Divergent consensuses on Arctic amplification influence on mid-latitude severe winter weather

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The Arctic has warmed more than twice as fast as the global average since the late 20th century, a phenomenon known as Arctic amplification (AA). Recently, there have been significant advances in understanding the physical contributions to AA and progress has been made in understanding the mechanisms linking AA to mid-latitude weather variability. Observational studies overwhelmingly support that AA is contributing to winter continental cooling. While some model experiments support the observational evidence, the majority of modeling results show little connection between AA and severe mid-latitude weather or suggest the export of excess heating from the Arctic to lower latitudes. Divergent conclusions

between model and observational studies, and even intra-model studies, continue to obfuscate a clear understanding of how AA is influencing mid-latitude weather.

Since the 1990s, Arctic winter temperatures have shown an almost monotonic warming trend and defines the period of AA (**Supplementary Figure 1a**). AA is strongest over the Arctic Ocean in fall and winter, while during the summer it is weaker and shifted over land and the Greenland ice sheet[1,2]. The most notable sign of climate change in the Arctic is the rapidly declining sea ice extent in summer and early fall[3] in response to a variety of reinforcing feedbacks[4,5,6].

Over the same period, eastern North America, and especially eastern Eurasia, land temperatures in winter have exhibited almost no warming and actually cooled from 2000–2013 followed by more variable winters. The recent mid-latitude winter cooling period has coincided with an increase in severe winter weather events[2,7,8,9].

The rapid warming of the Arctic coupled with cooling or lack of warming in the mid-latitudes has resulted in the diverging of Arctic and mid-latitude temperature trends (**Supplementary Figure 1b**). The pattern of a warm Arctic and cold continents/Eurasia (WACC/E) is the strongest observational evidence that some unaccounted-for mechanism has been offsetting greenhouse gas-forced warming over the Northern Hemisphere (NH) mid-latitudes[10,11,12,13].

Theories proposed for the mid-latitude winter cooling include internal variability and tropical forcing but also a new idea—AA. Over a decade ago it was proposed that Arctic warming (1988/89–2007/08) and associated changes in boundary forcing, including Arctic sea ice melt and increasing autumn snow cover extent, influence mid-latitude weather via a stratospheric pathway that favors cold temperatures across the mid-latitudes[14,15]. A composite of the temperature anomalies of the eleven subsequent winters (2009–2019 defined here as the months January–

March) shows a similar pattern of variability suggesting that the same physical mechanism is responsible for the WACC pattern observed in 1989–2008 and 2009–2019 (**Supplementary Figure 2**). However, some differences between the two periods are noted and discussed in the SI and **Supplementary Figure 3**. The WACE pattern was also detected during the previous AA period in the 1930s–1940s, which provides further observational support that winter continental cooling may be a forced response to AA[16].

The resiliency of mid-latitude winter weather was not projected by climate models[17] fanning climate change skepticism, which can impede implementation of mitigation and adaptation policies. Therefore, linking accelerated Arctic warming or AA to increased mid-latitude severe winter weather is societally-relevant and -important as it would assist the public and private sectors to prepare for adverse weather both in the short and long term.

Yet the challenge of demonstrating a linkage between AA and severe winter weather is daunting given differing observational analysis methods and the large spread in modeled responses (see SI and **Supplementary Figure 4** for a tabulation of observational and modeling studies). Simple causality statements for a general audience are not yet defendable. And despite a flurry of research and advances in the mechanisms linking AA to mid-latitude weather, the topic remains contentious.

In this Review, we focus on winter weather. For a brief discussion on AA and extreme weather see Supplementary Information (SI) and a separate review on summer mechanisms has recently been published[18].

The character of Arctic amplification

AA is evident in the Northern Hemsiphere (NH) and Arctic zonal mean winter air temperature trends between 1980–2019 from the surface to the upper atmosphere (**Figure 1; averaged in four reanalysis datasets, hence forth known as "observations" in this Review**). Statistically significant warming extends throughout the troposphere but is strongest near the surface with a second maximum in the upper troposphere and stratosphere (**Figure 1a**). This winter polar stratosphere warming trend is also evident in radiosonde data[17]. Coupled Model Intercomparison Models-5 (CMIP5)-simulated Arctic warming ensemble-mean is shifted south, lacks the magnitude and vertical extent. Also the second warming maximum in the upper troposphere and stratosphere is absent in CMIP5 compared with the observations (**Figure 1b)**. The shallower simulated warming could be related to coarse vertical resolution[20] or an Arctic temperature inversion that is too strong[21], which would inhibit the vertical distribution of surface warming.

Besides coupled models, we also analyzed the vertical distribution of temperature trends in the Atmospheric Model Intercomparison Project (AMIP) forced with observed sea surface temperatures (SSTs) and sea ice. The results are similar to those of CMIP5, with relatively shallow and southward-shifted Arctic warming and a mostly absent secondary maximum in the lower stratosphere (**Figure 1c** and **Supplementary Figure 5**). Further analysis of individual ensemble members reveals that several members closely match the distribution of observed temperature trends with deeper Arctic warming in the lower- to mid-troposphere and a secondary maximum in the stratosphere (**Supplementary Figure 6**); the best individual ensemble member match to the observations is included in **Figure 1d**. The large ensemble spread suggests that simulated and observed differences could be due to natural variability and therefore the observed temperature trends do not necessarily represent a forced response to AA.

Arctic amplification mechanisms

Understanding of contributors to AA has significantly evolved in the last decade, emphasizing that a suite of mechanisms is responsible for the enhanced sensitivity of the Arctic[6,22,23]. These mechanisms can be divided into local and remote forcings (summarized in **Figure 2)**. The local forcings include snow, sea ice-albedo, cloud and ice insulation feedbacks, which are typically considered the trigger in the causal chain leading to AA[3,24,25]. Remote forcing mechanisms involve atmospheric and ocean heat and atmospheric moisture transport from the mid-latitudes and tropics into the Arctic[26,27]. Recent studies argue that remote mechanisms have accelerated sea ice disappearance during both winter[28,29,30,31] and summer[28,29,32,33] and are important contributors to AA. Thus local and remote mechanisms may interact and amplify one another[24]. For instance, tropical convection-forced warming through the transport of heat and moisture may be further amplified by local feedback processes, e.g., increased clouds.

Perhaps the best-known Arctic feedback is sea ice albedo[34], caused by the stark albedo difference between ice-free ocean and snow-covered sea ice surfaces (cf. ~7% and ~80% reflectance, respectively). The long-term darkening of the Arctic surface resulting from sea ice loss has been observationally confirmed, indicating a mean surface albedo reduction from 0.52 to 0.48 since 1979[35]. The increase in vegetation over Arctic land further contributes to a darkening surface at high latitudes[36]. Additionally, rapid spring continental snow cover loss lowers the surface albedo and allows the underlying soil to dry out quicker, favoring earlier and more intense warming of high-latitude land areas[37].

During winter, insulation by sea ice is waning during AA[25]. Anomalously low summer sea ice extent exposes darker ocean water to sunlight, allowing greater absorption of solar radiation thus warming the Arctic upper-ocean mixing-layer and promoting anomalous latent and sensible heat fluxes in the fall. Subsequently, this process delays fall/winter sea ice-growth allowing for warmer and moister Arctic air masses, further contributing to AA[38,39,40]. Analysis of surface turbulent flux trends indicate enhanced fluxes from the ocean to the atmosphere in the Chukchi and Kara Seas in recent years[39,41,42,43].

The sea ice-albedo feedback is not the only important mechanism contributing to AA[44]. A new consideration of equal, or possibly more importance, is the local feedback related to the impact of low-level mixed-phase clouds[45]. The net radiative effect of Arctic clouds is to warm the surface via enhanced downward longwave radiation for much of the year (predominantly during the polar night in winter), except in June and July when the reflection of solar radiation by clouds may dominate, cooling the surface[46,47]. The impact of clouds is further complicated by the seasonal evolution of surface albedo, including the summer sea ice melt and production of melt ponds[48]. CMIP5 model results disagree on whether Arctic cloud changes dampen or amplify AA[4,47].

Emerging evidence suggests that downward longwave radiation from anomalous cloud cover during winter can hinder sea ice growth[49,50,51,52,53,54,55]. In addition, analysis of CMIP5 models indicate that changes in downward longwave radiation flux from a cloudless atmosphere, rather than the sea ice-albedo feedback, is the largest contributing factor to simulated AA[47]. Observations indicate that trends in downward longwave radiation are positive almost everywhere due to increased atmospheric water vapor over the Arctic Ocean for all seasons[2]. Additional discussion on AA mechanisms is included in the SI.

Despite the robust signal of AA, knowledge of the mechanisms remains incomplete. The role of meridional (poleward) atmospheric heat and moisture transport, oceanic heat transport from mid-latitudes into the Arctic[28,29] and particularly the importance of the episodic deposition of heat and moisture at the synoptic scale, is just beginning to be understood[40,56,57,58]. A more comprehensive understanding of the chain of events leading to AA and the individual contributions of each process is needed, as the magnitude and mechanisms of AA fundamentally influence the character and likelihood of Arctic and mid-latitude connections[59].

Arctic mid-latitude linkages

Extensive new sea ice-free areas in autumn and thinner sea ice in early winter months allows for greater heating of the overlying atmosphere which represents a possible mechanism linking AA to mid-latitude weather. Preferential warming of the Arctic atmospheric column leads to increased geopotential height thickness and a reduced meridional gradient as described by the geopotential tendency equation[60], which can slow the polar Jet Stream. It has been theorized that weakened zonal winds increases the likelihood of slower and more amplified Rossby waves, enhancing the possibility of blocking situations[1] and meridional transport of air masses associated with extremes. However this idea has encountered skepticism[61,62].

A research challenge is to identify and understand possible links of thermal heating from Arctic sources to mid-latitude weather. Amplified warming does increase the potential for Arctic change to influence weather outside of the region, especially if it increases the likelihood of high-latitude blocking. Blocking results from the breakdown of the background flow pattern, which makes weather systems move slower or even become stationary[63,64]. Like boulders blocking a river, once an atmospheric block forms, its impacts are felt both upstream and downstream of the block. Moreover, blocking events have been implicated as precursors for sudden stratospheric warmings[65,66,67], which in turn influence winter weather for up to two months[68,69,70].

Below normal temperatures during the winter months over Europe and North America are associated with blocking anticyclones over high-latitude areas of northwestern Eurasia and

Greenland, respectively[3,71,72,73,74,75,76]. In addition to cold temperatures, recent observations show that an increased high latitude blocking is related to more frequent heavy snowfalls in the Eastern US[74] and an index of disruptive Northeastern US snowfalls shows that over the most recent decade the population centers of this region have been adversely impacted by snowstorms by triple the number of any previous decade (**Supplementary Figure 7**).

Mid-latitude weather is also strongly steered by highly nonlinear Jet Stream dynamics including the impact of anomalous transient storm systems on the growth and phasing of planetary waves[77], the onset and maintenance of blocking, and the strength and location of the Siberian High[78] and/or masked by internal variability[79] creating intermittency[78,80]. Arctic-mid-latitude linkages may also be related to decadal variability in global SSTs[81,82,83]. The complexity of mid-latitude weather and the dependence on the background flow complicates the ability to link AA to mid-latitude weather, especially episodic events such as cold air outbreaks and heavy snowfalls.

Hemispheric-wide response to AA

The exchange of heat from the Arctic Ocean to the atmosphere during delayed re-freezing in autumn and reduced vertical stability can intensify storm systems over the Arctic[84,85,86]. The non-linear interaction between storm systems and planetary-scale waves contributes to changes in the atmospheric circulation, which can constructively or destructively interfere with the large climatological standing waves; enhancement (destruction) of these waves can increase (decrease) upward propagation of energy in early- to mid-winter that weakens (strengthens) the stratospheric polar vortex[77,87,88]. The tropospheric response to either a weakened or strengthened polar vortex is hemispheric in scale and most closely resembles the negative or positive Arctic Oscillation (AO), respectively[15,89,90].

The earliest modeling studies demonstrated that the complete melt of Arctic sea ice forced a negative AO temperature response[91,92]. Follow-up studies reaffirmed that regionally reduced sea ice extent predominately forced a negative AO circulation response with increased sea level pressure (SLP) over the Arctic and decreased SLP over the mid-latitudes in winter[93,94,95].

However, a numerical study published in 2005 where the Hadley Centre Atmosphere-3 (HadAM3) global climate model (GCM) was forced with pan-Arctic sea ice variability found no significant relationship between differences in sea-ice concentration and the AO[96]. Following this, a number of large ensemble modeling studies have come to the same conclusion, i.e., there is little modeling evidence of a significant atmospheric response to the pan-Arctic sea ice trend[97,98,99]. One possible explanation for the discrepancy in the hemispheric response between regionally and pan-Arctic-forced sea ice anomalies is that simultaneous forcing from different regions negate each other[51,100,101]. Though Scandinavian/Ural blocking has been shown to weaken the polar vortex, Eastern Asia/Northwest Pacific blocking has been shown to strengthen the polar vortex[102]. The response of the polar vortex to sea ice loss is dependent on the location of the ensuant blocking, which may help to interpret the diverse response to sea ice loss in models.

Regional response of AA

Previous review articles have focused on the influence of AA on mid-latitude weather related to the hemispheric response projected onto the AO pattern of variability[7,9]. However, research now suggests that regional anomalies in sea ice or temperature can force regional responses in mid-latitude weather. These have focused on the relationship between sea ice loss and/or warming in the Barents-Kara Seas region with cold temperatures across Siberia and Central Asia for the recent period or WACE pattern[71,103,104,105,106,107]. A link between sea ice melt and/or warming over the

Chukchi Sea and central North American cold temperatures[12,80] and sea ice melt and/or warming in and around Greenland and eastern North American and Northern European temperatures have also been suggested[74,108,109]. Additional detail on the regional response to AA is provided in the SI.

Though there is a lack of consensus between observational and modeling studies on the hemispheric response to sea ice loss, there is possibly more agreement on the downstream regional response to localized Arctic sea ice loss and/or warming. Analysis of recent Arctic sea ice concentration trends shows three main regions of sea ice retreat in winter: Barents-Kara Seas, Chukchi-Bering Seas and around Greenland (see **Supplementary Figure 8**). In **Figure 3**, we plot the temperature anomalies associated with above normal winter temperatures regionally in the Arctic, in both the observations and the Hadley Centre Global Environmental Model-2 (HadGEM2[51]). Regional warming in the Barents-Kara Seas is linked to below normal temperatures across Central and East Asia. Regional warming in the Canadian Archipelagos-Baffin Bay and Greenland Seas is associated with below normal temperatures across Northern and Central Europe, Siberia and to a lesser degree eastern North America. Finally, regional warming in the Chukchi-Bering Seas is related to below normal temperatures across Central and Eastern North America. Somewhat consistent results were found when the HadGEM2 was forced with regional sea ice loss[51] (**Figure 3**)—sea ice loss in the Barents-Kara Seas resulted in weak cooling across Eurasia, sea ice loss in the Canadian Archipelagos-Baffin Bay and Greenland Seas resulted in cooling across Europe, parts of Canada and the Eastern US and sea ice loss in the Beaufort-Chukchi Seas resulted in cooling in parts of North America.

However, even though the regression of pan-Arctic warmth with hemispheric temperatures yields mid-latitude cooling in both the observations and models, pan-Arctic sea ice loss does not force a weakened polar vortex in the models[51,100] and cooling across the mid-latitudes is nearly absent (**Figure 3**). Therefore, while models do simulate regional cooling forced by regional sea ice loss, the cumulative response to each separate region does not add linearly but rather destructively, resulting in overall warming across the continents[100,101].

In general, the cooling from the modeling experiments is weaker than that derived from observational analysis. Additionally, while simulated regional sea ice loss results in downstream localized cooling, pan-Arctic sea ice loss results in warming across the Arctic and adjacent land areas, with almost no discernable cooling[51].

Observational analysis versus modeling experiments

Based on the consideration of a large majority of observational studies, we identified a list of proposed physical processes and/or mechanisms linking Arctic change and mid-latitude weather ordered from high to low confidence. These include: increasing geopotential thickness over the Arctic[2,110]; weakening of the thermal wind[3,111,]; modulating stratosphere-troposphere coupling[67,89,112]; exciting anomalous planetary waves or stationary Rossby waves in winter; changes in the atmospheric circulation and associated strengthening of the Siberian high and Aleutian low[28,98,113]; altering storm tracks and behavior of blockings[86,114,115].

The dynamical pathway considered most robust involves Barents-Kara sea ice loss contributing to a northwestward expansion of the Siberian High or Ural blocking leading to cold Eurasian winters (e.g.,[9,106,107,116]). The Barents-Kara Seas has experienced the greatest winter sea ice loss in the Arctic (**Supplementary Figure 8**). This leads to large heating of the overlying atmosphere, dilation of the geopotential heights and a weakening of the westerly wind that favors increased blocking over the Barents-Kara Seas and adjacent Ural Mountains region[107,117]. A ridge over northwestern Eurasia with a trough over northeastern Eurasia is favorable for the direct forcing of planetary waves onto the stratosphere via enhanced vertical propagation of wave energy[88,89,118]. This can lead to wave breaking and disruption of the stratospheric polar vortex[119]. Significant disruption of the polar vortex is then followed by a negative AO response and widespread cold temperatures across the NH mid-latitude continents[69,112] but with a focus across Asia[70].

The simulated response to Arctic sea ice loss has spanned a wide spectrum from no response to warming and cooling of the mid-latitudes. Early modeling studies found that low sea ice, either pan-Arctic or east of Greenland and extending into the Barents-Kara seas, forced cold temperatures across the NH continents similar to the negative AO temperature pattern[91,92,93,94,95]. However, since then, modeling studies have supported the entire range of atmospheric response, including cold continents[12,69,71,105,106,112,116,120,121], a disrupted stratospheric polar vortex comparable to observed[69,112,118,121] and weaker and/or delayed relative to observed[51,100], a negative AO[118,122], a positive AO[123,124] with mild continental temperatures[125] and finally no robust impact on mid-latitude weather[97,98,99,126].

Still, despite the wide spectrum of modeled responses, in the majority of modeling investigations, especially those involving large ensembles, the atmospheric response to low sea ice forcing is small relative to the internal variability and does not include cold winters across the NH mid-latitude continents. Therefore, based on these studies, observed cooling is attributed to natural variability[12,97,98,99,124,126]. However, some of the differences in observed and modeled polar vortex behavior may be due to the fact that most GCMs are “low-top” models and only poorly resolve the stratosphere and stratosphere-troposphere coupling mechanisms[88,127]. Some recent "high-top" climate models with improved stratospheric variability support an atmospheric response to sea ice loss more consistent with observational analysis[100,112,121].

Recent NH winter temperature trends

Temperature anomalies for the mid-latitude continents (all land grid points 30-60°N)—December to March from 1988/89 through 2018/19 from observations and the corresponding predicted temperature anomalies from the North American Multi Model Ensemble (NMME[128]) initialized with atmospheric and oceanic conditions including sea ice on November 1 for each year—display little organization other than a warm temperature bias (**Figure 4a**). A fairly wide scatter of predicted and observed temperature anomalies exists over the period, which could be considered representative of the noisy nature of mid-latitude weather and/or the lack of consensus in Arctic forcing.

Comparison of observations and the model forecast mid-latitude continent temperature anomalies separately, however, reveals some systematic patterns (**Figure 4b**). The observed temperature anomalies are either on the cold extreme of the envelope of model forecasts, and many observed winters are even colder than the most extreme cold ensemble member. When the observed values are plotted with the ensemble mean of the model forecasts only, a clear dichotomy appears (**Figure 4c**)—the observed value is colder than the ensemble mean in the era of AA without exception. The models predict that the mid-latitudes should be warming at a rate nearly identical to the warming for the entire NH of +0.039°C/year. In contrast, the observations show that temperatures across the mid-latitude continents have remained nearly constant and the model simulated rate of warming is diverging from the observed rate by about +0.38°C/year. Similarly, trend lines diverge in the Arctic with the simulated rate of Arctic warming only half of that observed (**Figure 4d**). In contrast, comparison of the tropics, mid-latitude oceans (**Supplementary Figure 9**) and even NH land and ocean temperature for both the observations and the model forecasts shows good agreement between the model-predicted and observed hemispheric winter temperatures trends

(**Figure 4d**), despite the divergence in mid-latitude land and Arctic winter temperatures (**Figure 4c**). Finally, in the SI and **Supplementary Figure 10** we present summer temperature trends where the observed and simulated mid-latitude temperature trends are comparable.

These plots represent a new paradigm of two distinct and divergent camps on the influence of AA on mid-latitude winter weather. Though the NH is warming in the GCMs at a rate comparable to the observed warming, the distribution of that heating is clearly different in the era of AA. The models suggest that during AA, anomalous winter warming is more equitably distributed between the Arctic and the mid-latitudes so that both regions are warming at a rate comparable or faster than the hemispheric average. In contrast, the observed temperature trends coupled with observational studies suggest that AA favors the increase of the meridional exchange of air masses between the Arctic and the mid-latitudes, resulting in the NH mid-latitude continents cooling relative to the whole NH as Arctic warming accelerates. This asymmetric distribution of observed NH warming is consistent with the surface temperature anomaly pattern following polar vortex disruptions[90].

Empirical studies have highlighted that the excessive Arctic heat is distributed vertically through the lower- and mid-troposphere rather than horizontally (**Figure 1**). The vertical distribution of the heat in the Arctic that extends to the mid-troposphere supports high-latitude blocking that further favors a poleward transfer of heat into the polar stratosphere transported from lower latitudes that is conducive to disrupting the polar vortex. Following polar vortex disruptions, Arctic air is displaced into the mid-latitudes resulting in either cooling or a delay in the warming rate of the mid-latitudes relative to the remainder of the NH. In contrast, model simulated AA is relatively shallow but horizontally extensive (**Figure 1**), which is only favorable for a weak disruption of the polar vortex that does not significantly cool the mid-latitudes. A simplified explanation of the WACC pattern in the era of AA based on the majority of observational analysis and model data is provided in **Boxes 1** and **2**, respectively.

Conclusions

Improved understanding and parsing of the influence of Arctic, global SSTs and internal variability on mid-latitude weather provides a clear pathway forward for improving subseasonal to seasonal weather outlooks that will aid policy makers in decisions and activities related to climate change. Projections have been for winters to become increasingly mild with less frequent snowfalls. However, severe winter weather persists, and in some regions, heavy snowfalls have become more, not less, frequent[74]. Though a growing number of studies argue that AA has contributed to more frequent severe winter weather across the NH continents, these are countered by others that argue differently—the influence of pan-Arctic warming is either insignificant or, alternatively, contributes to milder mid-latitude winters. This divide on Arctic change influence has contributed to the impression that this research topic is controversial and lacking consensus[8,129,130,131]. An alternate interpretation is that the wide range of results should be expected owing to the varying approaches to study the problem and the complexity and intermittency of Arctic/mid-latitude connections[80,132,133].

Here we have attempted to elucidate the complexity of the topic by surveying and synthesizing observational and modeling studies to date (see **Supplementary Figure 4**). First, we highlight that AA is not limited to sea ice melt but rather has multiple causes with significant spread among climate model projections. While true consensus on the mechanisms of Arctic/mid-latitude weather linkages is lacking, a more comprehensive assessment reveals a convergence of scientific evidence and ideas. While early studies focused on the hemispheric response to sea ice anomalies, more recent studies highlight the importance of regional atmospheric response to localized sea ice anomalies; model and observational studies may share common ground demonstrating those linkages. However, we conclude that the majority of model and observational studies diverge on the hemispheric response to pan-Arctic sea ice anomalies and warming. Overwhelmingly, observational studies argue that AA forces winter cooling across the mid-latitude continents while the majority of modeling experiments do not. The spatial distribution of NH winter warming rates in the model simulations closely aligns with expectations of AA—the warming increases with latitude, the tropics warm the least, the Arctic warms the most and the mid-latitudes fall somewhere in between and close to the NH average. Furthermore, any observed mid-latitude winter continental cooling trends in the twenty first century are due to natural variability. In contrast, observed NH winter warming rates have been characterized by moderate warming in the tropics, amplified warming in the Arctic and almost no warming across the mid-latitude continents. The conclusion of empirical studies is that the distribution of observed heating rates likely cannot be explained without including dynamical arguments related to AA.

Currently, observed and simulated NH mid-latitude continental temperature trends are diverging. If future mid-latitude winters warm while converging towards simulated trends, then the current divergence was likely a result of natural variability. Alternatively, future modeling simulations may converge towards support of the observationally-derived hypothesis that AA favors colder mid-latitude winters. As discussed above, modeling studies with regional sea ice melt confined to the Barents-Kara Seas and a well resolved stratosphere with interactive stratospheric chemistry do simulate a weakened polar vortex and cold mid-latitudes[51,106,112,116,121] consistent with the observations. Precise representation of the stratosphere in models may help resolve discrepancies between model and observational studies. A set of coordinated modeling studies is underway[134] that is designed to better quantify the forced atmospheric response to sea ice loss[113].

While further research should elucidate the varying mechanisms of Arctic/mid-latitude weather linkages, it remains a challenge to extricate cause-and-effect signals from the inherently chaotic climate system. The present lack of certainty may frustrate policymakers and the general public, but science often advances slowly on issues with great complexity and intermittency. Regardless, this review of the state of research on connections between a rapidly melting Arctic and severe winter weather is timely as large population centers in North America and Eurasia continue to experience severe cold, snowstorms and weather whiplash. Ongoing research will provide progress towards consensus on this scientifically and societally important topic.

Box - B1 Observational studies:

Observational analyses support that AA, and in particular sea ice loss, can influence mid-latitude winter weather through a stratospheric pathway. Climatology favors a strong polar vortex supported by cold air over the Arctic and milder air at lower latitudes. This temperature distribution forces low geoptotential heights over the Arctic and higher heights in the mid-latitudes (**left panel**). In recent decades this climatologically-favored configuration of the polar vortex has become increasingly perturbed[15,70,88,116]. While Arctic warming is strongest at the surface (**Figure 1**), it extends throughout the mid-troposphere. In addition, the sea ice loss and associated warming is not uniform across the Arctic, but rather regionally focused. Concentration of Arctic warming in the Barents-Kara Seas dilates geopotential heights over northwestern Eurasia, leading to more frequent high latitude Scandinavian/Ural blocking that is favorable for the excitation of vertically propagating energy associated with large-scale planetary waves[9,67,69,88]. The increased vertical propagation of energy is coupled with more frequent intrusions of warm air from lower latitudes depositing heat in the polar stratosphere, which causes a second maximum of Arctic warming where the polar vortex normally resides (**Figure 1)**. Warming throughout the atmospheric column dilates the geopotential heights sufficiently to reverse the normal equator-pole geopotential height gradient, resulting in cold air previously trapped near the Pole to be displaced to the mid-latitudes. As air flows southward away from the North Pole towards the equator, the air is deflected to the west by the Coriolis force, forming an easterly wind around the North Pole. The redistribution of air masses that happens first in the stratosphere is then replicated through the troposphere to the surface. This completes the reversal of the NH circulation pattern with relatively warm temperatures and high geopotential heights over the Arctic and lower heights in the mid-latitudes accompanied by more frequent cold air outbreaks to the mid-latitudes (**right panel**).

Box – B2 Modeling data:

The large-scale hemispheric circulation is similar in model simulations to the bservations during the pre-AA period, with cold air over the Arctic, milder air over the mid-latitudes and subtropics and the stratosphere dominated by a strong polar vortex with higher geopotential heights at lower latitudes (**left panel Box 1 Figure**). However, in the ensuing period of AA, the excess warming generated in the Arctic due to sea ice loss and other mechanisms described above is not redistributed vertically in model simulations, but rather horizontally (**Figure 1**) via advection or conduction from the Arctic to lower latitudes[11]. Furthermore, the CMIP5 and AMIP simulations either lack or have a relatively weak second maxima in heating in the polar stratosphere during the AA era. The simulated AA atmospheric circulation is nearly unchanged from the pre-AA period other than a weakening of the equator to pole-height gradient, resulting in no increase in cold air outbreaks from the Arctic to the mid-latitudes. Instead, cold air outbreaks are moderated, contributing to further warming of the mid-latitudes (**left panel**). The simulated shallower Arctic heating either is insufficient to force a disruption of the polar vortex or one of comparably weak magnitude in many modeling experiments. Therefore, any induced dynamical cooling, either due to a simulated weaker stratospheric polar vortex or a negative AO, is overwhelmed by amplified Arctic warming and the transport of the milder Arctic air southward[135]. Conceptual mechanisms are derived from archived ensembles coordinated among modeling centers.

Instead, the majority of model simulations indicate that during AA, observed colder temperatures in the mid-latitudes are due to natural/internal variability or a remote forcing other than AA. As an example, changes in tropical convection transports additional heat both into the Arctic[136], resulting in amplified warming, and into the polar stratosphere, leading to a more highly disrupted polar vortex and displacement of cold air southwards to lower latitudes[137] (**right panel**).

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Methods

In **Figure 1**, air temperature (variable ta) was retrieved from the Earth System Grid Federation (ESGF) archive for the reanalysis of the Collaborative REAnalysis Technical Environment (CREATE-MERRA-2, ERA5, JRA-55 and CFSR) for the period December 1980 to February 2019 and was averaged on pressure level to obtain a seasonal and zonal mean. A linear trend was then computed at each point in the latitude-pressure plane. The trend was assumed to be distributed according to a t-distribution. For the RCP8.5 scenario of the CMIP5 project, trends were combined by first taking an average over all simulations for each model, then averaging over all models over an institute and then averaged over institutes to obtain a multi-model mean. The distribution of trends at each point in the latitude-pressure plane and for each season was found through bootstrapping with 50,000 samples. For each sample, we randomly select one simulation for each model and then combine all the chosen simulations to obtain a multi-model mean, and then compute a trend using this multi-model mean time series. By repeating this procedure, we obtain a distribution of trends. From this distribution of trends for each season, we can find at each point in the latitude-pressure plane the p-value for the null hypothesis of no trend. We then apply the False Discovery Rate correction[138] with a global p-value of 0.05. The False Discovery Rate correction is a field significance test that calculates a new threshold p-value based on the distribution of p-values. For the reanalyses of the Collaborative REAnalysis Technical Environment–Intercomparison Project, we applied the exact same analysis except that the 50,000 bootstrap samples for the trend distribution were generated in a slightly different fashion. Instead of selecting one simulation for each reanalysis (there is only one), we selected a random trend from each of the reanalyses' trends t-distribution. The linear air temperature trend in **Figure 1c, d** is based on the 16-member Atmosphere Model Intercomparison (AMIP) simulations with the "higher-top" version of the NCAR's Community Atmosphere Model version 5 (CAM5[139]) for 1980/1981–2015/2016. In **Figure 1c**, the air temperature is first averaged zonally and seasonally and over all 16 members before the linear trend is calculated. **Figure 1d** is the trend for member number 14 that best matches the observation. Significance was assessed in the same way as for the other the panels. With a single simulation the method reduces to a one-sided t-test onto which we apply the False Discovery Rate. The air temperature data in AMIP simulations and detailed forcing information are available at: https://www.esrl.noaa.gov/psd/repository/entry/show?entryid=e5555a12-84f8-4bc6-86e3-17b51124c459

In **Figure 3**, spatial relations among regional and full Arctic 850 hPa air temperature and NH near surface temperatures composited were examined with a series of composites computed with ERA-Interim Reanalysis[140]. Area-averaged reference means were formed from 1981–2010 in both the near surface temperature and 850 hPa air temperature for the Barents-Kara Sea (65N to 80N, 10E to 100E), Canadian Archipelagos and Baffin Bay (60N to 90N, 80W to 50W), east of Greenland (65N to 80N, 40W to 10W), and the Chukchi and Bering Seas (65N to 80N, 170E to 210E). The near surface temperature anomalies were regressed onto 850 hPa air temperature using daily data in winter (DJF) 1979/80 to 2018/19; all data is linearly detrended when the 850 hPa air temperatures were between 0.5 and 3 standard deviations above the climatological average. Completing this analysis is the Polar Cap Temperature at 850 hPa, area-averaged from 65 to 90°N and similarly regressed with NH near surface temperatures (**Figure 3e**). A comparable analysis was completed with HadGEM2 data. The model data is from 1600 winters simulated under present day conditions using the HadGEM2-ES model. Specifically, we ran 400 realizations of five years in length from 2008–2012 under the RCP8.5 scenario. Runs were started on Jan. 1st, so there are only four full winters in each five-year run. Initial conditions for the 400 realizations were generated by first branching off 16 different realizations at the year 1990 from historical simulations and then forcing with historical/RCP8.5 forcing until 2008. At year 2008, 25 realizations where branched off of each of the 16 different climate states by using the atmospheric initial conditions from 25 different dates (from Jan. 1st to 25th). Forced response to sea ice in **Figure 3k-o** are from Screen[51].

In **Figure 4**, the linear trend for December, January, February and March (DJFM) 2-m temperature was computed using both the National Centers for Environmental Prediction (NCEP) Reanalysis[141] and the November forecast components of the North American Multi-Model Ensemble (NMME[128]). Included in the NMME were models from the Canadian Meteorological Center (CMC1-CanCM3 and CMC2-CanCM4), the Center for Ocean-Land-Air Studies (COLA-RSMAS-CCSM4), and the Geophysical Fluid Dynamics Laboratory (GFDL-CM2p5-FLOR-A06 and GFDL-CM2p5-FLOR-B01). Reference means were computed from 1981–2010 for NCEP and 1982–2010 for NMME components (NMME hindcasts begin in 1982). For the NMME components, the zero-hour forecasts were treated as analyses for the DJFM period, with each model treated individually; so, for example, the CMC1-CanCM3 analyses for 1982–2010 were used to form the reference mean for computing anomalies in the CMC1-CanCM3 Nov. forecasts for DJFM. For the mid-latitude NH (30 to 60°N), all annual anomalies from 1989–2017 were computed for observed (NCEP) and forecast (NMME Nov. for DJFM), using all ensemble members of the individual NMME components (**Figure 4a** with all in gray, **Figure 4b** with NCEP in blue and NMME in red). The annual mean of all NMME components and ensembles was then used to compute the linear trend from 1989–2017 (**Figure 4c** in red) for comparison to the NCEP linear trend (**Figure 4c** in blue). For broader comparison, these calculations were repeated for the entire NH and Arctic only with trend lines for NMME (green/red) and NCEP (black/blue) shown in **Figure 4d**. Anomalies are calculated relative to climatology from reanalysis for 1981–2010 and from NMME 1982–2010 winter mean respectively.

In **Supplementary Figure 1a**, the near surface mean temperature zonally averaged from 90°S to 90°N and from 1960–2018 are plotted. Data is from NASA/GISS[142]. In **Supplementary Figure 1b,** 2-m air temperature anomalies and the five-year running mean for December through February are plotted for the Arctic, mid-latitudes land areas and the difference between the Arctic and mid-latitudes land areas. Climatology used is the thirty-year average of 1981–2010. Data is from NCEP/NCAR reanalysis data[141].

In **Supplementary Figure 2a** and **b**, the linear trend is computed for each grid cell in the Hadley Centre-Climate Research Unit CRU global temperature dataset-4 (HadCRUT4[143]) for land surface only, multiplied by ten to provide a trend in °C/decade for the months October through December and January through March, respectively from 1988–2008. In **Supplementary Figure 2c** and **d**, the average surface temperature anomaly is computed for each grid cell in the Hadley Centre CRU land surface data for the months October through December and January through March, respectively from 2008–2018. Climatology used is the thirty-year average of 1981–2010.

The simulations presented in **Supplementary Figures 5** and **6** are conducted at NOAA's Earth System Research Laboratory Physical Science Division. These are AMIP simulations from 1979 to present day forced by observed GHGs, ozone, aerosols and surface lower boundaries (i.e., sea surface temperature and sea ice conditions). Three model simulations from NCAR "low-top" Community Atmosphere Model Version 5 (30 members[144]), NCAR "higher-top" CAM5 (16 members[139]), and ECHAM5 (30 members[145]) are utilized for the decadal temperature trend across 1980-2015.

In **Supplementary Figure 5**, the air temperature is first averaged zonally and seasonally and over all available members before the linear trend is assessed. All the data and detailed model simulation information can be found at: https://www.esrl.noaa.gov/psd/repository/entry/show?entryid=e5555a12-84f8-4bc6-86e3-17b51124c459.

In **Supplementary Figure 7** we tabulated the number of disruptive Northeast snowstorms by decade from the NOAA website: https://www.ncdc.noaa.gov/snow-and-ice/rsi/nesis.

In **Supplementary Figure 8**, the linear trend in sea ice concentration from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST[146]) are shaded.

In **Supplementary Figure 9**, the winter near surface air temperature anomalies and the linear trend for December, January, February and March (DJFM) were computed using both the NCEP Reanalysis and the November forecast components of the NMME models for the tropics (0-30°N) and mid-latitude oceans (30-60°N). Climatology used for reanalysis is 1981–2010 and for NMME is 1982–2010 winter mean respectively .

In **Supplementary Figure 10**, reanalysis is repeated as in **Figure 4** and **Supplementary Figure 9** except that the climatology used is 1981–2010 winter mean from the NCEP Reanalysis for all NMME temperature anomalies.

Supplementary Figure 11 is same as **Figure 4** but for summer (June, July and August).

In **Supplementary Figure 12** we computed the difference in the trends from 1989-2019 between winter (December, January and February) and summer (June, July and August). Shown on the left hand side are the zonal mean difference in the trends.

Acknowledgements

We are grateful to R. Blackport, C. Deser, L. Sun, J. Screen and D. Smith for many helpful discussions and suggested revisions to the manuscript. We are also grateful for J. Screen and L. Sun for model data. J. Cohen is supported by the US National Science Foundation grants AGS-1657748 and PLR-1504361, 1901352. M. Wendisch gratefully acknowledges the funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project Number 268020496–TRR 172, within the Transregional Collaborative Research Center "Arctic Amplification: Climate Relevant Atmospheric and Surface Processes, and Feedback Mechanisms (AC)". T. Vihma was supported by the Academy of Finland (Grant 317999). JEO was supported by the NOAA Arctic Research Program. J.-H. Yoon was supported by the Korea Meteorological Administration Research and Development Program under Grant KMI2018-01015 and National Research Foundation Grant NRF_2017R1A2B4007480. D. Handorf is supported by the Helmholtz Association of German Research Centers (grant FKZ HRSF-0036, Project POLEX).

Author Contributions

Cohen led the team of authors in writing the text. F. Laliberte created Figure 1. P. Taylor, Aimee Amin and Sukyoung Lee created Figure 2. J. Cohen and K. Pfeiffer created Figure 3. J. Cohen and K. Pfeiffer created Figure 4. J. Cohen created Figures B1 and B2. J. Francis assisted with manuscript revision.

Competing Financial Interests

The authors declare no competing financial interests.

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Figure captions

Figure 1. **Observed and ensemble mean temperature trends show large discrepancies in winter**. **a** Winter (December, January, February) and zonal-mean air temperature trends from December 1980–February 2019 for the average of MERRA-2, ERA5, JRA-55 and CFSR reanalysis products for DJF. **b** Same as **a** but for the CMIP5 multi-model mean historical through 2004 and RCP8.5 thereafter. **c** Same as **a** but for the AMIP multi-model mean. **d** Same as **c** but for the AMIP ensemble member that best matches the reanalysis mean based on pattern correlation. Stippling indicates trends significant with a $p < 0.05$ after the false discovery rate was applied[136].

Figure 2. **Mechanisms of Arctic amplification are complicated**. Schematic illustrates the important processes and energy flows influencing Arctic amplification. Local processes, such as the sea ice albedo feedbacks, changes in surface turbulent fluxes, clouds, ocean heat storage, and ocean mixed layer change are highlighted in peach. Remote processes, such as atmosphere and ocean heat transport are highlighted in purple. An important aspect of Arctic amplification is the seasonal transfer of energy from sun-lit to the dark season denoted by the graduated arrow (orange-black).

Figure 3. Observed and simulated winter temperature relationships to Arctic warming share similarities regionally. Observed Northern Hemisphere near-surface air temperature anomalies for all days when 850 hPa temperature anomalies were between 0.5 and 3.0 standard deviations above the climatological average for all winters (December, January, February) 1950–2019 in **a** Barents-Kara Sea, **b** Canadian Archipelago-Baffin Bay, **c** Greenland Sea, **d** Chukchi-Beaufort Seas, and **e** Pan-Arctic regressed onto NH surface temperatures. Anomalies are calculated relative to climatological averages from 1981 to 2010. **f-j** same as for **a-e** but for atmospheric output from the ensemble-mean HadGEM2 GCM. October-to-March mean near-surface air temperature

responses in HadGEM2 model simulations from Screen (2017a) to observed sea-ice loss in the **k** Barents-Kara Sea, **l** Canadian Archipelago-Baffin Bay, **m** Greenland Sea, **n** Chukchi-Beaufort Seas, and **o** Pan-Arctic. Hashing denotes statistically significant response at the 95% confidence level using the Student's t-test. ERA-Interim used for observational data.

Figure 4. Observed and simulated mid-latitude winter temperature trends are diverging. **a** Reanalysis and hindcasted/predicted NMME individual ensemble members for NH mid-latitude continental temperature anomalies. **b** Same as **a** but reanalysis (blue) and NMME (red). **c** Reanalysis (blue) and hindcasted/predicted NMME ensemble mean (red) NH mid-latitude continental temperature anomalies. Also included is the linear trend line for each dataset. **d** Reanalysis (black) and hindcasted/predicted NMME ensemble mean (green) NH temperature anomalies and reanalysis (blue) and hindcasted/predicted NMME ensemble mean (red) Arctic temperature anomalies and linear trends. All temperature anomalies are for December, January, February and March from 1988/89 through 2018/2019. Anomalies are calculated relative to climatology from reanalysis 1981–2010 and from NMME 1982–2010 winter mean respectively. Variance (R^2) included for all trend lines. All trends except the NCEP NH mid-latitude land regions are statistically significant at the >99% confidence level. There is a cold bias in the climatology of the NMME models extratropical atmosphere compared to the observations In **Supplementary Figure 10,** we show the NMME temperature anomalies relative to the NMME climatology.

Figure Box 1. How Arctic amplification influences mid-latitude weather through the polar vortex based on observational analysis.

Figure Box 2. How Arctic amplification influences mid-latitude weather through the polar vortex based on numerical modeling experiments.