PERSPECTIVE
nature climate change

| DOI: 10.1038/NCLIMATE3121

Nonlinear response of mid-latitude weather to the changing Arctic

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Are continuing changes in the Arctic influencing wind patterns and the occurrence of extreme weather events in northern mid-latitudes? The chaotic nature of atmospheric circulation precludes easy answers. The topic is a major science challenge, as continued Arctic temperature increases are an inevitable aspect of anthropogenic climate change. We propose a perspective that rejects simple cause-and-effect pathways and notes diagnostic challenges in interpreting atmospheric dynamics. We present a way forward based on understanding multiple processes that lead to uncertainties in Arctic and mid-latitude weather and climate linkages. We emphasize community coordination for both scientific progress and communication to a broader public.

Various metrics indicate that the recent period of disproportionate Arctic warming relative to mid-latitudes — referred to as Arctic amplification (AA) — emerged from the noise of natural variability in the late 1990s[1]. This signal will strengthen as human activities continue to raise greenhouse gas concentrations[2]. The assessment of the potential for AA to influence broader hemispheric weather (referred to as linkages) is complex and controversial[3–6]. Yet with intensifying AA, we argue that the key question is not whether the melting Arctic will influence mid-latitude weather patterns over the next decades, but rather the nature and magnitude of this influence relative to non-Arctic factors, and whether it is limited to specific regions, seasons or types of weather events[7].

Although studies arguing for linkages often highlight a single causal pathway, the complexity of atmospheric dynamics implies that such singular linkage pathways are unlikely. Nonlinearities in the climate system are particularly important in the Arctic and subarctic[8–10]. The climate change signal is larger there than anywhere else in the Northern Hemisphere, and the region possesses multiple feedbacks. Coupling exists between the Arctic troposphere and the wintertime stratospheric polar vortex, which itself is highly nonlinear. A linkage pathway that may appear to be responsible for one series of events may not exist in another scenario with similar forcing. This is potentially reflected in observational studies that have struggled to find robust linkages[11,12]. Further, multiple runs of the same model with similar but slightly different initial conditions, termed ensemble members, show linkages in some subsets of ensemble runs but not in others[13]. This failure to detect direct connections is sometimes interpreted as evidence against linkages. Four properties (limitations) that contribute to the complexity of attribution of linkages are discussed in this Perspective: itinerancy (seemingly random variations from state to state), intermittency (apparently different atmospheric responses under conditions of similar external forcing, such as sea ice loss), multiple influences (simultaneous forcing by various factors, such as sea surface temperature anomalies in the tropics, mid-latitudes and Arctic), and state dependence (a response dependent on the prior state of the atmospheric circulation, for example, the phase of the Arctic oscillation (AO) atmospheric circulation index or the strength of the stratospheric vortex).

We propose a system-level approach that recognizes multiple simultaneous processes, internal instabilities and feedbacks. Progress in understanding Arctic–mid-latitude linkages will require the use of probabilistic model forecasts that are based on case studies and high-resolution, ensemble solutions to the equations of motion and thermodynamics. Community coordinated model experiments and diagnostic studies of atmospheric dynamics are essential to resolve controversy and benefit efforts to communicate the impacts of linkages and uncertainties with a broad public.

Arctic warming is unequivocal, substantial and ongoing

Changes in Arctic climate in the last three decades are substantial. Since 1980, Arctic temperature increases have exceeded those of the Northern Hemisphere average by at least a factor of two[14]. Over land north of 60° N, 12 of the past 15 years have exhibited the largest annual mean surface air temperature anomalies since 1900. AA is also manifested in the loss of sea ice, glaciers, snow and permafrost, a longer open-water season, and shifts in Arctic ecosystems. Sea ice has undergone an unprecedented decline over the past three decades with a two-thirds reduction in volume[2]. Comparable decreases in snow cover have occurred during May and June. AA is strongest in autumn/winter with largest values over regions of sea ice loss[15], while the areas of greatest warming in summer are located over high-latitude land where rates of spring snow loss have exceeded even those of sea-ice loss[16].

This amplification of warming in the Arctic occurs for several reasons, all based on fundamental physical processes[17,18]. Among these are feedbacks related to albedo owing to a loss of snow and sea ice along with increases in heat-trapping water vapour and clouds. Increasing temperatures in the lower atmosphere elevate the height of mid-level pressure surfaces (geopotential height), leading

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to changes in poleward and regional gradients and, consequently, wind patterns[19–21].

Based on over 30 climate model simulations presented in the most recent IPCC Assessment Report, future winter (November–March) surface temperatures in the Arctic (60–90° N) are projected to rise by ~4 °C by 2040, with a standard deviation of 1.6 °C, relative to the end of the previous century (1981–2000)[2]. This is roughly double the projected global increase and is likely to be accompanied by sea-ice-free summers. Past and near-future emissions of anthropogenic CO_2 assure mid-century AA and global warming.

Living with an uncertain climate system

The task of unravelling cause and effect of the mechanisms linking changes in the large-scale atmospheric circulation to AA is hampered by poor signal detection in a noisy system and complex climate dynamics, regardless of whether the approach is via statistical analyses or targeted model simulations. Nonlinear relationships are widespread in the Arctic climate system, in which responses are not directly proportional to the change in forcing[8,10,22]. Further, when discussing anomalous weather or climate conditions, causation can have different meanings. Typically, one factor is necessary but several supplementary factors may also be required. This can lead to confusion because only sufficient causes have deterministic predictive power[23,24]. Together these factors make linkage attribution challenging. Many previous data and modelling analyses start with straightforward Arctic changes using, for example, diminished sea ice, and at least implicitly assume quasi-linear, sufficient causal connections[5,7,25–37]. While this approach has been helpful in elucidating relevant linkage mechanisms, we provide a view that at the system level, multiple processes can mask simple cause and effect.

Thermodynamically (that is, related to temperature gradients) forced wind systems on a rotating planet produce west-to-east flow at mid-latitudes. This flow is dynamically unstable, creating north–south meanders that generate high- and low-pressure centres, which can produce disruptive weather events. In addition to internal instability, variability in the wind pattern is forced by influences external to the mid-latitude atmosphere that may themselves reflect internal variability on longer timescales, such as sea surface temperature anomalies in the tropics, mid-latitudes and ice-free parts of the Arctic. Remote forcings (that is, changes outside the mid-latitudes, remote in space and perhaps time) can influence the mid-latitude circulation through linear and nonlinear atmospheric patterns, known as teleconnections. Extensive regions of positive temperature anomalies in the Arctic may increase the persistence of weather systems[20,38]. Further, troposphere–stratosphere connections can trigger changes in the regional wind patterns[39]. Contributors to a lack of simple robust linkages include the four properties mentioned above, which are discussed in more detail in the following sections.

Itinerancy. This refers to the atmosphere spontaneously shifting from state to state based on instabilities in the wind field that can be amplified by internal and external variability. Such states can persist through nonlinear mechanisms[10,22]. Figure 1a,b illustrates two configurations of the northern hemispheric wind pattern (tropospheric polar vortex) occurring at different times: the case shown in Fig. 1a is for a day in November 2013 that had a relatively circular flow pattern around the North Pole, and Fig. 1b shows another day two months later exhibiting a more north–south wavy flow pattern. Although the phrase 'polar vortex' is often reserved for the stratosphere, it is a useful term for discussing tropospheric geopotential height/wind configurations such as those shown in Fig. 1. The jet stream flows from west to east parallel to these geopotential height contours and is strongest where the contours are closest together. Shifts to and from a wavy pattern — known historically as the index cycle — and the varying longitudinal locations of ridges (northward peaks) and troughs (southward excursions) in the geopotential height pattern are part of the seemingly random, internal variability of atmospheric circulation. A wavier jet stream allows cold air from the Arctic to penetrate southwards into mid-latitudes, and ridges transport warm air northward. Figure 1c,d shows corresponding temperature anomaly patterns for these two days. For the more circular jet stream, cold anomalies are mostly contained within the polar region along with warmer anomalies around mid-latitudes (Fig. 1c). This particular pattern is not perfectly symmetric around the North Pole, as the centre of the vortex is shifted into the western hemisphere. The wavier jet stream case has two warm and two cold anomaly regions in mid-latitudes (Fig. 1d), to the west and east of the region of increased heights (ridges) over Alaska and Scandinavia. Many extreme weather events associated with wavy circulation patterns have occurred in the last decade[40,41].

Multiple studies[42–44] illustrate the paradigm of itinerancy in describing the physical mechanisms driving shifts in atmospheric circulation. Atmospheric circulation can fluctuate between multiple states (referred to as local attractors) in irregular transitions, resulting in chaotic-like behaviour on monthly, seasonal and interannual timescales[42]. Chaos theory argues that the climate system can destabilize and suddenly shift into a new stable state[45,46]. On decadal timescales, increasing variability within a time series is a possible early warning signal of a critical transition to a different state[47].

Do observations indicate a recent increase in these types of sudden shifts in the atmospheric circulation? Although one might expect decreased sub-seasonal variability as the temperature contrast across the jet stream declines with AA[48], recent observations suggest contrary evidence of stable or larger circulation variability and new extremes in several circulation indices. For example, an enhanced magnitude of both positive and negative excursions of the AO circulation index is evident in the last decade during Decembers, based on data from 1950–2014[49]. Cohen[50] notes an increase in mid-latitude intraseasonal winter temperature variability from 1988/1989 to 2014/2015. Periods of relative persistence as well as increases in interannual variability have been noted in other related winter climate indices — such as the North Atlantic Oscillation (NAO), Greenland Blocking Index (GBI), and jet latitude metrics — although stability is more evident at other times of the year[51–53]. Observations from the next decade should reveal much about whether increasing variability and weather extremes are ongoing features of climate change or whether circulation-related extremes are damped by AA.

The ability of state-of-the-art climate models to correctly simulate the interplay between thermal and dynamical processes producing itinerancy on different spatial scales is limited. One manifestation of this is the continuing tendency for climate models to underestimate the frequency of blocking (a regional slowing of tropospheric winds)[54]. Further, the signal-to-noise ratio in models could be too weak, as appears to be the case for seasonal forecasts of the NAO[55–57].

Intermittency. This refers to necessary but insufficient causation, and suggests an inconsistent response, evident at some times and not at others, or the same response arising from different combinations of Arctic conditions. In other words, the response is not a unique function of the forcing. If responses are intermittent, a longer time series and/or a stronger signal would be needed to detect them. Often climate models and correlation analyses of observations produce differing estimates of how the climate will respond to the ongoing AA and loss of sea ice[48,58]. For example, climate model studies have reported shifts towards both the positive or negative phases of the AO and/or NAO, or no apparent shift, in response to AA[13,19,34,39,59]. Analyses that involve averaging over large areas, long time periods and/or many ensemble members may not reveal specific atmospheric responses to AA, such as enhanced jet stream ridges and troughs that occur in specific locations. Despite

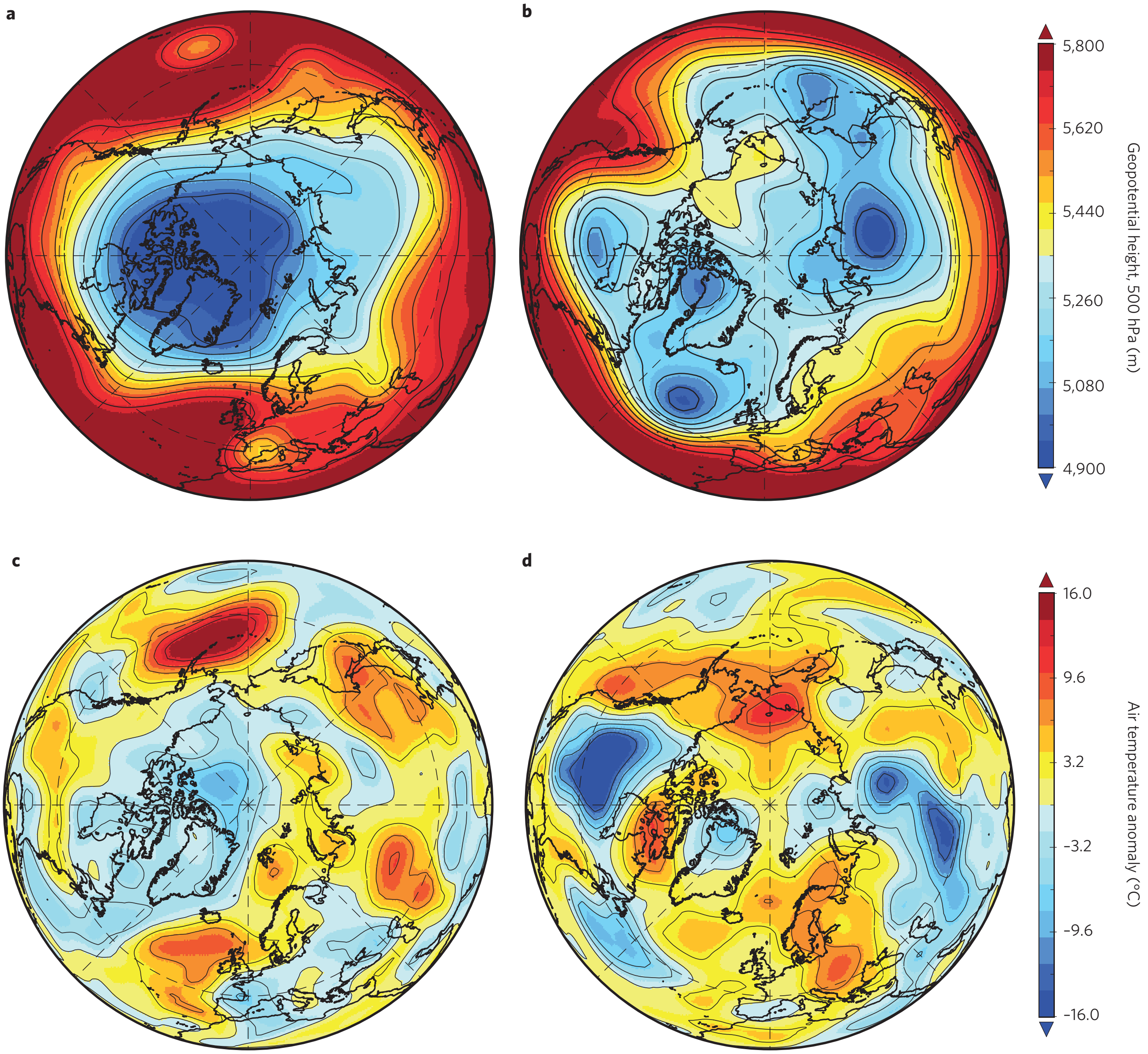

Figure 1 | Different configurations of the tropospheric polar vortex. a,**b**, Geopotential height (in metres) of the 500 hPa pressure surface, illustrating the Northern Hemisphere's tropospheric polar jet stream where height lines are closely spaced. Winds of the jet stream follow the direction parallel to contours, forming the persistent vortex that circulates counter-clockwise around the North Pole. The primarily west-to-east wind flow can adopt a relatively circular pattern (**a**, for 15 November 2013) or a wavy one (**b**, for 5 January 2014). **c**,**d**, These panels show the corresponding air temperature anomaly patterns (in °C) for the same days at a lower atmospheric level (850 hPa). Data from the NCEP/NCAR reanalysis product.

some clear hypotheses for linkages, it remains difficult to prove that Arctic change has already had (or not had) an impact on mid-latitude weather based on observations alone because of the short period since AA has become apparent[5].

One approach to overcome the signal-to-noise problem is to use model simulations[59]. Large ensembles of climate simulations have been run with observed sea ice loss as the only forcing factor. In such large ensembles, it is possible to determine how many years of simulation are required for the impacts of sea ice loss to become detectable over the noise of internal climate variability. Depending on the metric used to detect changes, for the spatial/temporal mean response to forcing this number often exceeds the length of observational records, suggesting that it may be a decade or more before the forced response to sea ice loss will clearly emerge from the noise of internal variability. Thermodynamic responses may be detected sooner than dynamical responses[59,60]. It may be that regional sea ice loss will elicit robust signals in a shorter period.

The Arctic climate system is especially sensitive to external forces that can fundamentally alter climate and ecosystem functioning[61,62]. Nonlinear threshold behaviour of the Arctic climate system to the loss of sea ice has been discussed[63]. There are qualitative hypotheses for the coupled Arctic/subarctic climate system[64] and new approaches such as nonlinear auto-regressive modelling for constructing linear and nonlinear dynamical models (for example, NARMAX)[65,66]. So far, NARMAX has been used to discern changing effects of glaciological, oceanographic and atmospheric conditions on Greenland iceberg numbers over the last century[67]. Novel methods to distinguish between statistical and causal relationships[68], the application of artificial intelligence such as evolutionary algorithms[69] and a Bayesian hierarchical model approach may enable progress.

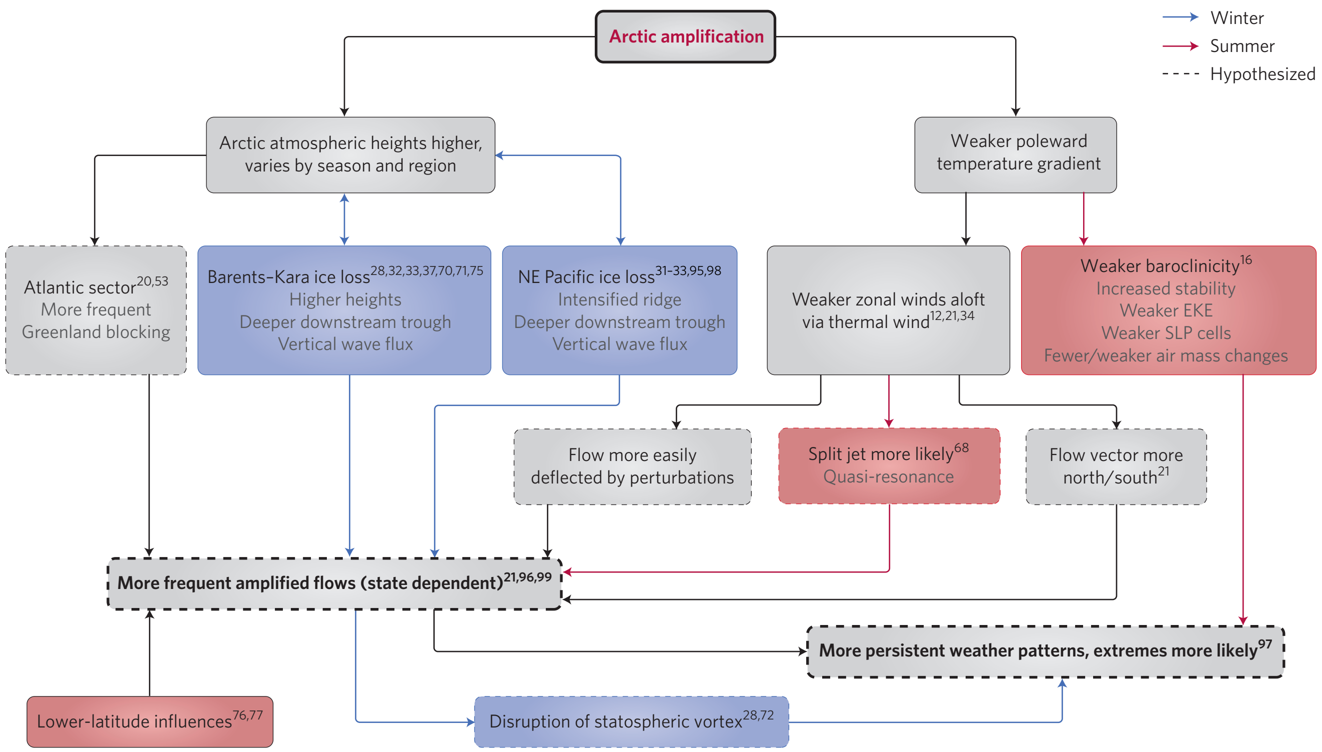

Figure 2 | A complex web of pathways summarizing examples of potential mechanisms that contribute to more frequent amplified flow and more persistent weather patterns in mid-latitudes. EKE, eddy kinetic energy; SLP, sea-level atmospheric pressure. For details on the processes, consult the original references.

Evidence for a variety of mid-latitude responses to Arctic warming is beginning to emerge[28–38]. Linkage mechanisms vary with season, region and system state, and they include both thermodynamic and dynamical processes. A complex web of pathways for linkages, as well as external forcing, is shown in Fig. 2, which summarizes selected recent references. Although these linkages shape the overall picture, considered individually they are subject to intermittency in cause and effect. So far, the most consistent regional linkage is supported by case studies and model simulations showing that reduced sea ice in the Barents and Kara seas (northeast of Scandinavia) can lead to cold continental Asian temperatures[33,70–74]. A doubled probability of severe winters in central Eurasia with increased regional sea ice loss has been reported[75]. But this singular linkage mechanism may be the exception rather than the rule[7]. Intermittency implies that frameworks allowing for multiple necessary causal factors may be required to accurately describe linkages in multiple locations.

Multiple influences. Although a more consistent picture of linkages may emerge in future scenarios as AA strengthens, one needs to remember that sea ice loss is only one factor of many that influence, and are influenced by, climate change. For example, eastern North American weather is affected by sea surface temperature patterns in the North Pacific and tropical Pacific[76–79] and perhaps by sea ice loss in the Pacific sector of the Arctic[32,33]. The so-named Snowmageddon blizzard that hit eastern North America in February 2010 was strengthened by the coincidence of moist, warm air associated with El Niño colliding with frigid air originating from Canada. Downstream influences on the Barents and Kara Sea region, noted for initiating sea ice linkages with eastern Asia, have been connected to the western North Atlantic[80].

The Arctic can also be influenced by variability from mid-latitudes. The period January–May 2016, for example, set new records for globally averaged temperatures along with the lowest recorded sea ice extent in those months since 1880. Extensive Arctic temperature anomalies of over 7 °C were associated with strong southerly winds and warm air originating from the North Pacific, southwestern Russia and the northeastern Atlantic; anomalies for January 2016 are shown in Fig. 3. In contrast, the large-scale wind pattern also resulted in a severe, week-long cold surge over eastern Asia during January 2016 (shown as the blue region in Fig. 3).

On a hemispheric scale, the relative importance of Arctic versus non-Arctic forcing on atmospheric circulation patterns is uncertain. While models generally suggest that AA and sea ice loss favour a weakened and equatorward-shifted mid-latitude storm track, warming

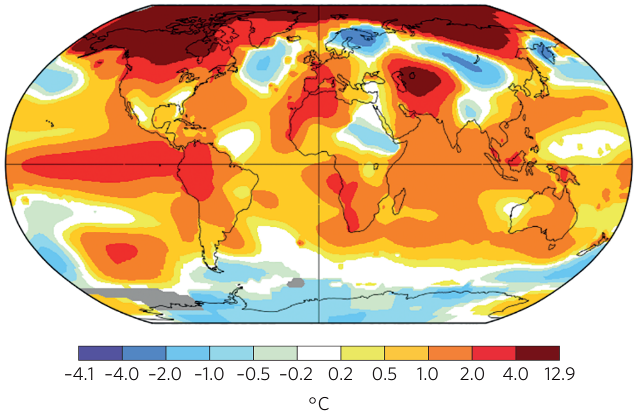

Figure 3 | Global air temperatures anomalies (°C) for January 2016. These were the highest in the historical record for any January since 1880. Southerly winds from mid-latitudes contributed to the largest anomalies in the Arctic (+7 °C). Note the cold anomaly (blue) over Asia. L-OTI, land-ocean temperature index; global mean temperature anomaly, 1.13; baseline, 1951–1980. Source: NASA.

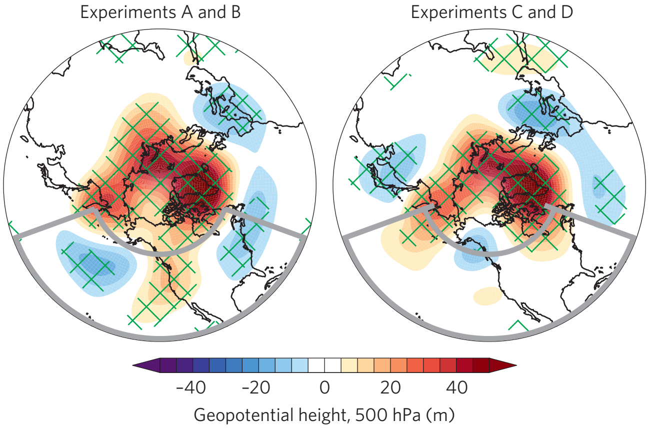

Figure 4 | State dependence of the atmospheric response to Arctic sea ice loss. Model-simulated wintertime 500 hPa geopotential height responses to Arctic sea ice loss for two different surface ocean states. The responses are estimated from four 100-year-long atmospheric model simulations, with prescribed sea ice concentrations and sea surface temperatures. Experiments A and C have identical below-average sea ice conditions, and experiments B and D have identical above-average sea ice conditions. Experiments A and B, and C and D, have identical sea surface temperatures, but the two pairs have different sea surface temperatures (that is, A and B differ from C and D; see Supplementary Fig. 1), capturing opposite phases of the Atlantic Multidecadal Oscillation (AMO). The response to sea ice loss, under different surface ocean states, is estimated by contrasting experiments A and B (left) and C and D (right). The grey outline highlights the mid-latitude Pacific-American region, where a wave-train response to sea ice loss is simulated for one SST state (left, negative AMO) but not the other (right, positive AMO), implying that the response to sea ice loss is state dependent. Green hatching denotes responses that are statistically significant at the 95% ($P = 0.05$) confidence level.

of the tropical upper troposphere favours the opposite response[81]. Recent work suggests that Arctic influences may have started to exceed tropical influences in explaining subarctic variability[50,82]. In the long term, the direct warming effect of raised greenhouse gas concentrations favours warm anomalies over cold anomalies, leading to an overall hemispheric tendency for warmer winters[4].

State dependence. Arctic thermodynamic influences (for example, heat fluxes due to snow and sea ice loss, increased water vapour, and changes in clouds) can either reinforce or counteract the amplitude of regional geopotential height fields[60,83]. This response can depend on pre-existing atmosphere–ocean conditions and the intensity of the index cycle[49] (state dependence), and can be considered a specific type of intermittency. For example, model simulations suggest that an amplification of the climatological ridge–trough pattern over North America, in response to Arctic sea ice loss, is conditional on the prevailing surface ocean state (Fig. 4). State dependence provides one explanation for why particular causal linkages may constitute only necessary, but not sufficient, causation.

Variability in the wintertime Arctic stratosphere is another mechanism for state dependence. In winter, planetary waves propagate between the troposphere and stratosphere, and the impacts of this propagation are sensitive to the state of the stratospheric polar vortex[84]. While a strong vortex is characterized by relatively fast-moving westerly winds and a cold core, sudden stratospheric warmings can occur, in which temperatures can increase by over 40 °C in a matter of days[85]. These events can weaken, or even reverse, the stratospheric winds, leading to an eventual downward propagation of the circulation feature into the troposphere[86] and a tendency for a negative phase of the AO. This mechanism establishes memory in the system, as sea ice loss and snow cover in late autumn can affect the tropospheric jet stream in late winter through lagged transfer of wave-induced disturbances involving the stratosphere[39]. Only models with realistic stratospheres are able to capture this mechanism.

The way forward

The various linkages among AA, large-scale mid-latitude and tropical sea surface temperature fluctuations, and internal variability of atmospheric circulation are obscured by the four limitations discussed above. These limitations reflect the nonlinearity of climate system dynamics, and the study of linkages remains an unfinished puzzle. Handorf and Dethloff[87] report that most current state-of-the-science climate models cannot yet reproduce observed changes in atmospheric teleconnection patterns because of shortcomings in capturing realistic natural variability as well as relationships between the most important teleconnections and patterns of temperature change. Until models are able to realistically reproduce these relationships, an understanding of subarctic climate variability and weather patterns in a warming world will remain a challenge.

The complexities and limitations of the linkage issue work against the idea of parsimony in science, of direct causality, or of finding simple pathways. Given the complex web of linkages as illustrated in Fig. 2, an appropriate physics analogy is the effort to understand bulk thermodynamics for an ideal gas by examining only the mechanisms of individual molecular collisions without aggregating statistics. An approach is needed that recognizes multiple processes that act sometimes separately and sometimes interactively in a framework based on the equations of motion and thermodynamics. This is not an easy task, but may be achieved through a combination of carefully designed, multi-investigator, coordinated, multi-model simulations, data analyses and diagnostics.

Studies of linkages are motivated by the potential that a better understanding will benefit decision-makers in their efforts to prepare for impacts of climate change on multiannual to decadal timescales, as well as weather prediction centres producing operational forecasts, particularly at the subseasonal to seasonal timescale. We offer the following recommendations:

- The climate science community needs to develop appropriate diagnostics to analyse model and reanalysis output to detect regional and intermittent responses. Here, major progress is achievable. Although internal variability is a principal characteristic of large-scale atmospheric motions, there can be order in large-scale atmospheric dynamics that should be further exploited, such as analyses based on potential vorticity, progression of long waves, blocking persistence, and regional surface coupling.
- Nonlinearity and state dependence suggest that idealized and low-resolution climate models have limited explanatory power. Ultimately we need to use realistic models that are validated against observations. Improving the horizontal and vertical resolution is required to properly represent many regional dynamic processes such as jet stream meanders, blocks, polarity of the AO and NAO, teleconnections, surface–atmosphere interaction, stratosphere–troposphere interactions, atmospheric wave propagation, and shifts in planetary waviness[88–90].
- Arctic and subarctic sub-regions are connected over large scales. System-wide studies can help in assessing polar versus tropical drivers on mid-latitude jet stream variability.
- Model realism as well as improvements to weather forecasts would benefit from additional observations[91] in the Arctic and subarctic, and by improving global and Arctic meteorological reanalyses, particularly in their representation of surface fluxes[92,93].
- Better coordination of the research community is needed for model experiments and data analyses, as the current controversy stems in part from uncoordinated efforts.

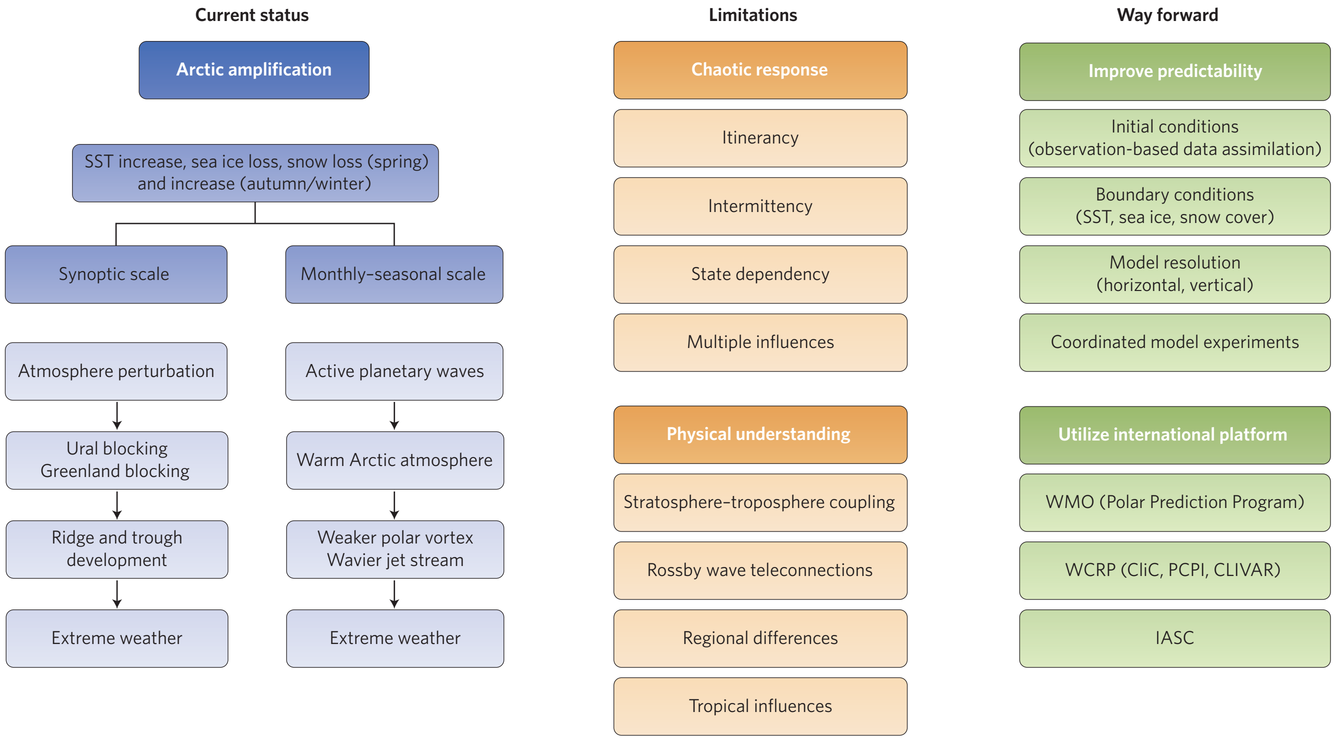

Figure 5 | Current state of the science for selected linkages. Arctic amplification and some pathways are known (left), but chaotic instabilities and multiple external forcing sources are noted under 'Limitations' (middle). A way forward (right) is through improved data, models and international cooperation of individual researchers.

Summary

Many recent studies of linkages have focused on direct effects attributed to specific changes in the Arctic, such as reductions in sea ice and snow cover. Disparate conclusions have been reached owing to the use of different data, models, approaches, metrics and interpretations. Low signal-to-noise ratios and the regional, episodic and state-dependent nature of linkages further complicate analyses and interpretations. Such efforts have rightly generated controversy.

Based on the large number of recent publications, progress is evident in understanding linkages and in uncovering their regional and seasonal nuances. However, basic limitations are inherent in these efforts. Figure 5 offers a visualization of the current state of the science, presenting likely pathways for linkages between AA and mid-latitude circulation at weather timescales (days) and for planetary waves (weeks to months), as noted on the left. Understanding such pathways can benefit from advanced atmospheric diagnostic and statistical methods. Limitations (middle) in deciphering cause and effect derive from both itinerancy and multiple simultaneous sources of external forcing. A way forward (right) is through improved data, diagnostics, models and international cooperation among scientists.

Wintertime cold spells, summer heatwaves, droughts and floods — and their connections to natural variability and forced change — will be topics of active research for years to come. We recommend that the meteorological community 'embrace the chaos' as a dominant component of linkages between a rapidly warming Arctic and the mid-latitude atmospheric circulation. Scientists should capitalize on and seek avenues to improve the realism and self-consistency of the physical processes in high-resolution numerical models that simultaneously incorporate multiple processes and internal instabilities. Use of multiple ensembles is essential. Coordination efforts are necessary to move towards community consensus in the understanding of linkages and to better communicate knowns and unknowns to the public. Because of the potential impacts on billions of people living in northern mid-latitudes, these priorities have been identified by national and international agencies, such as the WMO/Polar Prediction Program (PPP), WCRP Climate and Cryosphere (CliC), WCRP Polar Climate Predictability Initiative (PCPI), the International Arctic Science Committee (IASC), the International Arctic Systems for Observing the Atmosphere (IASOA), the US National Science Foundation, NOAA, and the US CLIVAR Arctic Midlatitude Working Group. Understanding and ultimately anticipating the role of rapid Arctic warming on changing mid-latitude weather patterns is a grand scientific challenge; the potential societal and economic benefits are enormous.

Received 4 April 2016; accepted 3 August 2016;

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Acknowledgements

J.E.O. is supported by NOAA Arctic Research Project of the Climate Program Office. J.A.F. is supported by NSF/ARCSS Grant 1304097. K.D. acknowledges support from the German DFG Transregional Collaborative Research Centre TR 172. J.A.S. was funded by the UK Natural Environment Research Council grants NE/J019585/1 and NE/M006123/1. R.J.H. and E.H. acknowledge support from the University of Sheffield's Project Sunshine. S.-J.K. was supported by the project of Korea Polar Research Institute (PE16010), and T.V. was supported by the Academy of Finland (Contract 259537). We appreciate the support of IASC, CliC and the University of Sheffield for hosting a productive workshop. PMEL Contribution Number 4429.

Author contributions

J.E.O. was the coordinating author and all other authors contributed ideas, analyses and text.

Additional information

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Competing financial interests

The authors declare no competing financial interests.