errors in simulating cloud amount and the cloud liquid/ice water optical path may be sufficient to perturb the surface energy balance and greatly influence sea ice concentrations simulated by climate models. Results presented at the workshop indicate that the Fifth Coupled Model Intercomparison Project (CMIP5) climate models disagree about whether Arctic cloud changes dampen or amplify AA (Taylor et al. 2017). This lack of consensus among models could be due to a number of factors discussed later.

The importance of downward longwave radiation on AA and sea ice has been identified by a number of studies (Uttal et al. 2002; Francis et al. 2005; Screen 2017). With respect to sea ice cover, emerging evidence suggests that anomalous cloud cover and downward longwave radiation during winter can hinder sea ice growth, thus impacting Arctic sea ice cover the following summer (Liu and Key 2014; Lee 2014; H.-S. Park et al. 2015b). As presented at the workshop, the CMIP5 climate models indicate that changes in the downwelling clear-sky longwave flux from the atmosphere, rather than the surface albedo feedback, are the largest contributing factor to simulated AA (Taylor et al. 2017), depending on partitioning of downward longwave and shortwave radiation due to cloud effects. The downward longwave radiation trend is positive almost everywhere over the Arctic Ocean for all seasons (Figure 3, bottom panel). The spatial trend patterns are substantially different from the corresponding surface heat flux, which exhibits both positive and negative signs (Figure 3, top panels). This dissonance in their trend patterns is consistent with the importance of the remote driving of the downward longwave radiation trends. During the period when AA has occurred and Arctic sea ice decrease has accelerated, it has been found that poleward atmospheric heat and moisture transport has been enhanced (Zhang et al. 2008; 2013), which acts as a remote driving of formation of clouds and increase in downward longwave radiation. Based on *in situ* measurements over Eureka, Canada (80°N, 86°W), Doyle et al. (2011) also report that warm, moist air intrusion events and attendant cloud radiative forcing regularly occur in Arctic winter (Kapsch et al. 2016). It was found that extreme warm and moist air intrusion from the North Atlantic into the Arctic can cause extreme warming event (Kim et al. 2017). This extreme intrusion occurs associated with poleward propagation of intense storms, which could be a manifestation of a long-term poleward shift of storm tracks (e.g., Zhang, et al. 2004; Serreze and Barrett 2008; Sepp and Jaagus 2011). Other recent studies have also highlighted the importance of spring extreme moisture transport into the Arctic in controlling the minimum sea-ice extent in the following September (Kapsch et al. 2013, Yang and Magnusdottir 2017, Yang and Magnusdottir 2018). Moisture transport is most pronounced through the N. Atlantic pathway and is favored during the Atlantic blocking weather regime (Yang and Magnusdottir 2017).

A comprehensive mechanistic understanding of AA requires knowledge of the source of increased Arctic heat and water vapor, as local sensible heat flux and evaporation versus remote transport have different implications to the causal chain of events leading to AA. The primary source of the Arctic atmospheric water is currently unclear. From the local process perspective, fluxes from the Arctic Ocean are obvious candidates. But with a global reanalysis dataset, it has been shown that over the past several decades horizontal moisture transport from lower latitudes has been a predominant source (Zhang et al. 2013), which could be a significant contributor to AA in the western Arctic during both winter (D.-S. Park et al. 2015a; Gong et al. 2017) and summer (Laliberté and Kushner 2014; Ding et al. 2017).

Tropical convection may also play an important role in forcing AA via heat and moisture transports during the cold season when the strong subtropical jet provides fertile grounds for a convection-driven Rossby wave source. Tropical convection can excite moisture intrusion events and Arctic warming on inter-decadal timescales (Lee et al. 2011; Cvijanovic et al. 2017) and in association with ENSO (Lee 2012). Furthermore, intraseasonal tropical convection also appears to influence daily Arctic surface temperature and sea ice concentration via the Madden Julian Oscillation (MJO) phase 5 in both summer and winter (Yoo et al. 2012a,b; Henderson et al. 2014). These heat and moisture transports are enhanced by poleward propagating Rossby waves, excited by the tropical convection, that constructively interfere with the climatological stationary eddies (Lee 2014; Goss et al. 2016; Cvijanovic et al 2017). Energetically, the convectively generated Rossby waves can warm the Arctic by releasing the mostly untapped zonal available potential energy, a process very effective at driving AA (Lee 2014).

Inter-model spread in AA

Despite unanimous agreement for the existence of AA, current-generation models strongly disagree on the overall strength and individual process contributions to rapid Arctic warming (Figure 4). The causes of this large inter-model spread in Arctic warming relate to many possible limitations in our modeling capabilities. In particular, uncertainties in model parameterizations hinder our ability to predict/project future Arctic sea ice extent and its potential interaction with mid-latitudes. Cloud microphysics, convection, boundary layer processes, and surface turbulent flux parameterizations primarily developed to ensure accurate forecasts in the tropics and the mid-latitudes are inadequate at high-latitudes (Bourassa et al. 2013). In fact, because tropical convective heating also triggers Arctic warming through Rossby wave propagation, inaccuracies outside of the Arctic, such as tropical convective parameterizations, could contribute to the uncertainty in the large-scale circulation (Stevens and Bony 2013; Sohn et al. 2016), hence Arctic warming. Deficiencies have also been identified in how models approximate the surface mass and momentum budget, including: surface albedo parameterizations (Dorn et al. 2009); sea ice rheology (Girard et al. 2009); fluxes across the atmosphere-ice-ocean boundary layer (Dorn et al. 2009; Hunke 2010); cloud radiative properties and simulation (Bromwich et al. 2009), and numerical techniques (Losch et al. 2010). This wide range of relevant processes speaks to the need for coupled models to realistically represent Arctic sea ice (Deser et al. 2015). Given these limitations, perhaps it is not surprising that the current generation of models disagree on the strength of the AA (Figure 4).

Improving our understanding of AA

Improving our understanding of AA requires increased accuracy of climate models and, therefore, improved process-level understanding. One major barrier to the development of the parameterizations specific to high-latitudes is the sparsity of observations, especially during the polar night. The logistics of cold and remote places demand that in situ data collection occur in short-lived and/or spatially concentrated field campaigns (Perovich et al. 1999; Wullschleger et al. 2011). Processes on scales of 1–10 km and 10 minutes to 6 hours are seldom resolved in the observational record, yet observational and modeling evidence indicates the importance of fine-scale features, especially in understanding Arctic interactions with the larger scales (Overland et al. 1995; Weiss and Marsan 2004). Moisture intrusions into the Arctic are often realized through atmospheric rivers (Liu and Barnes 2015; Baggett et al. 2016), yet they are not well represented by the current conventional climate models (Shields and Kiehl 2016). To address model deficiencies, we need ongoing and future field campaigns in all seasons that resolve key Arctic processes, including cloud-aerosol interactions, surface energy fluxes, sea ice processes, and snow on sea ice. We expect that progress on the polar atmospheric physics will be made possible through the assimilation of observations obtained during the Year of Polar Prediction and through other targeted field campaigns (e.g., MOSAiC and airborne Arctic cloud-aerosol measurements).

It has been well investigated that changes in the atmospheric circulation and resulting enhancement of poleward heat and moist air transport into the Arctic Ocean play an important role in causing Arctic warming and sea ice decrease (Rigor et al. 2002; Zhang et al. 2003). Recently studies further examined the observed structure of atmospheric warming. Although sea ice decline is found to be responsible for the recent Arctic warming (Screen and Simmonds 2010), it has recently been shown that remotely forced warming can also generate a bottom-heavy warming structure (Zhang et al. 2008; Yoo et al. 2013; Woods and Caballero 2016; Kim et al. 2017). Therefore, at least one symptom that had been perceived as key evidence of sea ice melting influencing AA could also be a consequence of warm, moist air intrusions. Whether the frequency and amplitude of moisture intrusions into the Arctic are changing remains an open question. Wood and Caballero (2016) find an increased frequency of moisture intrusions in the Barents and Kara seas, which would be attributed to changes in transient storm track dynamics (e.g. Zhang et al. 2004; Yin 2005; Villamil-Otero et al. 2018). Further research on this question is recommended.

A more realistic simulation of time-dependent conditions of the Arctic sea ice cover and its effect on air-sea interactions is needed and requires coupled models. In addition, seasonal space-time variability in the extent of snow cover over Arctic land areas, land surface water, and energy budgets of seasonal permafrost melt are not well represented in most coupled land-atmosphere-sea ice models (Vaganov et al. 2000). Disentangling the relative importance of these and other sources of uncertainty in modeling Arctic sea ice and climate presents a major challenge. Part of the solution rests in improving the representation of processes within models through increased resolution and improved parameterizations. Another part lies in increasing the number of Arctic processes included in models. There is growing interest in the combined use of global Earth system models with regional models to better characterize uncertainty and improve probabilistic projections (Giorgi 2005). We argue that it is critical to advance hierarchical climate modeling (Maslowski et al. 2012) coordinated with the future Arctic observing system.

Beyond model improvements, we recommend analyses of the chain of events leading to AA in the current generation of models. Such analyses would identify dynamical and process differences between models and observations, helping to pinpoint processes that require further observational constraint. Dynamical differences, associated with too much or too little Arctic warming, could also help the community understand the large inter-model spread. These dynamical analyses require the use of high-frequency data (daily or less; Laliberté and Kushner 2014; D.-S. Park et al. 2015; Gong et al. 2017) and/or a careful analysis of monthly changes (Krikken and Hazeleger 2015). Due to the large data volume associated with high-frequency data, the working group is aware that such an approach would likely require a sustained focus on the development of shared diagnostic tools that could easily be ported from models to reanalyses and vice versa. We support continued efforts to archive model output at daily and subdaily scales — enabling process-level model evaluation — and recommend a focused MIP) aimed at resolving the process contributions to AA in climate models. It would be further be beneficial to the community to make the model data publicly available and preferably allow users to create web-based plotting of the archived data.

2 Arctic and mid-latitude linkage physics

Understanding Arctic and mid-latitude linkages is a societally important topic but difficult given its complexity. Arctic impacts on mid-latitudes are increasing, but they are mediated by chaotic jet stream dynamics. As noted in Section I, Arctic temperatures have experienced dramatic increases with new record highs in the winters of 2015–16 and 2016–17, with a potential to modify tropospheric and stratospheric jet streams. Such impacts will play a role in future subseasonal-to-seasonal (S2S) forecasts across the mid-latitudes. The issue is difficult as mid-latitude S2S conditions are also affected by large internal variability and mid-latitude and equatorial sea surface temperature anomalies. It appears that Arctic impacts will be regional and intermittent, clouding the identification of cause-and-effect and raising the issue of how to effectively communicate potential Arctic impacts.

Figure 5 illustrates the pathways of potential linkages from global change, through AA, to large-scale atmospheric wind patterns and finally to regional weather and extreme events.

Tropospheric and stratospheric jet stream responses largely characterized by internal variability, which injects intermittency into linkage pathways, are particularly uncertain.

A well-predicted response of global climate change is the amplified Arctic warming, or AA, for the reasons noted in Section I. There is a greater thermodynamic connection of the surface with the overlying atmosphere due to extensive new sea ice-free areas in autumn and thinner sea ice in early winter months. This first link is through the thermal/geostrophic wind relationship that relates horizontal temperature gradients to vertical shear of the wind. A recent study using a regional reanalysis with the highest spatial resolution to date has revealed the complex, fine-scale relationships between winds, sea ice, and sea surface temperature, indicating an increase in surface wind towards the ice edge from both open water and thick sea ice areas (Zhang et al. 2018).

More complexity is introduced at the next stage where thermodynamic forcing and thermal wind modification in the Arctic interact with the internal variability of the tropospheric jet stream (white band in Figure 6) in the sub-Arctic, given by the gradient in the geopotential height field (Shepherd 2016). The tropospheric polar vortex structure is quasi-stable but can, chaotically to some degrees, shift between pattern shapes (such as in Figure 6a,b).

The physics driving changes in geopotential heights are described by the geopotential tendency equation (Holton 1979). Geopotential heights can change and, thus, modify wind fields by i) horizontal propagation of existing jet stream features that can be considered primarily a random part of atmospheric dynamics, ii) transport of low-level, warm air into a region, or iii) warming a region locally. Part of the difficulty with linkage research is quantifying the influence of thermal heating from Arctic sources relative to the other two contributions to geopotential height changes.

A final difficulty in the linkage chain (Figure 5) is the relationship of the large-scale atmospheric circulation patterns (Figure 6), which can last for weeks or can quickly break down, affecting local weather that can lead to extreme events. For example, the low geopotential height regions in Figure 6b can spawn local weather events regimes that travel eastward slowly, on timescales of days.

Possible links between how AA manifests and mid-latitude weather

A host of mechanisms and processes influence the surface and atmospheric temperatures in the Arctic and potentially contribute to AA as discussed in Section I. In recent years, significant attention has been given to the potential influence of AA on mid-latitude weather through its influence on the background temperature gradient and possible effects on the polar jet stream and storm track. For instance, enhanced surface turbulent fluxes from the surface to the atmosphere due to reduced sea ice cover represents a possible mechanism linking AA to mid-latitude weather. However, a probability distribution of Arctic sensible and latent heat fluxes reveals that at most times the fluxes are near zero, punctuated by significant episodic heat exchange events where surface turbulent fluxes exceed 100 W m^{-2} (Taylor et al. 2018). Therefore, the spatial variability and episodic nature of surface turbulent fluxes must be considered.

This has two very important implications for AA and its linkages to mid-latitude weather. The first, and the most important, is that the exchange of sensible and latent heat fluxes from the surface is not constant in time but state-dependent. As indicated in previous studies (e.g., Rigor et al. 2002; Zhang et al. 2003; Zhang et al. 2008), there are strong heat and moisture transport from lower latitudes into the Arctic associated with the positive phase of the Arctic Oscillation (AO) or negative phase of the Arctic rapid change pattern. Under these conditions, very little exchange of heat and moisture occurs between the surface and the atmosphere owing to the associated weak vertical gradients in temperature and moisture. The lateral influx of heat and moisture due to changes in the atmospheric circulation, however, restricts sea ice growth and in some cases melts sea ice during winter (e.g., Rigor et al. 2002; Zhang et al. 2003; Zhang et al. 2008; Park et al. 2015a). However, when there is a flow of colder, drier air from the continent or solid ice pack associated with a particular atmospheric circulation pattern, such as the negative AO, an intense flux of heat and moisture occurs from the surface to the atmosphere. These conditions favor a strong forcing of the atmosphere by an ocean with no or thin ice cover, representing a state-dependent forcing. The second implication is that there is also a strong spatial variability in this forcing such that it is most prevalent in the marginal sea ice areas, such as the Barents and Kara seas.

We can also argue that hypothesized pathways linking the Arctic to mid-latitudes rely on a warming over the Arctic and not necessarily the disappearance of the sea ice. As described above, previous studies have indicated that changes in the atmospheric circulation, and their resultant poleward heat and moisture transport, play important driving role in Arctic warming and sea ice retreat (e.g., Rigor et al. 2002; Zhang et al. 2003; Zhang et al. 2008). Recent studies further suggest that a warming of the atmosphere over the Arctic through warm, moist air intrusions is an important contributor to sea ice loss (D.-S. Park et al. 2015; Woods and Caballero 2016), and these intrusions are caused by changes in the hemispheric atmospheric circulation in lower latitudes, rather than changes in the specific humidity (Lee et al. 2011; Zhang et al. 2013; Gong et al. 2017). Intruding mid-latitude warm, moist air leads to increased infrared radiation both upward and downward, the latter hindering sea ice growth (H.-S. Park et al. 2015a). This increase in downward infrared radiation arises from multiple factors, including the presence of warmer air due to both warm advection and latent heat release that results during cloud formation, as well as the increase in all three phases of water (Gong et al. 2017). This effect on sea ice is noticeable within several days of the intrusion (H.-S. Park et al. 2015a; Kapsch et al. 2016). Furthermore, studies such as D.-S. Park et al. (2015) and Gong et al. (2017) find that upward turbulent heat fluxes at the surface arise after the intrusions of warm, moist air. Therefore, even if this mechanism only partially accounts for the warming, it could have important implications for understanding linkages between the Arctic and mid-latitudes. For example, in climate model experiments that specify sea ice concentration and/or sea surface temperature anomalies, it is the upward turbulent heat fluxes from the surface that drive the Arctic and mid-latitude circulation (Deser et al. 2007). However, the aforementioned observational evidence suggests that the imposed negative sea ice concentration and positive sea surface temperature anomalies could in fact be caused by warm, moist intrusions from lower latitudes, which would result in a downward heat flux. If this is indeed correct, the causal chain of events is misrepresented in the model experiment, likely misrepresenting turbulent heat fluxes.

Hemispheric-wide response of AA

A key area of research for Arctic and mid-latitude linkages is to understand the two-way interactions between the tropospheric and stratospheric polar vortex. The jet stream from autumn to early winter is largely characterized by i) non-linear interactions between enhanced atmospheric planetary waves, such as in Figure 6, ii) irregular transitions between predominantly zonal and meridional flows, and iii) the maintenance of atmospheric blocking (near-stationary large-amplitude atmospheric waves) — all of which are not well understood or predicted by operational forecast models. The surface warming over the Arctic Ocean during the delayed re-freezing in autumn — along with increased heat fluxes and reduced vertical stability — may fuel strong storm systems to develop over the Arctic (Jaiser et al. 2012; Semmler et al. 2016; Basu et al. 2018). The non-linear interaction between storm systems and planetary-scale waves contributes to changes in atmospheric circulation, which allows enhanced upward propagation of energy in early- to mid-winter to weaken the stratospheric polar vortex. The conditions that trigger this interaction (e.g., wave structure and number: how many wavelengths there are around a latitude circle) are hard to predict, as they have a large chaotic component. Arctic and mid-latitude linkages may also be state-dependent, i.e., linkages may be more favorable in one atmospheric wave pattern than another, creating intermittency (Overland et al. 2016). The impact of anomalous transient storm systems on the growth and phasing of planetary waves, the onset and maintenance of blocks, and the strength and location of the Siberian high may be preconditioned by the state of the hemispheric atmospheric background flow.

While linkages in early winter have received the most attention by researchers owing to their influence on extreme winter weather, progress has also been made in understanding summer linkages. Here, there is an interaction of newly open water areas, atmospheric and oceanic frontal features, and phasing with high-amplitude/high-wavenumber atmospheric circulation features (Overland et al. 2012; Coumou et al. 2014). The summer season has seen an overall weakening of storm tracks over the last decades (Coumou et al. 2015), and this is also projected by future model projections (Lehmann et al, 2014). How a weakened flow might affect weather systems and especially their frequency is not fully understood (Coumou et al. 2017).

Though one might think that the concept of wavy versus zonal circulation patterns is straightforward, we have found challenges in quantifying these states. Approaches can be roughly separated into geometric and dynamic methods. The former focuses on the geometry of the circulation to characterize the departure of the flow from zonality in terms of wave amplitude, sinuosity, or circularity (Francis and Vavrus 2012; Cattiaux et al. 2016; Rohli et al. 2005; Di Capua and Coumou 2016). These metrics have the advantage of being intuitive and readily visualized from geopotential height contours, but they have been criticized for lacking a firm physical basis. By contrast, dynamically based waviness metrics, such as effective diffusivity of potential vorticity and finite-amplitude wave activity (Nakamura and Solomon 2010), are derived from first-order energy conservation principles.

These measures provide a theoretical basis for relating changes in zonal wind speed to accompanying changes in wave amplitude, at least under idealized conditions. Such approaches are being applied in climatological studies of circulation trends and extreme weather events related to amplified flow patterns (Chen et al. 2015), but their derivation is more technical and their application more involved than recent geometric methods. An example of the results from sinuosity is shown in Figure 7. The time series for the North Atlantic (top) shows a weak trend and highlights year-to-year internal variability in such indices. The bottom diagram highlights the regional and seasonal nature of long-term positive trends.

At this point, there is no scientific consensus on which waviness metric or even category of methods is preferable. Our field may benefit from the variety of approaches to sort the most useful measures of waviness. In the meantime, the diversity of employed metrics complicates direct comparisons and conclusions drawn among studies. For example, Francis and Vavrus (2012) reported increasing wave amplitudes over the North American-Atlantic region during recent decades, whereas Barnes and Polvani (2015) applied a different wave-amplitude definition over the same domain and generally did not find increases observed in the past or projected into the future. More recent studies suggest complex circulation behavior, consisting of opposing trends in waviness depending on season, longitude, and latitude. For instance, future climate projections exhibit a trend towards increased sinuosity over the North American sector only, while other sectors exhibit unchanged or decreased waviness/blockings (Cattiaux et al. 2016, Di Capua and Coumou 2016; Peings et al. 2017; Vavrus et al. 2017). However, these changes are subject to high uncertainties due to internal variability and competing effect of low-latitude versus high-latitude warming on the response of the mid-latitude atmospheric dynamics (Peings et al. 2017, Deser et al. 2015, Blackport and Kushner 2017).

Regional Analyses

Asia—It has been well understood that AO modulates Asia surface air temperatures through altering warm and moist air transport (e.g., Thompson and Wallace 1998). Associated with positive (negative) AO, warm (cold) winter occurs in Eurasia and the Arctic and sea ice extent decreases (increases) (e.g., Rigor et al. 2002; Zhang et al. 2003). Honda et al. (2009) specifically examined a tropospheric dynamical pathway in which negative sea ice and positive air temperature anomalies over the Barents-Kara seas during autumn cause cold Eurasia-Far East temperatures in mid-to-late winter. In the troposphere, persistent constructive interference of lower-atmospheric warming with atmospheric Rossby waves into December/January may induce a negative AO-like pattern, which may continue into February/March. Kim et al. (2014) investigated the stratosphere pathway from both observational analysis and modeling experiments and found that sea ice loss can induce vertical propagation of planetary wave energy, which weakens the stratospheric polar vortex and then propagates wave energy downward into the troposphere, maintaining an amplified jet-stream pattern into mid-to-late winter (Figure 8).

In December and January, the additional oceanic heat and moisture release to the Arctic atmosphere can increase Siberian snow cover (Wegmann et al. 2015). The increased snow cover may enhance continental cooling and troughing over East Asia while strengthening the Siberian high upstream over northwest Eurasia. A ridge over northwestern Eurasia with a trough over northeastern Eurasia is favorable for the direct forcing of planetary waves with enhanced vertical propagation of wave energy into the stratosphere (Cohen et al. 2007; Nakamura et al. 2015). This can lead to wave breaking and disruption of the stratospheric polar vortex (Jaiser et al. 2016).

Such a negative AO-like circulation tends to produce atmospheric blocking over the Ural regions with an enhanced Siberian high (Hopsch et al. 2012; Mori et al. 2014). Such dynamically forced links can be extracted from observational data using causal discovery algorithms (Figure 9; from Kretschmer et al. 2016), indicating that these are real pathways and not spurious correlations. Figure 9 illustrates that low sea ice concentrations over the Barents-Kara seas lead to high pressure over Ural mountains, which leads to upward wave propagation (“v-flux”) and weakening of the stratospheric polar vortex. The anticyclonic anomaly first occurs over the Barents-Kara seas and Ural regions, bringing cold air from the Arctic to central Asia, which extends southeastward owing to a strengthened Siberian high. This southward flow of Arctic air has been implicated in more frequent or intensified cold surges over East Asia (Overland et al. 2015; Zuo et al. 2016). These processes are complicated by Arctic sea ice feedbacks (Li and Wang 2014; Luo et al. 2016; McCusker et al. 2016). While model simulations exhibit uncertainties in the Siberian high response, there is increasing evidence for the aforementioned processes taking place in recent decades.

North America—Potential connections between the North American Arctic and mid-latitudes depend on the constructive or destructive interactions with locations of existing large-scale waves in the jet stream. Climatological waves during winter usually consist of a ridge of higher geopotential heights over the northeastern Pacific and/or Greenland along with a trough of lower heights over central and eastern North America (Figure 6b), although a great deal of interannual variability is common. Of particular interest is the winter cooling trend in eastern North America since 1990 (Cohen et al. 2014). Although this trend coincides with Arctic warming (Kug et al. 2015; Lee et al. 2015; Cohen 2016), studies have also pointed to internal variability (Baxter and Nigam 2015) and influences from the tropical Pacific (Basu et al. 2013; Sun et al. 2016). Very recent work suggests a tropical response to Arctic warming that feeds back to the Arctic (Cvanovic et al 2017). Furthermore, Ayarzagüena and Screen (2016) and Trenary et al. (2016) do not see an increase in the number of cold events in data or future model projections.

The potential for the Arctic to influence eastern North America involves a modification and added persistence to the existing long-wave pattern. Figure 10 (left) shows the pattern of near-surface air temperatures that occurs during eastern North America cold events (note the warm Arctic/cold continent type pattern with positive temperature anomalies near southern Baffin Bay and in Alaska/East Siberia). Figure 10 (right) is the corresponding 250 hPa geopotential height anomaly field for cold events in eastern North America. Higher anomalies are collocated with the two regions of positive temperature anomalies, suggesting a surface/geopotential thickness connection. Higher regional Arctic geopotential heights increase the likelihood of Alaskan and/or Greenland blocks; further analyses suggest that these regional blocks are independent features. The geopotential height ridge along the US

West Coast and the low heights over eastern North America are an amplification of the climatological late-autumn/early-winter wave pattern. The anomaly pattern over the North Atlantic Ocean exhibits a strong downstream storm track coincident with eastern North America cold events. While these historical teleconnections in Figure 10 do not necessarily involve Arctic change, Kug et al. (2015) suggest a recent (1980–2014) winter connection between warm temperatures in the Chukchi Sea and cold spells in eastern North America. Further, extreme sea ice loss and warm temperatures in the Chukchi region during November 2016 were consistent with this pattern, including a northward extension of the western ridge into the central Arctic along with an eastern cold event in early December 2016. Likewise, Ballinger et al. (2017) and Chen and Luo (2017) found variations in sea ice freeze onset in Baffin Bay and regional positive sea surface temperature anomalies were linked to 500-hPa blocking patterns and years of extreme late freeze conditions since 2006. Thus, it is overly simplistic to say that the Arctic could cause eastern North American cold spells, but near-future Arctic change has the potential to reinforce such cold events through tendencies to trigger the formation of Alaskan and Greenland blocks.

Europe—As is the case everywhere, potential linkages between Arctic warming and weather in Europe are complex in the sense that severe weather involves multiple causes. Greenland blocking tends to be associated with an abnormally southerly latitude of the storm track across the eastern Atlantic, which favors cold winters in northwestern Europe (Woollings et al. 2010). Evidence of connectivity between Barents-Kara sea ice loss and winter weather in northern Europe has been reported (Petoukhov and Semenov 2010; Orsolini et al. 2012; Liptak and Strong 2014), although variability in Europe's weather is principally associated with the North Atlantic Oscillation (NAO) and high-pressure cold air masses from the east. Over the North Atlantic, understanding NAO variability is complicated by differing factors that affect the strength and location of the Aleutian Low and Bermuda/Azores high, which, in turn, affect the strength and position of the eddy-driven jet. Further complexity is introduced by factors affecting the east Atlantic pattern, which is related to blocking over the eastern North Atlantic (Handorf and Dethloff 2012; Hall et al. 2015). Changes in the NAO and east Atlantic indices explain about 60% of the variability in the jet stream shift and strength. The primary influence of the North Atlantic eddy-driven jet stream on climate variability in northern and central Europe — together with the multitude of potential drivers for the variability of the eddy-driven jet, including North Atlantic SST, ENSO, quasi-biennial oscillation, and the highly non-linear intractions between the synoptic and planetary waves — point to large uncertainty in detecting robust impacts of Arctic climate changes on weather and climate over the North Atlantic-European region. Modeling experiments show a diversity of NAO and stratospheric polar vortex response to reduced Arctic sea ice. The atmospheric response is dependent on the pattern (Sun et al. 2015; Screen 2017), on the amplitude (Pethoukov and Semenov 2010, Peings and Magnusdottir 2014, Semenov and Latif 2015, Chen et al. 2016), and even in certain studies on the sign of sea ice anomalies (Liptak and Strong 2014). Dedicated multimodel experiments with coordinated protocol in sea ice prescription are needed to reconcile model results, as discussed in Section 3.

Tropical influences

Observational studies suggest that tropical intraseasonal variations (e.g., MJO) may modulate Arctic temperature and atmospheric circulation (Yoo et al. 2013). Tropical influences stem from converging northward heat and moisture fluxes into the sub-Arctic, as well as through a stratospheric pathway from which anomalously warm Pacific sea surface temperatures during El Niño affect sub-Arctic weather conditions. Positive Pacific and/or Atlantic Ocean sea surface temperature anomalies can influence high-amplitude, stationary jet stream pattern anomalies (Basu et al. 2013; Sato et al. 2014; Cohen 2016). For example, Lee et al. (2015) found that the anomalously cold North American winter of 2013–14 was a result of the combination of anomalously warm sea surface temperatures in the tropical western Pacific, anomalously warm sea surface temperatures in the extratropical Pacific, and low sea ice concentration on the North Pacific side of the Arctic.

Cold Arctic outflows often intensify cyclonic disturbances that originate in mid-latitudes. The combination of extremely cold air with tropical inflow that occurs in typical/extratropical storms created recent severe weather events, such as Snowmaggedon in 2010, Superstorm Sandy in 2012, and the eastern North American cold outbreaks in January 2014 and February 2015. In early 2016, an extreme Arctic warming episode occurred concurrently with several extreme events worldwide, including heavy snow in the southwestern and northeastern US and over portions of Europe, as well as flooding in Great Britain and Ireland. These events also coincided with the near-record El Niño in 2016, which had a strong teleconnection influence conflating the impacts of Arctic influence, complicating attribution (Wang et al. 2017). Future progress on Arctic linkages and mid-latitude weather cannot remain an Arctic-only activity. The combination of Arctic forcing of mid-latitude weather linkages, combined with internal variability and equatorial and mid-latitude sea surface temperature forcings, provide a clear pathway forward for improving S2S weather outlooks.

Attribution of extreme weather events

The literature suggests that most linkages are regional and episodic, with timescales of weeks to a few months (Overland et al. 2016). As noted in earlier sections, the jet stream can act as a bridge between AA forcing and mid-latitude weather events. However, as noted earlier, there are many influences competing to modify mid-latitude weather including internal variability, and sometimes these other competing factors constructively and destructively interfere with Arctic forcing. A case for a potential linkage was December 2010, when a late freeze-up in Baffin Bay caused warm regional temperature anomalies and the dilation of upper-level atmospheric pressure surfaces (Ballinger et al. 2017). This contributed to the formation of a block in the geopotential height field, which in turn resulted in cold temperature anomalies in the eastern US. Rather than extremely cold temperatures, the main impact of this event was to increase the duration of the cold spell (Francis et al. 2017). Taken over a timescale of a whole season, however, there is less evidence for linkage impacts. Screen and Simmonds (2014) note the lack of changes in cold seasons during the last three decades and discount Arctic impacts based on seasonal and large-domain statistics, which may actually obscure the response as patterns align differently from one year to the next. Furthermore, Screen et al. (2015) and Ayarzaguena and Screen

(2016) show future decreases in the frequency of occurrence of record-breaking cold seasons.

Often two or more weather events occur simultaneously owing to an amplified ridge/trough pattern across a continent. One example was the blizzard of February 2010 in the Washington, DC-region, referred to as Snowmageddon, in which cold air from the north met unusually warm, moist air from the south boosted by the coincident El Niño. A second example is hurricane Sandy in October 2012, one of the costliest hurricanes in US history. An extratropical weather system from the west merged with hurricane Sandy as it moved north, creating an intense, hybrid storm. Sandy tracked westward instead of a more normal track out to sea, owing to an atmospheric block southwest of Greenland. The storm surge, augmented by sea level rise, flooded about 1000 km of the eastern seaboard, including the New York subway system. It has been suggested that the exceptionally warm Arctic may have strengthened the blocking high that steered Sandy on its unusual path at the time (Greene et al. 2013).

Potential linkage pathways and confidence

Future progress on Arctic linkages to mid-latitude weather cannot remain an Arctic-only activity. The combination of Arctic forcing of mid-latitude weather linkages, combined with internal variability and equatorial and mid-latitude sea surface temperature forcings, provide a clear pathway forward for improving S2S weather outlooks.

Based on results from observational and modeling studies, physical processes or mechanisms have been proposed that may explain linkages between Arctic amplification and changes in mid-latitude climate and weather patterns. This list is not exhaustive and is ordered from high to low confidence based on the consensus of the scientists attending the workshop:

1. Low Barents-Kara sea ice favors a northwestward expansion and intensification of the Siberian high, contributing to cold Asian winters
2. Arctic warming causes increased geopotential thickness over the polar cap or regionally, leading to an equatorward shifted jet stream across the mid-latitude, which may have constructive/destructive interference with climatological ridging, and associated weather anomalies (e.g., colder temperatures, increased snowfall).
3. Weakening of horizontal temperature gradients and the thermal wind, working in opposition to prevailing wind direction
4. Modulating stratosphere-troposphere coupling
5. Exciting anomalous planetary waves or stationary Rossby waves in winter, weaker transient synoptic waves in summer and occurrence of blocks in all seasons.
6. Altering storm tracks and changes in the latitude of jet stream flow
7. Increasing frequency of occurrence of wave resonance

3 Next steps and recommendations

An important goal of the workshop was achieved: to hasten progress towards consensus understanding and identification of knowledge gaps. Based on the workshop findings, we identify specific opportunities to utilize observations and models, particularly a combination of them, to enable and accelerate progress in determining the mechanisms of rapid Arctic change and its mid-latitude linkages.

Observations and reanalyses recommendations

Improvement of observational information concerning the Arctic can be achieved via i) better identification of datasets and assimilation of existing *in situ* and remote sensing observations into atmospheric and oceanic reanalyses, ii) increasing the spatial and temporal coverage of observations, and iii) developing new observational methods.

Forcing datasets available to investigate Arctic and mid-latitude linkages—To analyze the atmospheric response to changes in the Arctic, accurate data are needed for Arctic surface air pressure, atmospheric temperature profiles, sea ice concentration and thickness, snow extent and thickness, and soil moisture (e.g., Figure 11). These data will aid in assessing the realism of reanalysis fields as well as output from numerical weather prediction and climate models. They can also provide lower boundary conditions for atmospheric models and be assimilated into reanalyses.

Information on surface air pressure and air temperature profiles is vital for the analyses of Arctic and mid-latitude linkages. The surface air pressure field in the Arctic was considered to be reasonably well captured by atmospheric reanalyses already a decade ago (Bromwich and Fogt 2007). However, Inoue et al. (2009) found that poor coverage of drifting buoy data prior to 1979 led to inaccuracies in reanalyses and numerical forecasts. Inoue et al. (2009) further pointed out that the observational record may deteriorate in the future due to fewer opportunities for buoy deployments over the sea ice. The global surface temperature field is relatively accurate during the satellite era, and observations are available from various government centers (e.g., Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA)). Although the effects of sea surface temperature changes on mid-latitude weather has been studied (Screen et al. 2012), the importance of the accuracy of the sea surface temperature datasets has not received much attention, but it is probably not a major issue in studies addressing the satellite era.

To assess the response of the Arctic atmosphere to changes in sea ice cover, a realistic representation of its temporal evolution is crucial. In general, the state is characterized by the sea ice concentration, thickness distribution, and snow depth. Since the advent of satellite multi-channel passive microwave observation systems in 1979, it has been possible to monitor the sea ice extent with a temporal resolution of less than a day and spatial resolution of about 25 km. Changes in the multi-year ice coverage (frequently used as a proxy for ice thickness) can also be estimated using passive and active microwave instruments on satellite platforms (Comiso 2012). During the ice growth season, estimates of monthly fields of sea ice thickness can now be derived from satellite altimeters (lidar and radar) at a fairly coarse resolution of about 25 km (Kwok et al. 2009).

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Not only is the abundance of open water important for assessing the atmospheric response, but also the thin ice (less than ~0.5 m) coverage within each grid element is essential. Available large-scale datasets are not tailored to provide this portion of the ice thickness distribution, thus it is essential that a 'realistic' dataset is synthesized using available observations for use in simulations. In parallel, an understanding of the sensitivity of the atmospheric responses to time-varying ice conditions should be developed, such that the shortcomings of available datasets could be better identified. There is an urgent need for more accurate information on sea ice and snow properties in conditions of compact ice cover (> 90% ice concentration) in winter and for better distinguishing between melt ponds and leads in summer.

Large-scale anomalies in soil moisture may generate surface temperature anomalies, which in turn effect planetary wave patterns and associated teleconnections. In addition, soil moisture may serve as an indicator of the Arctic's influence on the hydroclimate in different regions. One of the only long-term observational datasets of global surface soil moisture is assembled from multiple active and passive remote sensors by the European Space Agency (ESA), covering the period from 1978–2015 with 0.25° resolution (Liu et al. 2012). From 2002 to present, the Gravity Recovery and Climate Experiment (GRACE) satellite provides estimates of drought, through measurements of total terrestrial water storage in addition to surface soil moisture (Houborg et al. 2012). One of the limitations of such datasets is that they are only available at the monthly resolution. Soil moisture data with a higher temporal resolution (i.e., 3 hours) are available through data assimilation products like the Global Land Data Assimilation System (GLDAS), allowing more detailed investigations of the links between Arctic and mid-latitude extreme events that occur on sub-monthly timescales. Finally, more recent satellite missions, including ESA's Soil Moisture and Ocean Salinity (SMOS) launched in 2009 and NASA's Soil Moisture Active Passive (SMAP) launched in 2015, are aimed at providing high-resolution soil moisture measurements with global coverage in the near future.

High-quality observations of terrestrial snow cover are needed, as snow insulates the atmosphere from the ground heat source in autumn, insulates the ground from cold winter air, reflects most of spring insolation, and may contribute to the intensification of extended Ural and Siberian high pressure systems. Spring snow melt is important for the transition towards summer, controlling the strength and timing of processes involving the albedo feedback. Different datasets give contrasting results for the trend of Eurasian snow cover in autumn, and a recent study suggests that there are large spatial variations among datasets (Wegmann et al. 2017). The spring and early summer decline of terrestrial snow cover is evident, being twice as fast in June as the Arctic sea ice decline in September (Derksen et al. 2015). Long-term observations on snow water equivalent are limited in the high Arctic. Even GlobSnow, considered the most reliable snow water equivalent dataset, is inadequate for identifying the exact date of snowmelt. Snow products need to be improved in the Arctic for use in understanding climate trends and mechanisms. Observations of permafrost temperature and its relationship with snow depth have become available in recent decades (Romanovsky et al. 2010).

New observational datasets and reanalyses that span most of the 20th century—Most of the research on past linkages between the Arctic and mid-latitudes is restricted to the period since 1979. To extend the time series and to investigate the effects of AA prior to the satellite era, additional sources of information are needed. For example, Walsh et al. (2015) have estimated the Arctic sea ice concentration from 1850 to 1979 based on ship observations, compilations by naval oceanographers, and analyses by national ice services. Monthly data are available in 0.25° × 0.25° resolution. Information on long-term snow, lake ice, and river ice data from the Eurasian Arctic exist at least in written archives, if not in digital format. Digitally available data include several long time series from the Scandinavian Arctic, ice breakup data from the Torne River since 1693, and snow cover data from Abisko, Sweden, since 1913, among others. A climatology of visually observed cloudiness over the Norwegian, Barents, and Kara seas is available since the late 19th century (Chernokulsky et al. 2017).

The reanalyses data starting from the late 1800s or 1900 are summarized in Table 1, along with information on spatial resolution and respective references. Two atmosphere-only reanalyses are available: the NOAA 20th century reanalysis (20CR) and the ECWMF’s atmospheric reanalysis of the 20th century (ERA-20C). These reanalyses are generated by forcing the models with historical, time-varying sea surface temperature, sea ice concentration, and radiative fluxes, while assimilating surface air pressure observations. The 20CR reanalysis has a longer temporal coverage and provides a 56-member ensemble. The ERA-20C does not include an ensemble but has a higher horizontal (Table 1), vertical (91 levels relative to 28 levels in 20CR), and time (3-hourly compared to 6-hourly for 20CR) resolution. Both reanalyses are influenced by changes in the observational network of different variables. Due to its ensemble, the 20CR allows for a comprehensive examination of uncertainties. However, the higher resolution in the ERA-20C provides opportunities to study finer-scale processes. A coupled atmosphere-ocean reanalysis has been produced by the ECMWF, covering the same period as ERA-20C. In addition, two long-term ocean reanalyses are available. Using reanalyses in studies of AA and Arctic mid-latitude interactions, one should be aware of their errors and uncertainties, which are largest for clouds (Liu and Key 2016), Arctic boundary layer variables (Jakobson et al. 2012), as well as radiative and turbulent surface fluxes (Tastula et al. 2013). Fortunately the synoptic- and large-scale atmospheric circulation is better represented, although the products for years prior to 1979 suffer from the lack of assimilation of satellite data.

Paleoclimate perspective—Paleoclimate data offer centennial- to millennial-scale perspectives on environmental changes. Key intervals in Earth’s past provide potential analogues to assess the impacts of Arctic warming on the mid-latitudes. For example, the early Holocene (~10,000 – 8,000 years ago) is one such interval when the Arctic and high-latitudes received enhanced average annual insolation with respect to the equator relative to the present, reducing the latitudinal temperature gradient. Also, on more recent timescales (e.g., over the past two millennia) variations in the mid-latitude and Arctic temperature gradient have occurred.

Paleoclimate archives include tree rings, sediments (lake, marine, and peat), speleothems, and glacier ice cores. Lake and marine sediments, as well as glacier ice cores, provide records of climate (e.g., temperature, moisture, and sea ice) over timescales from centuries to millennia. Annually resolved records, such as tree rings, provide high-resolution information, usually over shorter timescales of several parameters, including temperature, precipitation, and atmospheric circulation. The increasing number of gridded tree ring reconstructions facilitate detailed studies of Arctic impacts on mid-latitude climate during the last two millennia. Recent and ongoing paleoclimate data synthesis efforts give a unique opportunity to address the impacts of the Arctic on mid-latitude climate on a hemispheric scale: The Past Global Changes (PAGES) 2k project has synthesized over 600 global high-resolution temperature reconstructions. Presently, several regional, highly resolved (in time and space) reconstructions of drought and temperature exist for North America, Europe, and Asia, as well as for the whole Northern Hemisphere (Anchukaitis et al. 2017). Such products, together with reconstructions of Arctic climate conditions including sea ice changes (Kinnard et al. 2011), provide excellent means for fingerprinting regional mid-latitude impacts on Arctic climate change (Figure 12). Also, on longer timescales, such comparisons will soon become feasible. Preliminary global Holocene paleoclimate datasets have been published for temperature reconstructions (Marcott et al. 2013), and more comprehensive efforts to synthesize Holocene temperature and moisture records are underway.

Together, paleoclimate archives and recent data compilations will enable us to characterize past climate variability including Arctic sea ice extent and the Northern Hemisphere latitudinal temperature gradient, and to test if these changes had an impact on circulation and mid-latitude drought on timescales from centuries to millennia.

Process-level observations and new methods—Process-level observations from the Arctic originate from a limited number of partly permanent ground-based stations in the terrestrial Arctic (e.g., the International Arctic Systems for Observing the Atmosphere (IASOA)) and measurement campaigns (e.g., ship, aircraft) over the Arctic Ocean, mainly during spring and summer. Additional observations are needed of interactions between the open sea and atmosphere, sea ice and atmosphere, as well as terrestrial snow/ice and atmosphere. Among the key processes are the local and regional atmospheric responses to surface heating (e.g., due to loss of sea ice or snow), which depends on the physics of the boundary layer, cloud formation and persistence, vertical and horizontal distribution of radiative and turbulent energy fluxes, and baroclinicity around the lateral boundaries of the surface heat source. The observations should include solar (0.2–5 μm, shortwave) and terrestrial/thermal-infrared (3–50 μm, longwave) radiative fluxes; turbulent fluxes of momentum, heat, and moisture; and the effects of the fluxes on cloud formation and lifetime, air temperature, humidity, and wind in local and regional scales.

Recent advances in observation technology provide improved opportunities to quantify the state of the atmosphere, cryosphere, and the ocean. There is potential for a more extensive application of unmanned aerial vehicles (UAVs) in local and regional scales. Vertical profiles of air temperature, as well as wind speed and direction up to roughly 2 km, can be measured using small, cost-effective UAVs (Jonassen et al. 2015), and activities are ongoing to assimilate the data into numerical weather prediction models. Regional-scale UAV measurements are possible by using long-range aircraft, some of which can also release dropsondes (Intrieri et al. 2014). Further, controlled meteorological balloons have a high potential to contribute to regional wind and temperature observations from the Arctic. The balloons can drift for a few thousand kilometers horizontally, taking vertical soundings of wind and temperature (Hole et al. 2016). We have already developed the technology to extensively use UAVs and balloons for observing the Arctic atmosphere, but the actual advance is hampered by limited financial resources and various legal regulations. Furthermore, the instrumentation and operation range of manned research aircraft have improved, allowing studies covering wider regions, but also faces the same limitations.

Major advances have also been made in ground/ship/ice-based remote sensing of the Arctic atmosphere. High-resolution vertical profiling of air temperature, humidity, and cloud ice and water content is now possible using scanning multi-wavelength microwave radiometers and Doppler cloud radars, as well as wind profiling using sodars, lidars, radars, and passive solar sensors. The new methods for *in situ* observations and surface-based remote sensing will be important in filling the existing major gap of data on the vertical profiles throughout the Arctic troposphere. Developments in autonomous buoys, floats, and platforms to observe the ocean (Lee et al. 2016) and sea ice (Jackson et al. 2013) yield possibilities to better quantify i) the instantaneous lower boundary conditions for the Arctic and mid-latitude atmosphere, and ii) the heat capacity of the ocean and sea ice, which is important for seasonal forecasts.

To best utilize the existing and new observational methods, data should be collected during dedicated field campaigns, by regular observations at well-instrumented super sites (such as the IASOA observatories), and by satellites. Field campaigns should be performed in different seasons, as the surface thermal forcing to the Arctic atmosphere strongly depends on the season, as also does the atmospheric response to surface forcing. Surface–based measurements should be carried out in different conditions over various surface types with a focus on vertical profiles of mean variables, as well as turbulent and radiative fluxes, and airborne measurements are needed to observe the spatial variability. The observations should be supplemented by process model experiments to i) evaluate the model performance, ii) evaluate the factors controlling the fluxes, and iii) improve flux parameterizations. The year-round drifting ice station MOSAiC — planned from autumn 2019 to autumn 2020 — supported by research aircraft observations (e.g., planned activities in the framework of the $(AC)^3$ project, Wendisch et al. (2017)), other research vessel cruises, enhanced activities at IASOA stations, and various model experiments are expected to advance understanding of local and remote drivers of the AA and the processes that result in teleconnections from the Arctic to mid-latitudes.

Metrics to identify Arctic and mid-latitude linkages—Different metrics, applied to observations, reanalyses, and climate model output, can be used to analyze the relationships between conditions in the Arctic and mid-latitudes, and the mechanisms potentially responsible for these relationships. Among the most direct measures of the Arctic effects on mid-latitudes are the occurrence, duration, and intensity of cold-air outbreaks. AA tends to reduce their intensity but simultaneously favor more meridional circulation patterns, which may favor their increased frequency and persistence. Metrics applied to quantify the meridionality of the jet stream include the meridional circulation index, the frequency of

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occurrence of high-amplitude wave patterns, the meandering index, and sinuosity (Francis and Vavrus 2015; Di Capua and Coumou 2016; Cattiaux et al. 2016).

Developments in novel analysis methods have resulted in application of new metrics. Clustering of patterns of different variables, for example applying self-organizing maps (SOMs), yields information on their relationships, which can be further quantified — by dividing temporal changes into contributions due to changes in a) frequency of occurrence of patterns, b) intensity of patterns (e.g., warming or decrease in sea ice or snow cover), and c) both of them (Francis and Skific, 2015). To test for conditionally dependent relationships, we can apply a multivariate approach called causal effect networks (CEN). The CEN algorithm distinguishes between spurious correlations and causal relationships. Kretschmer et al. (2016) applied the method to test the hypothesis about Arctic-induced drivers of the wintertime stratospheric polar vortex. They concluded that the reduction in Barents-Kara sea ice in autumn causes an increased surface air pressure over the Ural Mountains, followed by an increased vertical wave activity flux and a weakened stratospheric polar vortex (Figure 9). The CEN algorithm has limitations: the causal interpretations are only possible with respect to the time series included in the analysis, whereas the excluded external drivers may affect the network structure. Hence, a more sophisticated method, the response-guided causal precursor detection (RG-CPD), has been developed. Also, the maximum covariance analysis (MCA) method has been applied to evaluate climate model output using a reanalysis as a reference. It revealed that atmosphere-only simulations of ECHAM6 climate model did not reproduce the negative AO/NAO response to Arctic sea-ice loss seen in ERA-Interim reanalysis (Handorf et al. 2015).

To progress, we need a standardization of metrics so that various studies can be better inter-compared. We also need to more extensively apply promising novel methods, such as CEN, RG-CPD, MCA, SOM, and evolutionary algorithms, some of which can distinguish between forced signals and natural variability. In particular, novel metrics that are found to be applicable in reanalysis studies should be used to evaluate climate and weather prediction model performance.

Recommendations—Six recommendations to expand the observational datasets and analyses approaches of change and mid-latitude linkages include:

1. Synthesize new Arctic observations to provide the best high-resolution estimate of the atmospheric state for better understanding sea ice and ocean surface processes;
2. Assess physically-based sea ice/ocean surface forcing data sets available to investigate Arctic mid-latitude linkages and provide improvements;
3. Systematically employ proven and new metrics to identify forced signals of atmospheric circulation from natural variability;
4. Analyze paleoclimate data and new observational datasets that span most of the past century, including reanalysis and sea ice;

5. Utilize new observational analysis methods (e.g., fluctuation dissipation analysis, causal effect networks) that extend beyond correlative relationships to establish causal links between forcing and response; and

6. Consider both established and new theories of atmospheric and oceanic dynamics to interpret and guide observations and modeling studies.

Modeling recommendations

Modeling experiments are needed to establish the causality of linkages between the Arctic and mid-latitudes. This is illustrated in Figure 13, which compares the winter mean sea level response to reduced Arctic sea ice inferred from lagged regression with the simulated response obtained in model experiments driven by changes in sea ice (Smith et al. 2017). Lagged regression shows a pattern that projects onto a negative NAO, in both the observations and in atmosphere model experiments. The regressions imply a negative NAO response to reduced Arctic sea ice (e.g., Liu et al. 2012). However, the actual response to reduced Arctic sea ice determined from these model experiments is a weak positive NAO. Hence, although statistical analysis can provide useful insights, the results can sometimes be misleading and need to be supported by dedicated modeling experiments.

Modeling uncertainties—Many modeling experiments have been carried out to try to determine the atmospheric response to Arctic sea ice loss, but the results are inconclusive. For example, a key question is how the NAO responds, since this major teleconnection pattern is related to winter climate in North America, Europe, and parts of Asia. However, studies show a full range of responses, including negative NAO (e.g., Deser et al. 2015), positive NAO (e.g., Screen et al. 2014), very little response (e.g., Petrie et al. 2015; Blackport and Kushner 2016), and a response that depends on the details of the forcing (Petoukhov and Semenov 2010; Sun et al. 2015; Chen et al. 2016). It could also be that the NAO is not an optimal response index, as the two features that determine its sign — strength of the Icelandic low and Azores/Bermuda high — can be affected by independent factors, leading to sign variations that are difficult to interpret. Moreover, the centers of action characterized by the Icelandic low and Azores/Bermuda high could be also shifted as revealed by previous studies (Jung et al. 2003; Zhang et al. 2008; Wang and Magnusdottir 2012). In particular, Screen et al. (2018) reviewed the existing fully coupled climate model experiment results and found consistent atmospheric circulation responses to Arctic sea ice across the models resembling the negative phase of Arctic rapid change pattern, which is characterized by the strengthening of two different centers of action from NAO, corresponding to the Siberian high and Aleutian low (Zhang et al. 2008).

There are many potential reasons for the different responses found in modeling studies, including:

- Differences in the magnitude of the forcing. Some studies have investigated the response to sea ice perturbations typical of the present day and near future (e.g., Chen et al. 2016; Smith et al. 2017), while others have investigated the impact of larger changes expected towards the end of the century (e.g,. Deser et al. 2016; Blackport and Kushner 2016). Furthermore, interpreting the impact of differences in the magnitude of the forcing is particularly difficult because the relationship could be non-linear (Petoukhov and Semenov 2010; Peings and Magnusdottir 2014; Chen et al. 2016). It has also been shown that sea ice variability alone captures only a fraction of total Arctic amplification (e.g., Perlwitz et al. 2015, thus the response signal is weaker than in the real world.

- Differences in the pattern of forcing. Studies have demonstrated that the response is sensitive to the pattern of sea ice anomalies. For example, Sun et al. (2015) obtained opposite responses in the northern polar vortex to sea ice forcing from the Pacific and Atlantic sectors. Furthermore, the responses to regional sea ice anomalies do not add linearly (Screen 2017), complicating their interpretation.
- Atmosphere/ocean coupling. Although many studies have used atmosphere-only models, changes in Arctic sea ice can influence sea surface temperatures surrounding the ice pack and also in remote regions, including the tropics (e.g., Smith et al. 2017). Coupled models are essential to simulate these effects and have been found to amplify the winter mid-latitude wind response to Arctic sea ice (Deser et al. 2016).
- How the forcing is applied. Changes in sea ice can be imposed in different ways in coupled models, for example by nudging the model to the required state (e.g., Smith et al. 2017) or by changing the fluxes of energy in order to melt some of the sea ice (e.g., Deser et al. 2016; Blackport and Kushner 2016). The latter approach appears to induce a “mini-global warming” signal with enhanced warming in the tropical upper troposphere that could affect mid-latitude winds, whereas the former approach could potentially induce undesired ocean circulation changes in response to the nudging increments. Hence, the different approaches could lead to different atmospheric responses even if the sea ice changes are similar.
- Different models. The response can be very sensitive to the model used. For example, Sun et al. (2015) obtained opposite responses in the winter polar vortex in identical forcing experiments with two different models.
- Background state. Identical forcing experiments — with the same model but with different background states induced by different sea surface temperature biases — can produce opposite NAO responses (Smith et al. 2017). Furthermore, responses may not be robust across experiments due to strong nonlinearities in the system, which can depend on the background state (Chen et al. 2016).
- Low signal to noise ratio. The atmospheric response to Arctic sea ice simulated by models is typically small compared to internal variability so that a large ensemble of simulations is required to obtain robust signals (e.g., Mori et al. 2014). Some of the different responses reported in the literature could therefore arise from sampling errors. If the low signal-to-noise ratio in models is correct, then the response to Arctic sea ice could be swamped by internal variability (McCusker et al. 2016). However, the signal-to-noise ratio in seasonal forecasts

of the NAO is too small in models (Eade et al. 2014), suggesting that the magnitude of the simulated response to sea ice could also be too small.

Coordinated experiments—At the workshop, the modeling breakout group proposed the creation of a modeling task force to coordinate modeling experiments. Given the variety of different factors that can influence the simulated response to Arctic sea ice loss, there is a clear need for coordinated modeling experiments so that these factors can be controlled, allowing the different model responses to be better understood. This will be addressed by a new CMIP6 Polar Amplification MIP (PAMIP), which will investigate the causes and consequences of polar amplification.

Coordinated modeling experiments are currently being designed and will investigate several of the factors listed above, including the roles of coupling, the background state, and the pattern of forcing. Tier one experiments would consist of two fast-track sets of atmosphere MIP (AMIP)-like simulations that can be conducted by different groups and made available to the community for analysis relatively quickly. Fast-track #1 would exploit the CMIP6 AMIP (from 1979-present) as the control run, and modeling groups would then execute two sets of sensitivity experiments — one with climatological sea ice and the other with climatological sea surface temperatures — to evaluate the atmospheric response to recent AA. For fast-track #2, modeling groups would run AMIP-like control simulations with observed climatological sea ice and sea surface temperature, and then three different time slice experiments using modeled sea ice and sea surface temperature patterns from the past (pre-industrial), the present (transient runs), and future (pattern under +2°C warming). Protocols for these fast-track experiments have been determined in autumn 2017. In addition, atmosphere-ocean coupled models will be forced with pre-industrial, the present, and future Arctic and Antarctic sea ice. It is planned to make the model simulation outputs from the experiments accessible through the Earth System Grid to allow the broader community to evaluate the proposed mechanisms linking changes in the Arctic to mid-latitudes.

Analysis of these experiments will seek to exploit the different model responses to obtain the real-world response using an “emergent constraint.” In this constraint, a relationship is sought between the different simulated responses and an observable parameter that is related to the underlying physical cause of the simulated differences. For example, Smith et al. (2017) found that changes in mid-latitude winds in response to reduced Arctic sea ice are sensitive to the refraction of anomalous planetary waves. By relating the simulated response to the observed atmospheric refractive index, they obtained an emergent constraint that suggests a weakening of the Atlantic jet (a negative NAO response) (Figure 14). However, this result is based on just three sets of simulations with a single model. PAMIP will provide a much larger sample of model responses, potentially providing more robust emergent constraints. Furthermore, we anticipate that a hierarchy of models, ranging from simplified dry dynamical cores to fully coupled general circulation models, will participate in the PAMIP, enabling the physical processes involved in the atmospheric response to Arctic sea ice to be explored in detail.

An initial proposal for coordinated modeling experiments to be carried out at multiple modeling centers for PAMIP is shown in Table 2. An update of the proposed PAMIP experiments can be found in Smith et al. (2018). These multi-tiered set of MIP experiments draw from the initial planning and discussions of the US CLIVAR Working Group and planned modeling elements of the European Horizon 2020 projects (APPLICATE, Blue Action, and PRIMAVERA). Twenty-two modeling centers and groups in the US, Canada, Europe, and Asia have expressed interest in conducting the experiments.

Recommendations—Three recommendations to advance modeling and synthesis understanding of Arctic change and midlatitude linkages include:

1. Establish a Modeling Task Force to plan protocols, forcing, and output parameters for coordinated modeling experiments (PAMIP);
2. Furnish experiment datasets to the community through open access (via Earth System Grid); and
3. Promote analysis within the community of simulations to understand mechanisms for AA and to further understand pathways for Arctic mid-latitude linkages.

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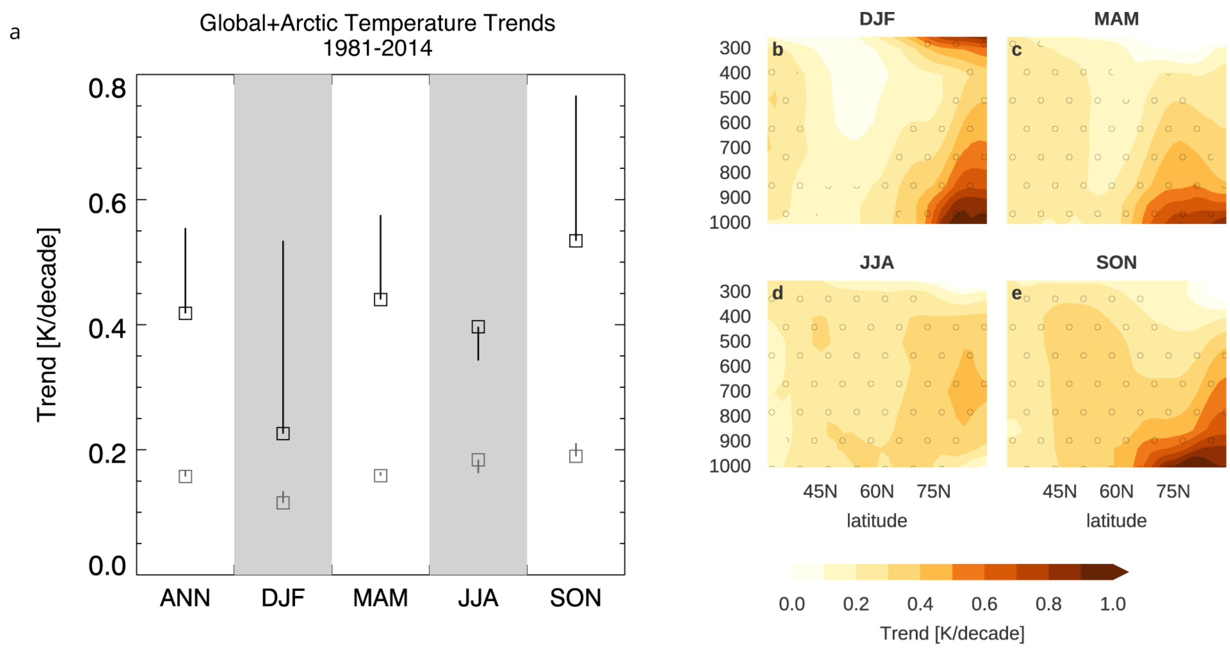

Figure 1.

(a) Annual (ANN) and seasonal (DJF, MAM, JJA, SON) surface air temperature (SAT) trends from 1981 to 2014 in the Arctic (black squares, north of 60°N) and for the whole globe (gray squares) using the average of four observational products (CRU, NOAA, GISS, and BEST) masked in such a way that all four products share a uniform missing data mask over the ocean. The vertical lines show trends for the average of CRU and BEST without applying this uniform mask. This line therefore indicates, in large part, the uncertainty coming from the limited observational temperature record over the Arctic ocean. (b–e) Seasonal and zonal-mean air temperature trends from 1981–2015 for the average of the MERRA, MERRA-2, ERA-Interim, JRA-55, and CFSR reanalysis products. Stippling indicates trends significant with a $p < 0.05$ after the false discovery rate was applied (Wilks 2006).

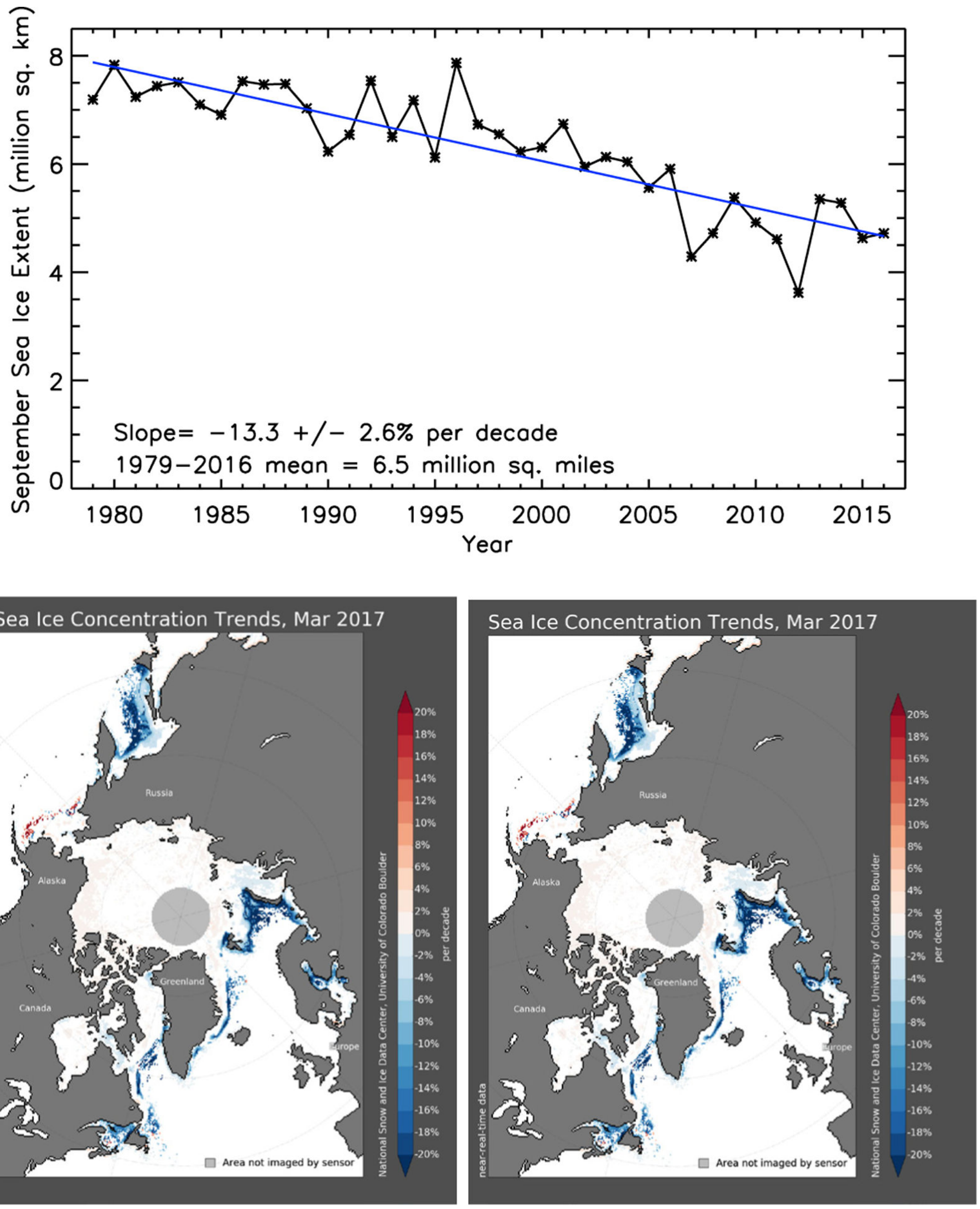

Figure 2.

Satellite-era Arctic sea ice trends from 1979–2016 are shown for (top) September areal extent (courtesy Patrick Taylor, NASA) and (bottom) March and September regional ice concentration trends (units: % per decade; courtesy of Julienne Stroeve, NSIDC).

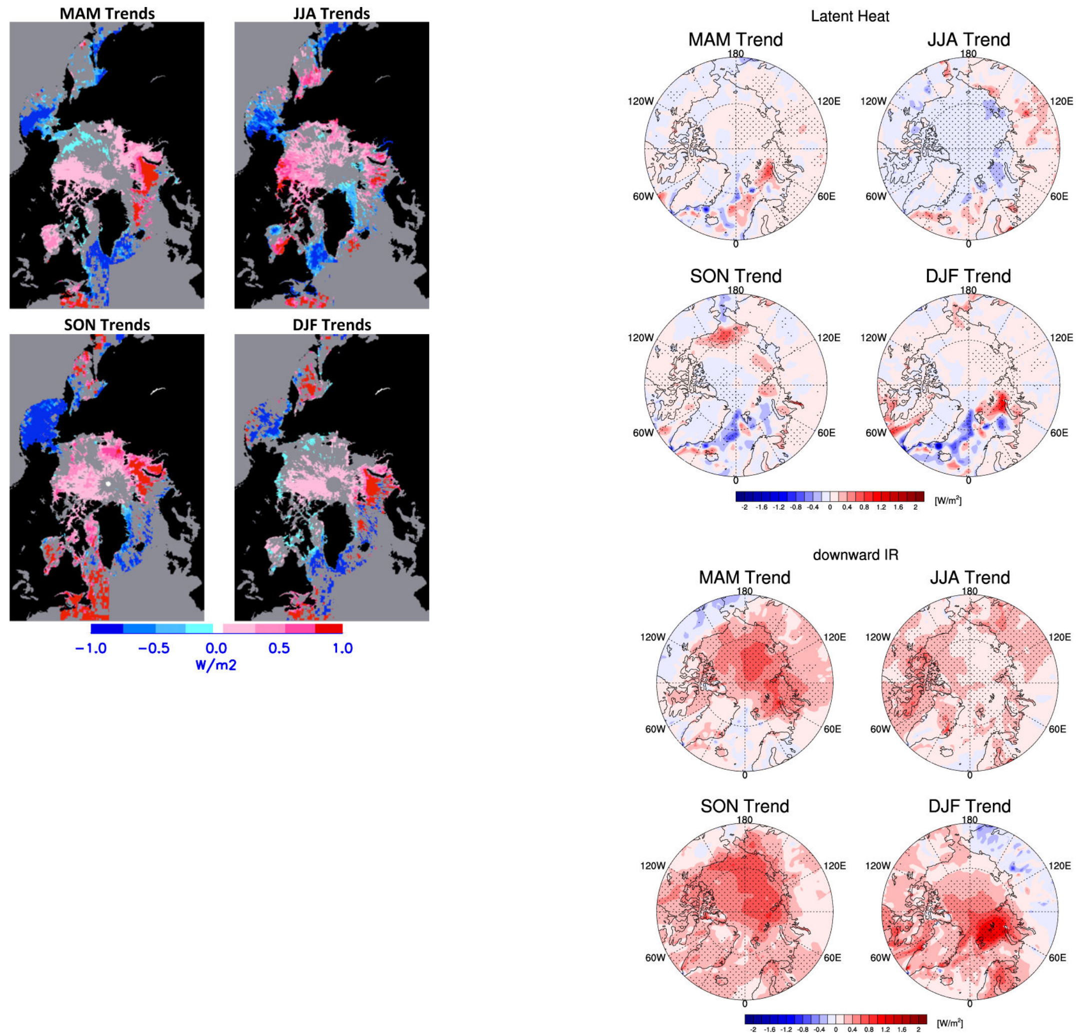

Figure 3.

Trends in selected components of the Arctic surface energy budget: (top left) Atmospheric Infrared Sounder (AIRS)-based observational surface latent heat flux trends constrained from 2002–2016 (W m^{-2} yr^{-1}; adapted by Linette Boisvert, U. Maryland, from Boisvert and Stroeve 2015); (top right) ERA-I surface latent heat flux trends for 1979–2016 (W m^{-2} yr^{-1}; courtesy of Tingting Gong, Qingdao National Lab. for Marine Science and Technology); and (bottom) ERA-I surface downwelling longwave radiation from 1979–2016 (courtesy Tingting Gong). Positive latent heat fluxes are defined as surface to atmosphere, whereas positive surface downwelling longwave trends are from atmosphere to surface.

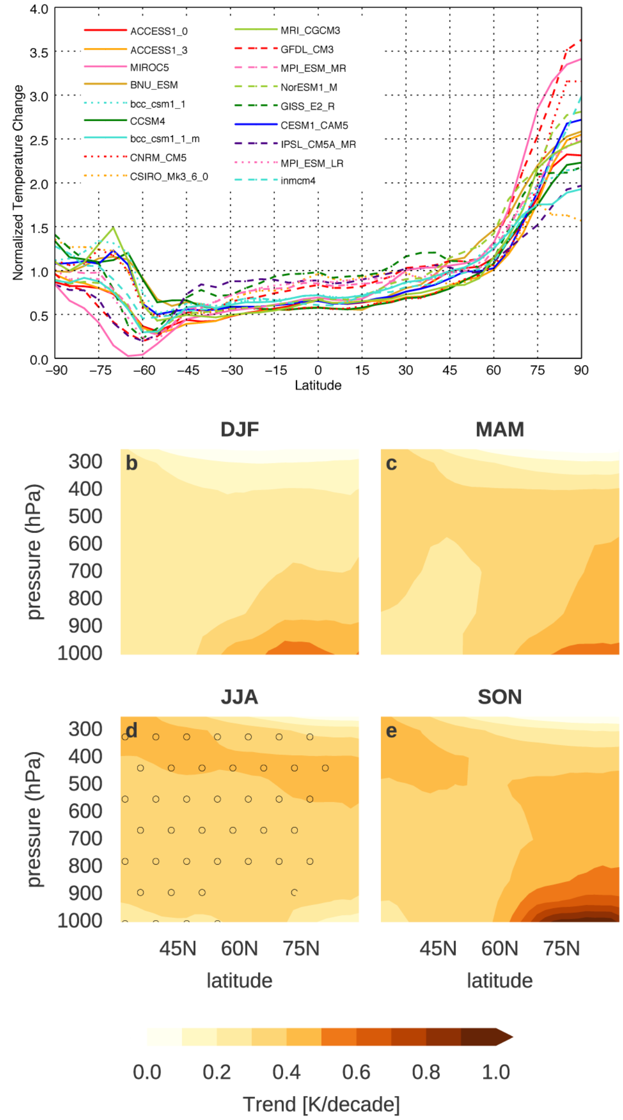

Figure 4.

CMIP5 models simulations of (a) zonal-mean temperature changes normalized by the global mean change (2080–2100 minus 2005–2025) and (b–e) same as Figure 1b–e but for the CMIP5 multi-model mean historical + RCP8.5 for 1981–2015. Stippling indicates trends significant with a $p < 0.05$ after the false discovery rate was applied (Wilks 2006).

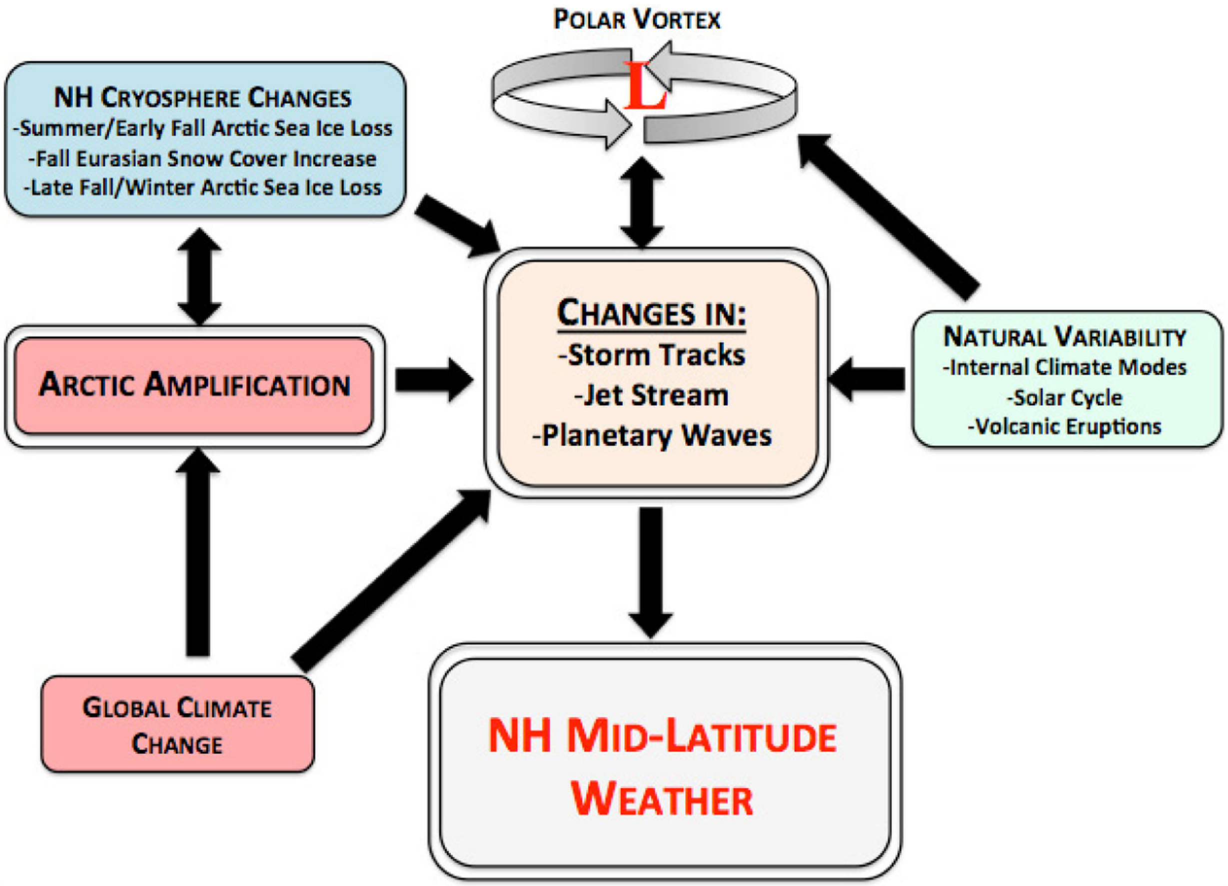

Figure 5.
Complexity of linkage pathways. (Figure from Cohen et al. 2014).

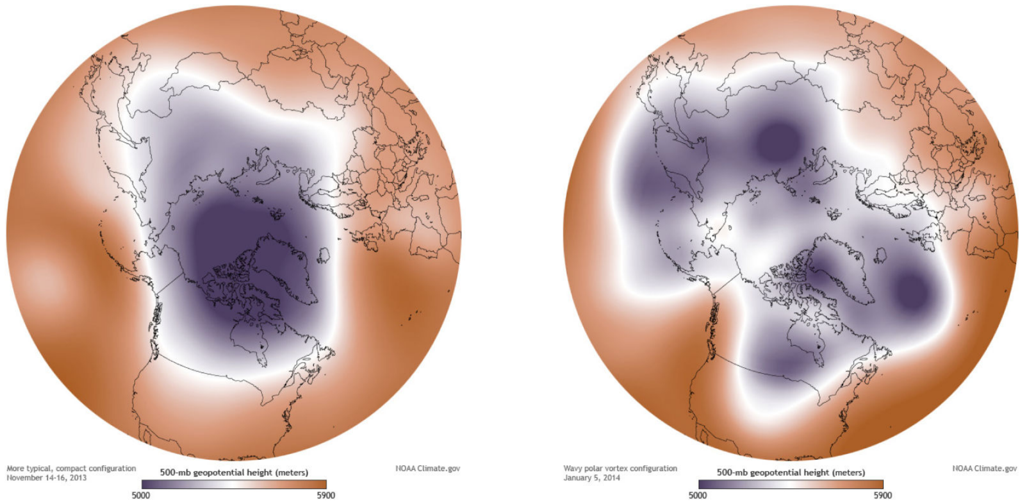

Figure 6.

Sample geopotential height fields for 500 hPa with lower values in purple and the jet stream in white. (a) Contrasts a single, more zonal path encircling the tropospheric polar vortex versus a wavier configuration (b) with multiple low centers. (Figure from NOAA Climate.gov).

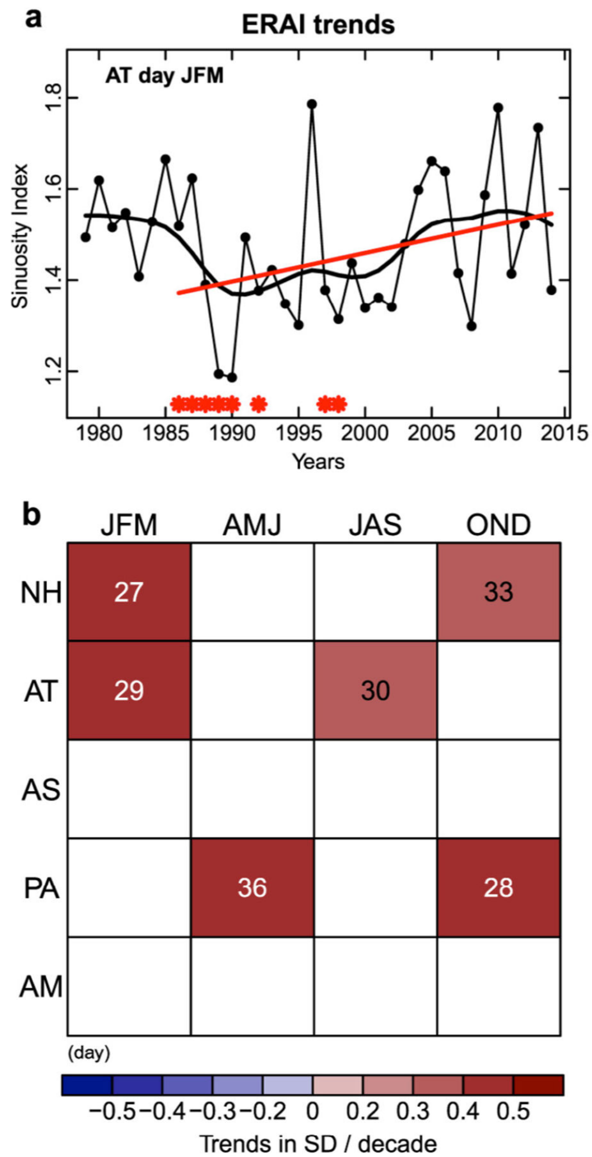

Figure 7.
ERA-Interim recent trends in sinuosity. a) Time series of Atlantic JFM sinuosity, with a 5-year spline smoothing, and b) longest significant trends in sinuosity for all geographic domains (rows) and seasons (columns). Colors represent trends in standard deviation (SD) per decade. (Figure from Cattiaux et al. 2016).

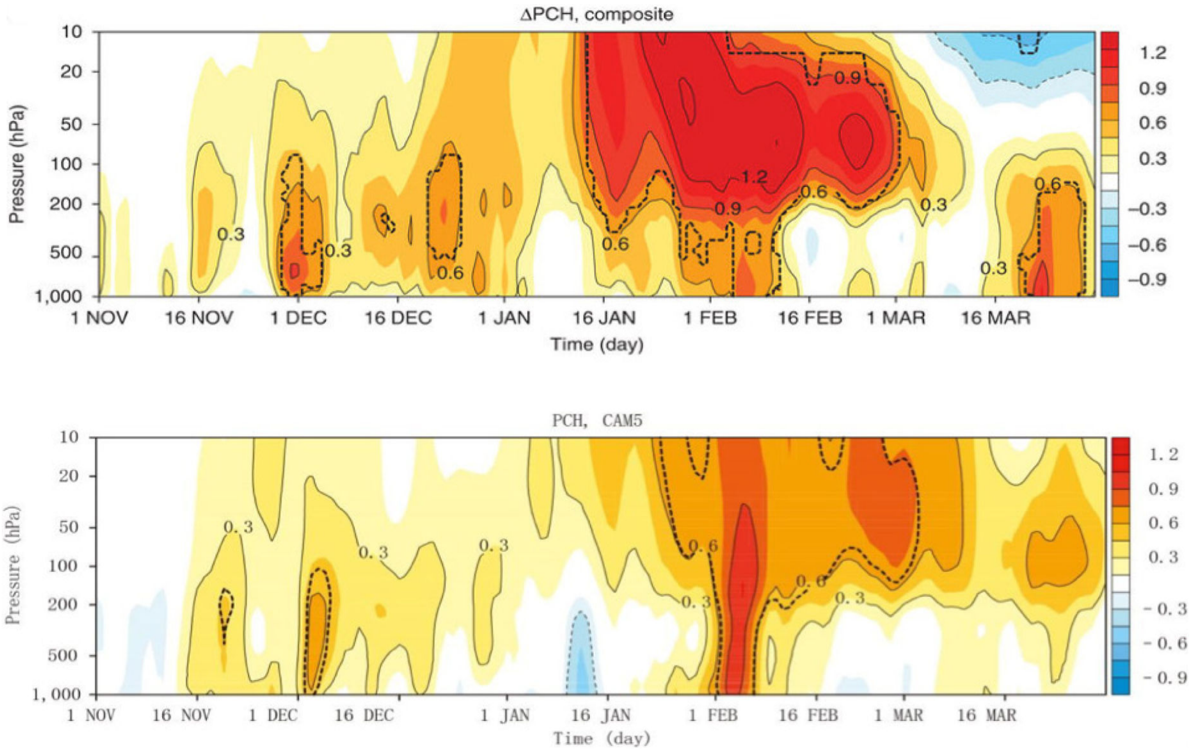

Figure 8.

Observed (top) and modeled (bottom) ensemble-mean responses to reduced sea ice over Barents-Kara seas for the subseasonal evolution of the polar cap height anomaly (PCH; shading is standard deviation) as a function of pressure (hPa; Figure from Kim et al. 2014).

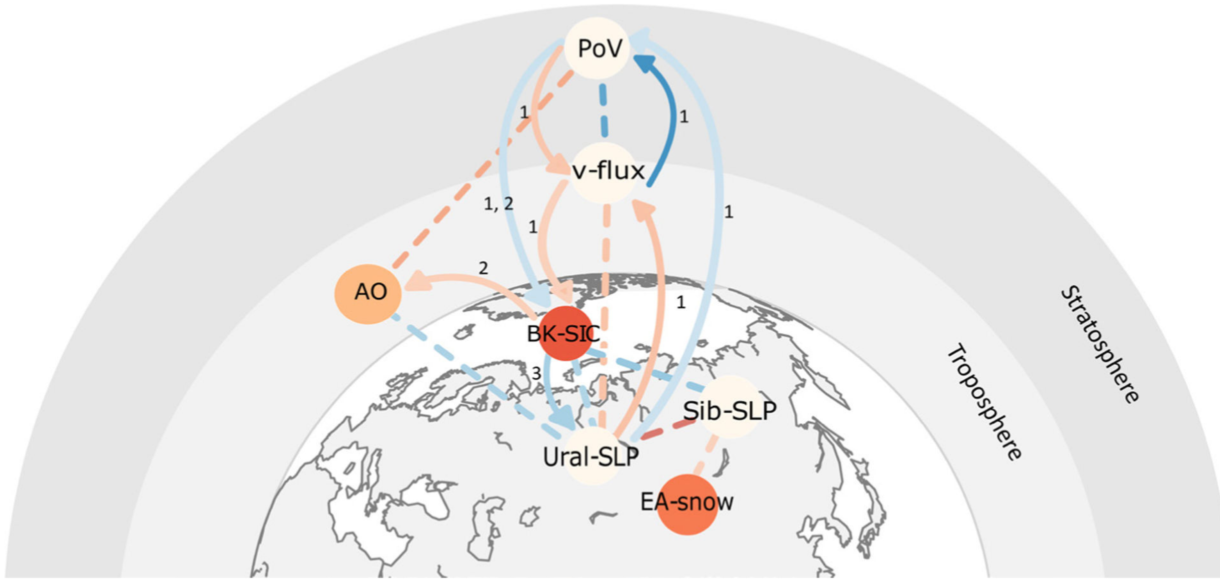

Figure 9.
Causal pathways between different Arctic actors extracted from observations. Blue arrows indicate a negative causal influence, red arrows a positive causal influence, and the number next to the arrows indicates the lag in months. The regional actors, Barents-Kara sea ice concentration (BK-SIC), Ural region sea level pressure (Ural-SLP), Siberian sea level pressure (Sib-SLP), and East Asia snow cover (EA-snow), are presented according to their approximate geographical location. The hemispheric actors (Arctic Oscillation (AO), upward wave propagation (v-flux), and polar vortex (PoV)), are presented according to their approximate latitude and pressure levels. (Figure from Kretschmer et al. 2016).

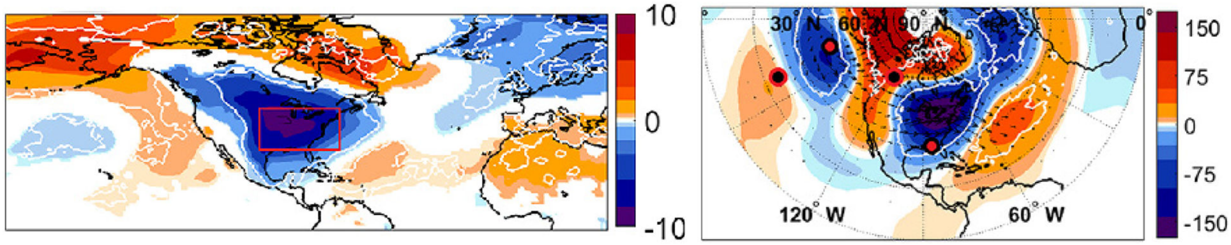

Figure 10.

(left) Surface temperature anomalies (K) and (right) 250 hPa geopotential height anomalies (m, shading) during North American cold spells as determined in the red box region. Only anomalies exceeding the 95% confidence level derived from a random Monte Carlo sampling procedure are shown. The data covers ERA-20C DJFs over the period 1900–2010. (Figure from Messori et al. 2016).

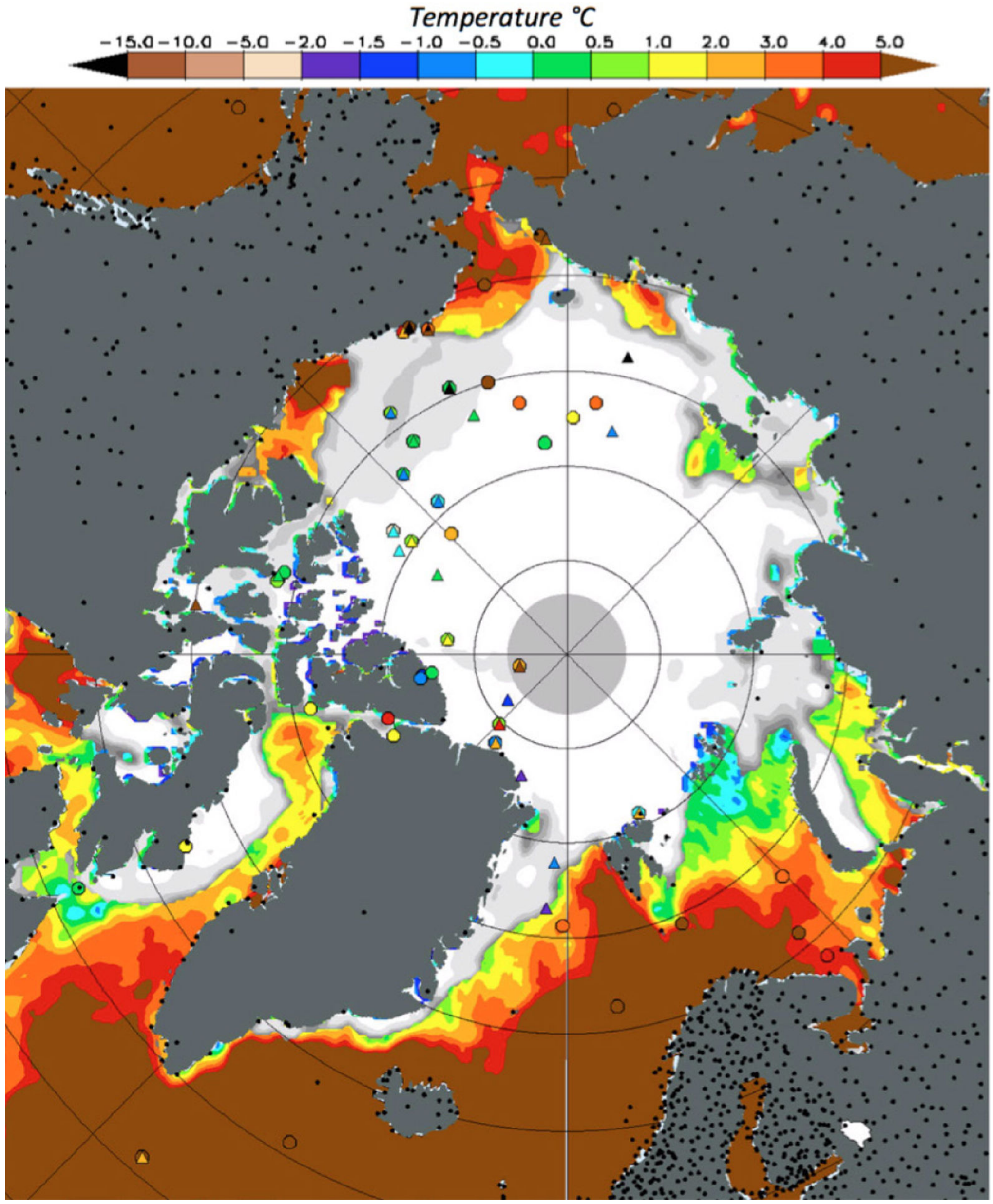

Figure 11.

Map of *in situ* observations on June 28, 2017 of surface temperature (colored circles) and air temperature (colored triangles) from the International Arctic Buoy Programme (IABP); analyses of SST from NOAA OISST; and ice concentration from NSIDC Daily Polar Gridded Sea Ice Concentration. Also shown are the positions of land stations (black dots; courtesy of Wendy Ermold, University of Washington).

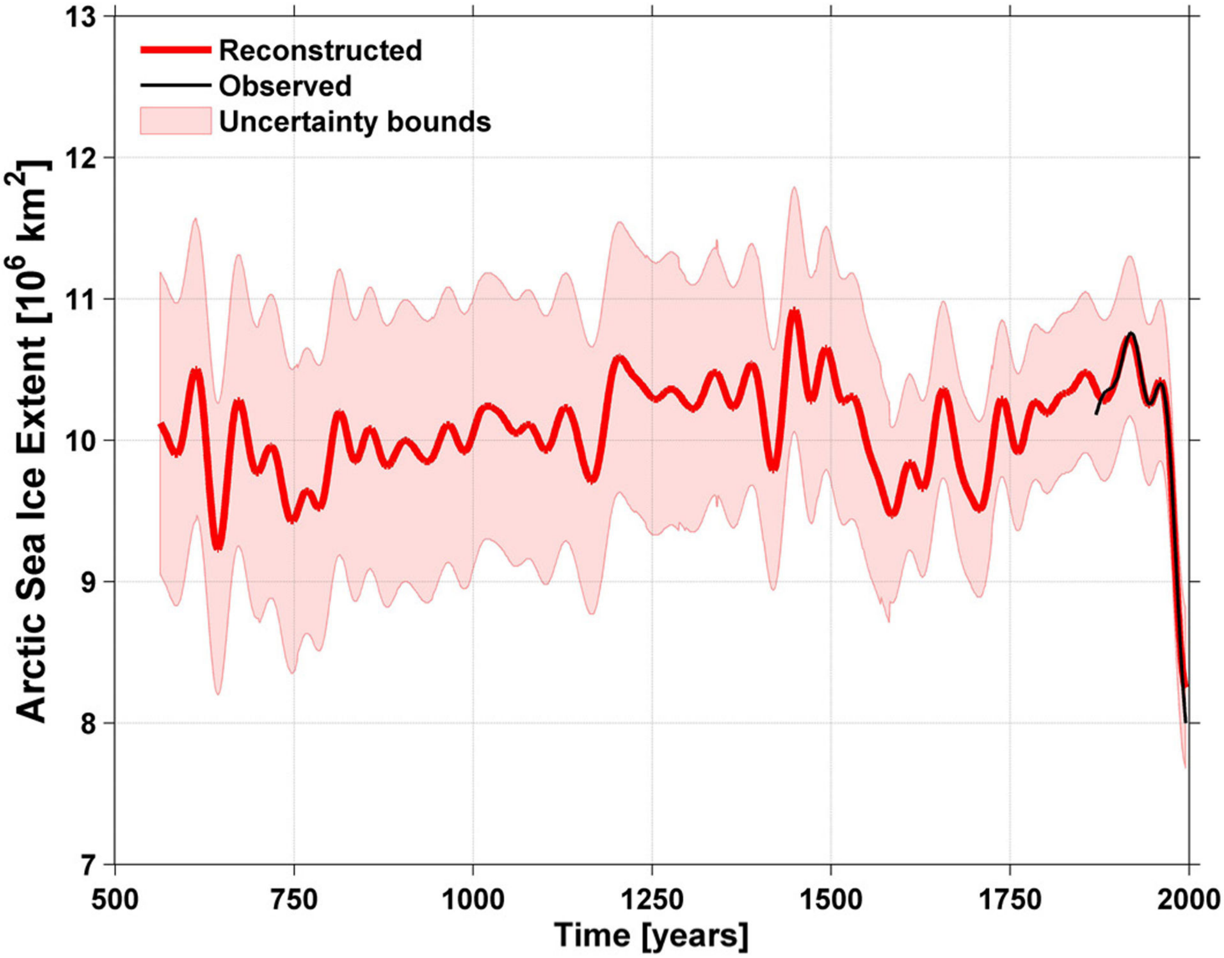

Figure 12.
Fourty-years of smoothed reconstructed late summer Arctic sea ice extent with 95% confidence interval (red line) and modern observations (black line) from 800 to present. (Figure from Kinnard et al. 2011).

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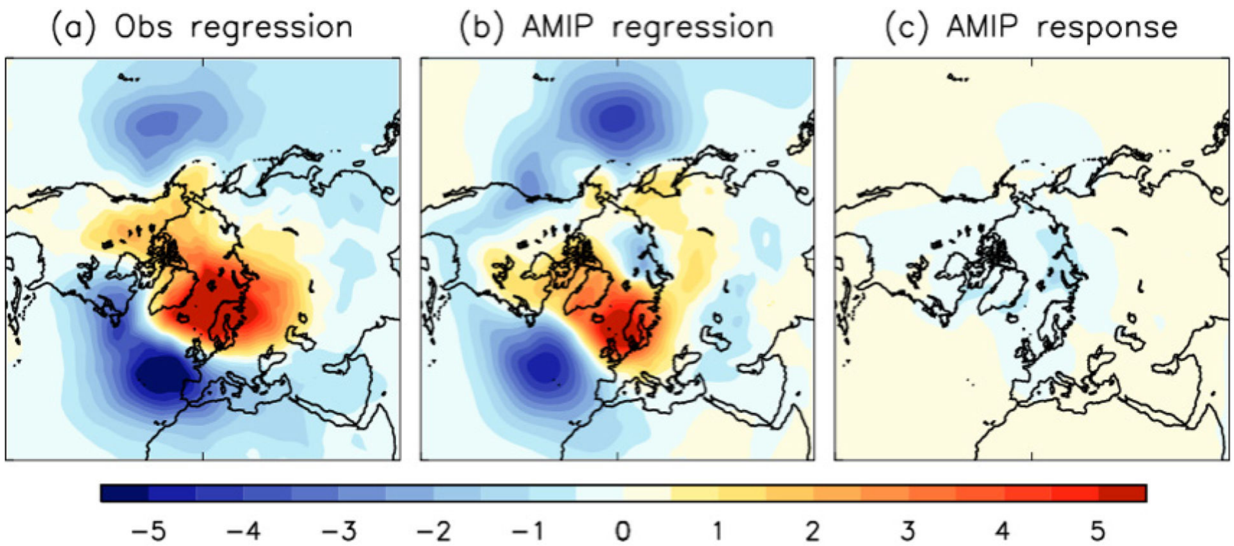

Figure 13.

Linear regression between autumn (September-November) Arctic sea ice extent and winter (December-February) mean sea level pressure (reversed sign) in (a) observations and (b) atmosphere model experiments forced by observed sea ice and sea surface temperatures following the Atmosphere Model Intercomparison Project (AMIP) protocol. All time series were linearly detrended and cover the period December 1979 to November 2009. (c) Winter mean sea level response to reduced sea ice in atmospheric model experiments (scaled by the average autumn sea ice extent reduction). Units are hPa per million km^2. (Figure from Smith et al. 2017).

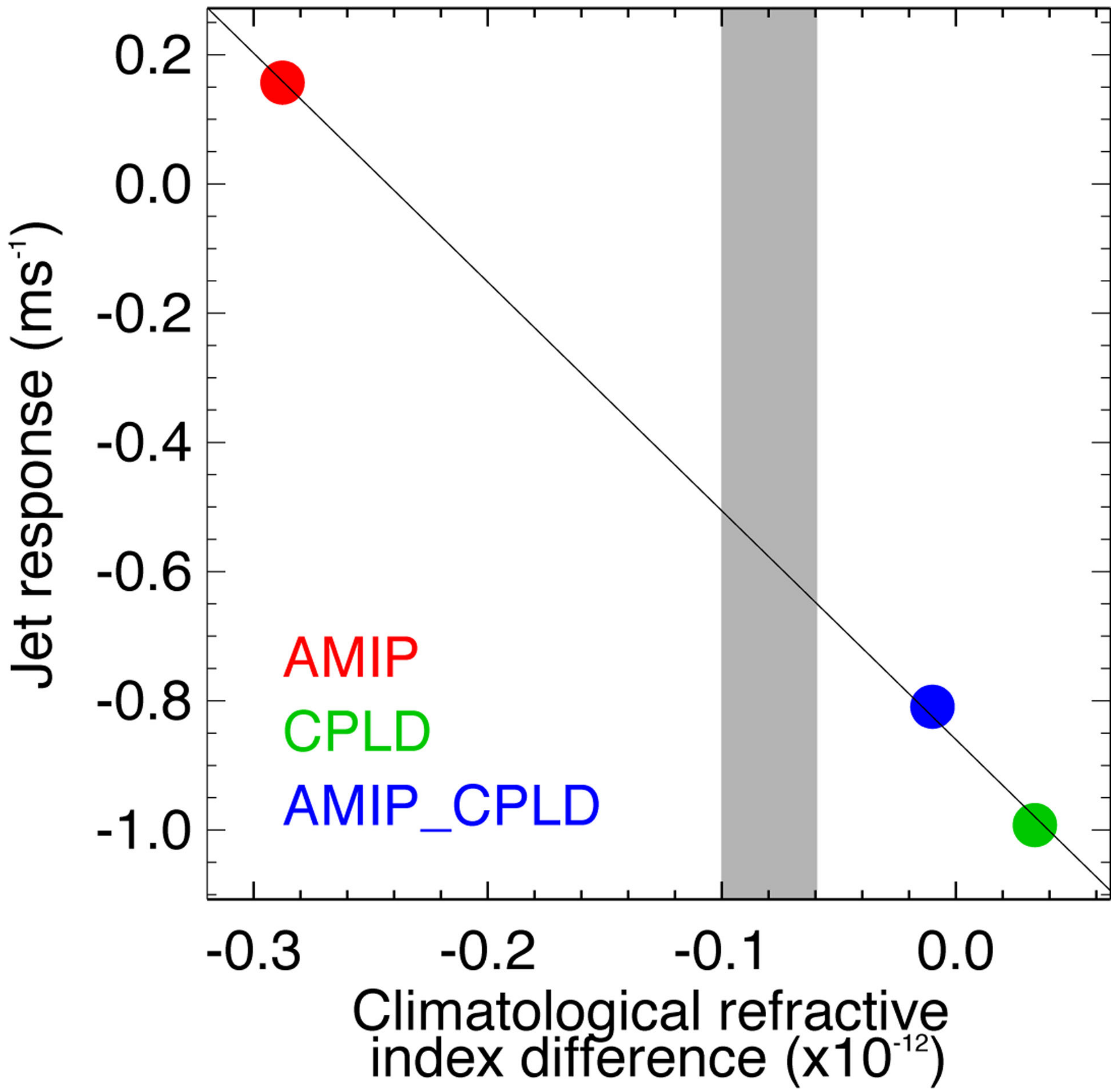

Figure 14.

Dependence of Atlantic jet response on the background climatological refractive index difference between mid (25–35oN) and high (60–80oN) latitudes at 200 hPa. Grey shading shows the observed range from the ERA-Interim and NCEP II reanalyses. The Atlantic jet response is defined as the difference in zonal mean zonal wind at 200 hPa over the region 60–0oW, 50–60oN between model experiments with reduced and climatological Arctic sea ice. Experiments were performed with the same model but with three different configurations: atmosphere only (AMIP); fully coupled (CPLD); and atmosphere only but with SST biases from the coupled model (AMIP_CPLD). An “emergent constraint” is obtained where the observed refractive index difference (grey shading) intersects the simulated response (black line), suggesting a modest weakening of the Atlantic jet in response to reduced Arctic sea ice (Figure from Smith et al. 2017).

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Table 1.

Atmospheric and oceanic reanalysis datasets covering at least 100 years.

Name	Resolution	Coverage	Reference
20CR (V2c) (Atmosphere)	2° × 2°	1850 – 2014 (V2: 1971–2010)	Compo et al. (2011)
ERA-20C (Atmosphere)	1° × 1°	1900 – 2010	Poli et al. (2016)
CERA-20C (Atmosphere + Ocean)	1° × 1°	1900 – 2010	Laloyaux et al. (2016)
EN.4.2.0 (Ocean)	1° × 1°	1900 – up to date	Good et al. (2013)
SODA2.2.4 (Ocean)	0.25° × 0.25°	1871 – 2008	Carton and Giese (2008)

Table 2.

Proposed Coordinated Multi-Model Experiments: Polar Amplification Multi-model Intercomparison Project (PAMIP)

Experiment - Time Slice			Forcing
1. AMIP *	Control		Present-day climatological SST and sea ice (SIC)
	SST	pi	Pre-industry SST
		2 degree	Future 2 degree warming SST
	Arctic SIC	pi	Pre-industry SIC
		2 degree	Future 2 degree warming SIC
	Antarctic SIC	pi	Pre-industry SIC
		2 degree	Future 2 degree warming SIC
2. Coupled	Control		Constrained by present-day climatological SIC
	Arctic SIC	pi	Constrained by pre-industry SIC
		2 degree	Constrained by future 2 degree warming SIC
	Antarctic SIC	pi	Constrained by pre-industry SIC
		2 degree	Constrained by future 2 degree warming SIC
3. AMIP-Reg **	Arctic SIC - Pacific	2 degree	Future 2 degree warming SIC in the Pacific Arctic
	Arctic SIC - Atlantic	2 degree	Future 2 degree warming SIC in the Atlantic Arctic
4. AMIP-BKGD ***	Arctic SIC	present-day	Present-day SIC
	Arctic SIC	2 degree	Future 2 degree warming SIC
5. AMIP	SIC	1979–2014	Climatological SST and transient SIC
	SST	1979–2014	Transient SST and climatological SIC
6. Coupled	SIC	present-day	Constrained by present-day SIC
	SIC	2 degree	Constrained by 2 degree warming SIC

* Experiment “SST”, “Arctic SIC”, and “Antarctic SIC” are designed the same as “Control” except the specified forcing of “SST” or “SIC”.

** The same as Experiment “Arctic SIC” but SIC is prescribed in the Pacific or Atlantic Arctic seas.

*** SST in both experiments are from experiment “Coupled Control” above, instead of observation.