

Nonlinear response of mid-latitude weather to the changing Arctic

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1 2	Nonlinear Response of Midlatitude Weather to the Changing Arctic
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30 Are continuing changes in the Arctic influencing wind patterns and the occurrence of extreme 31 weather events in northern midlatitudes? The chaotic nature of atmospheric circulation precludes 32 easy answers. Yet the topic is a major science challenge, as continued Arctic temperature 33 increases are an inevitable aspect of anthropogenic global change. We propose a perspective that rejects simple cause-and-effect pathways, notes diagnostic challenges in interpreting atmospheric 34 35 dynamics, and present a way forward based on understanding multiple processes that lead to 36 uncertainties in Arctic/midlatitude weather and climate linkages. We emphasize community 37 coordination for both scientific progress and communication to a broader public.

38

Various metrics indicate that the recent period of disproportionate Arctic warming relative to 39 40 midlatitudes-referred to as Arctic Amplification (AA)-emerged from the noise of natural variability in the late 1990s¹. This signal will strengthen as human activities continue to raise 41 greenhouse gas concentrations². The assessment of the potential for AA to influence broader 42 hemispheric weather (referred to as linkages) is complex and controversial³⁻⁶. Yet with 43 44 intensifying AA, we argue that the key question is not whether the melting Arctic will influence midlatitude weather patterns over the next decades, but rather what is the nature and magnitude 45 of this influence relative to non-Arctic factors, and is it limited to specific regions, seasons, or 46 types of weather events⁷? 47

48

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^{8,9,10}. The climate change
signal is larger than anywhere else in the Northern Hemisphere and the region possesses multiple

53 feedbacks. Coupling exists between the Arctic troposphere and the wintertime stratospheric polar 54 vortex, which itself is highly nonlinear. A linkage pathway that may appear to be responsible for 55 one series of events may not exist in another scenario with similar forcing. This is potentially reflected in observationally based studies that have struggled to find robust linkages^{11,12}. Further, 56 57 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 others¹³. This 58 59 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 developed 60 61 in this Perspective: *itinerancy* [seemingly random variations from state to state], *intermittency* 62 [apparently different atmospheric responses under conditions of similar external forcing, such 63 as sea-ice loss], multiple influences [simultaneous forcing by various factors, such as seasurface temperature anomalies in the tropics, midlatitudes and Arctic], and state dependence [a 64 response dependent on the prior state of the atmospheric circulation, e.g., the phase of the Arctic 65 66 Oscillation (AO) atmospheric circulation index or the strength of the stratospheric vortex].

67

We propose a system-level approach that recognizes multiple simultaneous processes, internal instabilities, and feedbacks. Progress in understanding Arctic/midlatitude 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.

76 Arctic warming is unequivocal, substantial, and ongoing

Changes in Arctic climate in the last two decades are substantial. Since 1980 Arctic temperature 77 increases have exceeded those of the Northern Hemisphere average by at least a factor of two¹⁴. 78 79 Over land north of 60°N, 12 of the past 15 years have exhibited the highest annual mean surface air temperatures since 1900. AA is also manifested in loss of sea ice, glaciers, snow and 80 permafrost, a longer open-water season, and shifts in Arctic ecosystems. Sea ice has undergone 81 an unprecedented decline over the past three decades with a two-thirds reduction in volume². 82 Comparable decreases in snow cover have occurred during May and June. AA is strongest in 83 fall/winter with largest values over regions of sea ice loss¹⁵, while the areas of greatest warming 84 in summer are located over high-latitude land where spring snow loss has occurred progressively 85 earlier¹⁶. 86

87

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 vapor and clouds. Increasing temperatures in the lower atmosphere elevate the height of mid-level pressure surfaces (geopotential height), leading to changes in poleward and regional gradients and, consequently, wind patterns^{19,20,21}.

Based on over 30 climate model simulations presented in the most recent Intergovernmental
Panel on Climate Change (IPCC) Assessment Report, future winter (November-March) surface
temperatures in the Arctic (60-90°N) are projected to rise ~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 will likely be accompanied by sea ice free summers.

99 Past and near future emissions of anthropogenic CO₂ assure mid-century AA and global100 warming.

101

102 Living with an uncertain climate system

The task of unraveling cause and effect of mechanisms linking changes in the large scale 103 104 atmospheric circulation to AA is hampered by poor signal detection in a noisy system and 105 complex climate dynamics, regardless of whether the approach is statistical analyses or targeted 106 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 107 108 discussing anomalous weather or climate conditions, causation can have different meanings. 109 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}. 110 111 Together these factors make linkage attribution challenging. Many previous data and modeling 112 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 113 been helpful in elucidating relevant linkage mechanisms, we provide a view at the system level 114 that can mask simple cause and effect. 115

116

117 Thermodynamically (i.e., related to temperature gradients) forced wind systems on a rotating 118 planet produce west-to-east flow at midlatitudes. This flow is dynamically unstable, creating 119 north–south meanders that generate high- and low-pressure centers which can produce disruptive 120 weather events. In addition to internal instability, variability in the wind pattern is forced by 121 influences external to the midlatitude atmosphere that may themselves reflect internal variability

122 on longer timescales, such as sea-surface temperature anomalies in the tropics, midlatitudes, and 123 ice-free parts of the Arctic. Remote forcings (i.e., changes outside the midlatitudes, remote in 124 space and perhaps time) can influence the midlatitude circulation through linear and nonlinear 125 atmospheric patterns, known as teleconnections. Extensive regions of positive temperature anomalies in the Arctic may increase the persistence of weather systems 20,38 . Further, 126 troposphere-stratosphere connections can trigger changes in the regional wind patterns³⁹. 127 128 Contributors to a lack of simple robust linkages include the four properties discussed as follows: 129 130 Itinerancy 131 Itinerancy refers to the atmosphere spontaneously shifting from state to state based on

132 instabilities in the wind field that can be amplified by internal and external variability. Such states can persist through nonlinear mechanisms 10,22 . Fig. 1(a, b) illustrates two configurations of 133 134 the northern hemispheric wind pattern (tropospheric polar vortex) occurring at different times: 135 the case shown in Fig. 1a is for a day in November 2013 that had a relatively circular flow 136 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 formally reserved for the 137 stratosphere, it is a useful term for discussing tropospheric geopotential height/wind 138 139 configurations such as those shown in Fig. 1. The jet stream flows from west to east parallel to 140 these geopotential height contours and is strongest where the contours are closest together. Shifts 141 to and from a wavy pattern—known historically as the index cycle—and the varying longitudinal 142 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 143 144 wavier jet stream allows cold air from the Arctic to penetrate southward into midlatitudes, and

145 ridges transport warm air northward. Fig. 1(c, d) are corresponding temperature anomaly patterns 146 for these two days. For the more circular jet stream, cold anomalies are mostly contained within 147 the polar region along with warmer anomalies around midlatitudes (Fig. 1c). This particular 148 pattern is not perfectly symmetric around the North Pole, as the center of the vortex is shifted into the western hemisphere. The wavier jet stream case has two warm and two cold anomaly 149 150 regions in midlatitudes (Fig. 1d), to the west and east of the region of increased heights (ridges) 151 over Alaska and Scandinavia. Many extreme weather events associated with wavy circulation patterns have occurred in the last decade^{40,41}. 152

153

Multiple studies ^{42,43,44} 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 behavior on monthly, seasonal, and interannual time scales⁴². 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 state⁴⁷.

161

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 AA⁴⁸, 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 1950-2014⁴⁹. Cohen⁵⁰

notes an increase in midlatitude intraseasonal winter temperature variability from 1988/89 to
2014/15. 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^{51,52,53}. 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.

175

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. Also the signal to noise in models could be too weak, as appears to be the case for seasonal forecasts of the NAO^{55,56,57}.

181

182 *Intermittency*

183 Intermittency 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 184 185 of Arctic conditions. In other words, the response is not a unique function of the forcing. If 186 responses are intermittent, one will need a longer time series and/or a stronger signal to detect 187 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 188 model studies have reported shifts towards both the positive or negative phases of the AO and/or 189 NAO, or no apparent shift, in response to AA^{13,19,34,39,59}. Analyses that involve averaging over 190

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 some clear hypotheses for linkages, it remains difficult to prove that
Arctic change has already had or not had an impact on midlatitude weather based on
observations alone because of the short period since AA has become apparent⁵.

196

One approach to overcome the signal-to-noise problem is to use model simulations⁵⁹. Large 197 198 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 answer the question: how many years of 199 200 simulation are required for the impacts of sea ice loss to become detectable over the noise of 201 internal climate variability? Depending on the metric used to detect changes, the spatial/temporal 202 mean response to forcing often exceeds the length of observational records, suggesting that it 203 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 204 responses^{59,60}. It may be that regional sea-ice loss will elicit robust signals in a shorter period. 205 206

The Arctic climate system is especially sensitive to external forces that can fundamentally alter
climate and ecosystem functioning⁶². Nonlinear threshold behavior of the Arctic climate system
to the loss of sea ice has been discussed⁶³. There are qualitative hypotheses for the coupled
Arctic/subarctic climate system⁶⁴ and new approaches such as nonlinear auto-regressive
modeling for constructing linear and non-linear dynamical models (e.g. 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 century⁶⁷. Novel methods to

distinguish between statistical and causal relationships⁶⁸, the application of artificial intelligence
 such as evolutionary algorithms⁶⁹, and a Bayeasian Hierarchical Model approach may enable
 progress.

217

Evidence of systematic midlatitude responses to Arctic warming is beginning to $emerge^{28-38}$. 218 219 Linkage mechanisms vary with season, region, and system state, and they include both 220 thermodynamic and dynamical processes. A complex web of pathways for linkages, as well as 221 external forcing, is shown in Fig. 2, which summarizes selected recent references. Whilst these linkages shape the overall picture, considered individually they are subject to intermittency in 222 223 cause and effect. To date, the most consistent regional linkage is supported by case studies and 224 model simulations showing that reduced sea ice in the Barents/Kara Seas (northeast of Scandinavia) can lead to cold continental Asian temperatures^{33,70-74}. A doubled probability of 225 severe winters in central Eurasia with increased regional sea ice loss has been reported⁷⁵. This 226 singular linkage mechanism may be the exception rather than the rule⁷. Intermittency implies that 227 228 frameworks allowing for multiple necessary causal factors may be required to accurately 229 describe linkages in multiple locations.

230

231 Multiple influences

Whilst 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 influences, and is
influenced by, climate change. For example, eastern North American weather is affected by seasurface temperature patterns in the North Pacific and tropical Pacific⁷⁶⁻⁷⁹ and also 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/Kara Sea region, noted for initiating sea ice linkages with eastern Asia,
have been connected to the western North Atlantic⁸⁰.

241

The Arctic can also be influenced by variability from midlatitudes. January through 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.
In contrast, the large scale wind pattern also resulted in a severe, week-long cold surge over
eastern Asia during January 2016, evident as the blue region in Fig. 3.

249

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 favor a weakened and equatorward-shifted midlatitude storm track, warming of the
tropical upper troposphere favors the opposite response⁸¹. 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 favors warm
anomalies over cold anomalies, leading to an overall hemispheric tendency for warmer winters⁴.

258 *State dependence*

259 Arctic thermodynamic influences (e.g., heat fluxes due to snow and sea ice loss, increased water

260 vapor, changes in clouds) can either reinforce or counteract the amplitude of regional geopotential height fields^{60,83}. This response can depend on preexisting atmosphere-ocean 261 conditions and the intensity of the index cycle⁴⁹ (state dependence), and can be considered a 262 263 specific type of intermittency. For example, model simulations suggest that an amplification of 264 the climatological ridge-trough pattern over North America, in response to Arctic sea ice loss, is 265 conditional on the prevailing surface ocean state (Fig. 4). State dependence provides one 266 explanation for why particular causal linkages may only constitute necessary but not sufficient 267 causation.

268

Variability in the wintertime Arctic stratospheric is another mechanism for state dependence. In 269 270 winter, planetary waves propagate between the troposphere and stratosphere, and the impacts of this propagation are sensitive to the state of the stratospheric polar vortex⁸⁴. While a strong 271 272 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 273 of days⁸⁵. These events can weaken, or even reverse, the stratospheric winds, leading to an 274 eventual downward propagation of the circulation feature into the troposphere⁸⁶ and a tendency 275 276 for a negative phase of the AO. This mechanism establishes memory in the system, as sea ice 277 loss and snow cover in late fall can affect the tropospheric jet stream in late winter through lagged transfer of wave-induced disturbances involving the stratosphere³⁹. Only models with 278 279 realistic stratospheres are able to capture this mechanism.

280

281 Way Forward

282 To summarize, the various linkages between AA, large scale midlatitude and tropical sea surface 283 temperature fluctuations, and internal variability of atmospheric circulation are obscured by the 284 four limitations discussed above. These limitations reflect the nonlinearity of climate system dynamics, and the study of linkages remains an unfinished puzzle. Handorf and Dethloff⁸⁷ report 285 286 that current state-of-the-science climate models cannot yet reproduce observed changes in 287 atmospheric teleconnection patterns because of shortcomings in capturing realistic natural 288 variability as well as relationships between the most important teleconnections and patterns of 289 temperature change. Until models are able to realistically reproduce these relationships, an 290 understanding of subarctic climate variability and weather patterns in a warming world remains a 291 challenge.

292

293 The complexities and limitations of the linkage issue work against the idea of parsimony in 294 science, of direct causality, or of finding simple pathways. Given the complex web of linkages as 295 illustrated in Fig. 2, an appropriate physics analogy is the effort to understand bulk 296 thermodynamics for an ideal gas by examining only the mechanisms of individual molecular 297 collisions without aggregating statistics. An approach is needed that recognizes multiple processes that act sometimes separately, sometimes interactively in a framework based on the 298 299 equations of motion and thermodynamics. This is not an easy task but may be achieved through a 300 combination of carefully designed, multi-investigator, coordinated, multi-model simulations, 301 data analyses, and diagnostics.

302

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 multi-annual to

305	decadal timescales, as well as weather-prediction centers producing operational forecasts,
306	particularly at the subseasonal to seasonal timescale. We offer the following recommendations:

308	•	The climate science community needs to develop appropriate diagnostics to analyze model
309		and reanalysis output to detect regional and intermittent responses. Here, major progress is
310		achievable. Although internal variability is a principal characteristic of large scale
311		atmospheric motions, there can be order in large scale atmospheric dynamics that should be
312		further exploited, such as analyses based on potential vorticity (PV), progression of long
313		waves, blocking persistence, and regional surface coupling.
314	•	Nonlinearity and state dependence suggest that idealized and low-resolution climate models
315		have limited explanatory power. Ultimately we need to use realistic models that are validated
316		against observations. Improving the horizontal and vertical resolution is required to properly
317		represent many regional dynamic processes such as jet stream meanders, blocks, polarity of
318		the AO and NAO, teleconnections, surface-atmosphere interaction, stratosphere-troposphere
319		interactions, atmospheric wave propagation, and shifts in planetary waviness ^{88,89,90} .
320	•	Arctic and subarctic sub-regions are connected over large scales. System-wide studies can
321		help in assessing polar versus tropical drivers on midlatitude jet stream variability.
322	•	Model realism as well as improvements to weather forecasts would benefit from additional
323		observations ⁹¹ in the Arctic and subarctic, and by improving global and Arctic
324		meteorological reanalyses, particularly in their representation of surface fluxes ^{92,93} .
325	•	Better coordination of the research community is needed for model experiments and data
326		analyses, as the current controversy stems in part from uncoordinated efforts.
327		

328 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.

334

335 Based on the large number of recent publications, progress is evident in understanding linkages 336 and in uncovering their regional and seasonal nuances. However, basic limitations are inherent in 337 these efforts. Fig. 5 offers a visualization of the current state of the science, presenting likely 338 pathways for linkages between AA and midlatitude circulation at both the weather timescales 339 (days) and for planetary waves (weeks), as noted on the left. Understanding such pathways can 340 benefit from advanced atmospheric diagnostic and statistical methods. Limitations (center) in 341 deciphering cause-and-effect derive from both itinerancy and multiple simultaneous sources of 342 external forcing. A way forward (right) is through improved data, diagnostics, models, and 343 international cooperation among scientists.

344

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 midlatitude 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

351	proces	sses and internal instabilities. Use of multiple ensembles is essential. Coordination efforts	
352	are ne	are necessary to move toward community consensus in the understanding of linkages and to	
353	better	communicate knowns and unknowns to the public. Because of the potential impacts on	
354	billior	ns of people living in northern midlatitudes, these priorities have been identified by national	
355	and in	ternational agencies, such as: the WMO/Polar Prediction Program (PPP), WCRP Climate	
356	and C	ryosphere (CliC), WCRP Polar Climate Predictability Initiative (PCPI), the International	
357	Arctic	e Science Committee (IASC), the International Arctic Systems for Observing the	
358	Atmo	sphere (IASOA), the US National Science Foundation, NOAA, and the US CLIVAR	
359	Arctic	e-midlatitude working group.	
360			
361	Refer	ences	
362	1	Serreze, M., Barrett, A., Stroeve, J., Kindig, D. & Holland, M. The emergence of surface-	
363		based Arctic amplification. The Cryosphere 3, 11–19 (2009).	
364	2	Overland, J. E., Wang, M., Walsh, J. E. & Stroeve, J. C. Future Arctic climate changes:	
365		Adaptation and mitigation timescales. Earth's Future 2, 68–74,	
366		doi:10.1002/2013EF000162 (2014).	
367	3	Francis, J. A. & Vavrus, S. J. Evidence for a wavier jet stream in response to rapid Arctic	
368		warming. Environ. Res. Lett. 10, 014005, doi:10.1088/1748-9326/10/1/014005 (2015).	
369	4	Wallace, J. M., Held, I. M., Thompson, D. W. J., Trenberth, K. E. & Walsh, J. E. Global	
370		warming and winter weather. Science 343, 729–730, doi:10.1126/science.343.6172.729	
371		(2014).	
372	5	Barnes, E. A. & Screen, J. A. The impact of Arctic warming on the midlatitude jet-	

373 stream: Can it? Has it? Will it? *Clim. Change* **6**, 277–286, doi:10.1002/wcc.337 (2015).

374	6	Sun, L., Perlwitz, J., & Hoerling, M. What caused the recent "Warm Arctic, Cold
375		Continents" trend pattern in winter temperatures? Geophys. Res. Lett. 43,
376		doi:10.1002/2016GL069024,(2016).
377	7	Overland, J. E. et al. The melting Arctic and mid-latitude weather patterns: Are they
378		connected? J. Clim. 28, 7917-7932, doi:10.1175/JCLI-D-14-00822.1 (2015).
379	8	Petoukhov, V. & Semenov, V. A. A link between reduced Barents-Kara sea ice and cold
380		winter extremes over northern continents. J. Geophys. Res. 115, D21111,
381		doi:10.1029/2009JD013568 (2010).
382	9	Peings, Y. & Magnusdottir, G. Response of the wintertime Northern Hemisphere
383		atmospheric circulation to current and projected Arctic sea ice decline. J. Clim. 27, 244-
384		264, doi:10.1175/JCLI-D-13-00272.1 (2014).
385	10	Semenov, V. A. & Latif, M. Nonlinear winter atmospheric circulation response to Arctic
386		sea ice concentration anomalies for different periods during 1966-2012. Environ. Res.
387		Lett. 10, 054020, doi:10.1088/1748-9326/10/5/054020 (2015).
388	11	Screen, J. A. & Simmonds, I. Exploring links between Arctic amplification and mid-
389		latitude weather. Geophys. Res. Lett. 40, 959–964, doi:10.1002/grl.50174 (2013).
390	12	Barnes, E. A. Revisiting the evidence linking Arctic amplification to extreme weather in
391		midlatitudes. Geophys. Res. Lett. 40, 4734–4739, doi:10.1002/grl.50880 (2013).
392	13	Orsolini, Y. J., Senan, R., Benestad, R. E. & Melsom, A. Autumn atmospheric response
393		to the 2007 low Arctic sea ice extent in coupled ocean-atmosphere hindcasts. Clim.
394		<i>Dynam.</i> 38, 2437–2448, doi:10.1007/s00382-011-1169-z (2012).

395	14	Overland, J. E. et al. Air temperature in Arctic Report Card: Update for 2015 (2015);
396		http://www.arctic.noaa.gov/report15/air_temperature.html.
397	15	Screen, J. A. & Simmonds, I. The central role of diminishing sea ice in recent Arctic
398		temperature amplification. <i>Nature</i> 464 , 1334–1337, doi:10.1038/nature09051 (2010).
399	16	Coumou, D., Lehmann, J. & Beckmann, J. The weakening summer circulation in the
400		Northern Hemisphere mid-latitudes. Science 348, 324–327, doi:10.1126/science.1261768
401		(2015).
402	17	Pithan, F. & Mauritsen, T. Arctic amplification dominated by temperature feedbacks in
403		contemporary climate models. Nature Geosci. 7, 181–184, doi:10.1038/ngeo2071 (2014).
404	18	Taylor, P. C. et al. A decomposition of feedback contributions to polar warming
405		amplification. J. Clim. 26, 7023-7043, doi:10.1175/JCLI-D-12-00696.1 (2013).
406	19	Porter, D. F., Cassano, J. J. & Serreze, M. C. Local and large-scale atmospheric responses
407		to reduced Arctic sea ice and ocean warming in the WRF model. J. Geophys. Res. 117,
408		D11115, doi:10.1029/2011JD016969 (2012).
409	20	Overland, J. E. & Wang, M. Y. Large-scale atmospheric circulation changes are
410		associated with the recent loss of Arctic sea ice. Tellus A 62, 1–9, doi:10.1111/j.1600-
411		0870.2009.00421.x (2010).
412	21	Francis, J. A. & Vavrus, S. J. Evidence linking Arctic amplification to extreme weather in
413		mid-latitudes. Geophys. Res. Lett. 39, doi:10.1029/2012GL051000 (2012).
414	22	Palmer, T. N. A nonlinear dynamical perspective on climate prediction. J. Clim. 12, 575-
415		591 (1999).

- 416 23 Pearl, J. *Causality: Models, Reasoning and Inference* 2nd ed. (Cambridge University
 417 Press, 2009).
- 418 24 Hannart, A., Pearl, J., Otto, F. E. L., Naveau, P. & Ghil, M. Causal counterfactual theory
- for the attribution of weather and climate-related events. *Bull. Am. Meteorol. Soc.* 97, 99–
- 420 110, doi:10.1175/BAMS-D-14-00034.1 (2015).
- 421 25 Vihma, T. Effects of Arctic sea ice decline on weather and climate: A review. Surv.
- 422 *Geophys.*, **35**, 1175–1214, doi:10.1007/s10712-014-9284-0 (2014).
- 423 26 Walsh, J. E. Intensified warming of the Arctic: Causes and impacts on middle latitudes.

424 *Global Planet. Change* **117,** 52–63, doi:10.1016/j.gloplacha.2014.03.003 (2014).

- 425 27 Thomas, K. (ed.) National Academy of Sciences *Linkages between Arctic Warming and*426 *Mid-Latitude Weather Patterns* (The National Academies Press, 2014);
- 427 http://www.nap.edu/catalog/18727/linkages-between-arctic-warming-and-
- 428 <u>midlatitudeweather-patterns</u>.
- 429 28 Cohen, J. et al. Recent Arctic amplification and extreme mid-latitude weather. Nature
- 430 *Geosci.* 7, 627–637, doi:10.1038/ngeo2234 (2014).
- Jung, T. *et al.* Polar lower-latitude linkages and their role in weather and climate
 prediction. *Bull. Am. Meteorol. Soc.* 96, ES197–ES200, doi:10.1175/BAMS-D-15-
- **433** 00121.1 (2015).
- Hopsch, S., Cohen, J. & Dethloff, K. Analysis of a link between fall Arctic sea ice
 concentration and atmospheric patterns in the following winter. *Tellus A* 64, 18624,
- doi:10.3402/tellusa.v64i0.18624 (2012).

- Lee, M.-Y., Hong, C.-C. & Hsu, H.-H. Compounding effects of warm SST and reduced
 sea ice on the extreme circulation over the extratropical North Pacific and North America
 during the 2013–2014 boreal winter. *Geophys. Res. Lett.* 42, 1612–1618,
 doi:10.1002/2014GL062956 (2015).
 Kug, J.-S. *et al.* Two distinct influences of Arctic warming on cold winters over North
 America and East Asia. *Nature Geosci.* 8, 759–762, doi:10.1038/ngeo2517 (2015).
- 443 33 King, M. P., Hell, M. & Keenlyside, N. Investigation of the atmospheric mechanisms

related to the autumn sea ice and winter circulation link in the Northern Hemisphere.

445 *Clim. Dynam.* **46,** 1185–1195, doi:10.1007/s00382-015-2639-5 (2015).

- 446 34 Pedersen, R., Cvijanovic, I., Langen, P. & Vinther, B. The impact of regional Arctic sea
 447 ice loss on atmospheric circulation and the NAO. *J. Clim.* 29, 889–902,
- 448 doi:10.1175/JCLI-D-15-0315.1 (2016).
- Tang, Q., Zhang, X. Yang, X. & Francis, J. A. Cold winter extremes in northern
 continents linked to Arctic sea ice loss. *Environ. Res. Lett.* 8, 014036, doi:10.1088/17489326/8/1/014036 (2013).
- 452 36 Furtado, J. C., Cohen, J. L. & Tziperman, E. The combined influences of autumnal snow
 453 and sea ice on Northern Hemisphere winters. *Geophys. Res. Lett.* 43, 3478–3485,
- 454 doi:10.1002/2016GL068108 (2016).
- 455 37 Dobricic, S., Vignati, E. & Russo, S. Large-scale atmospheric warming in winter and the
 456 Arctic sea ice retreat. J. Clim. 29, 2869–2888, doi:10.1175/JCLI-D-15-0417.1 (2016).

457	38	Rinke, A., Dethloff, K., Dorn, W., Handorf, D. & Moore, J. C. Simulated Arctic
458		atmospheric feedbacks associated with late summer sea ice anomalies. J. Geophys. Res.
459		118, 7698–7714, doi:10.1002/jgrd.50584 (2013).
460	39	Nakamura, T. et al. A negative phase shift of the winter AO/NAO due to the recent
461		Arctic sea-ice reduction in late autumn. J. Geophys. Res. (Atmos.) 120, 3209-3227,
462		doi:10.1002/2014JD022848 (2015).
463	40	Duarte, C., Lenton, T., Wadhams, P. & Wassmann, P. Abrupt climate change in the
464		Arctic. Nature Clim. Change 2, 60–62, doi:10.1038/nclimate1386 (2012).
465	41	Wu, B., Handorf, D., Dethloff, K., Rinke, A. & Hu, A. Winter weather patterns over
466		northern Eurasia and Arctic sea ice loss. Mon. Weather Rev. 141, 3786-3800,
467		doi:10.1175/MWR-D-13-00046.1 (2013).
468	42	Corti, S., Molteni, F. & Palmer, T. N. Signature of recent climate change in frequencies
469		of natural atmospheric circulation regimes. Nature 396, 799-802 (1999).
470	43	Itoh, H. & Kimoto, M. Weather regimes, low-frequency oscillations, and principal
471		patterns of variability: A perspective of extratropical low-frequency variability. J. Atmos.
472		<i>Sci.</i> 56, 2684–2705 (1999).
473	44	Sempf, M., Dethloff, K., Handorf, D. & Kurgansky, M. V. Toward understanding the
474		dynamical origin of atmospheric regime behavior in a baroclinic model. J. Atmos. Sci. 64,
475		887–904, doi:10.1175/JAS3862.1 (2007).
476	45	Slingo, J. & Palmer, T. Uncertainty in weather and climate prediction. Philos. Trans.
477		<i>Roy. Soc. A</i> 369, 4751-4767 (2011).

- 478 46 Schmeits, M. J. & Dijkstra, H. A. Bimodal behavior of the Kuroshio and the Gulf Stream.
 479 *J. Phys. Oceanogr.* 31, 3435–3456 (2001).
- 480 47 Davos, V. *et al.* Methods for detecting early warnings of critical transitions in time series
 481 illustrated using ecological data. *PLoS ONE* 7, e41010,
- 482 doi:10.1371/journal.pone.0041010 (2013).
- 483 48 Screen, J. A., Deser, C. & Sun, L. Projected changes in regional climate extremes arising
 484 from Arctic sea ice loss. *Environ. Res. Lett.* 10, 084006 (2015).
- 485 49 Overland, J. E. & Wang, M. Increased variability in the early winter subarctic North
- 486 American atmospheric circulation. *J. Clim.* 28, 7297–7305, doi:10.1175/JCLI-D-15487 0395.1 (2015).
- 488 50 Cohen, J. An observational analysis: Tropical relative to Arctic influence on midlatitude
 489 weather in the era of Arctic amplification. *Geophys. Res. Lett.* 43,
- doi:10.1002/2016GL069102 (2016).
- 491 51 Hanna, E., Cropper, T. E., Jones, P. D., Scaife, A. A. & Allan, R. Recent seasonal
- 492 asymmetric changes in the NAO (a marked summer decline and increased winter
- 493 variability) and associated changes in the AO and Greenland Blocking Index. *Int. J.*
- 494 *Climatol.* **35**, 2540–2554, doi:10.1002/joc.4157 (2015).
- 495 52 Woollings, T., Hannachi, A. & Hoskins, B. Variability of the North Atlantic eddy-driven
 496 jet stream. *Q. J. Rov. Meteorol. Soc.* 136, 856–868, doi:10.1002/qj.625 (2010).
- 497 53 Hanna, E., Cropper, T. E., Hall, R. J. & Cappelen, J. Greenland Blocking Index 1851–
- 498 2015: A regional climate change signal. *Int. J. Climatol.*, doi:10.1002/joc.4673 (2016).

499	54	Masato, G., Hoskins, B. J. & Woollings, T. Winter and summer Northern Hemisphere
500		blocking in CMIP5 models. J Clim. 26, 7044–7059, doi:10.1175/JCLI-D-12-00466.1
501		(2013).
502	55	Scaife, A. A. et al. Skillful long-range prediction of European and North American
503		winters. Geophys. Res. Lett. 41, 2514–2519, doi:10.1002/2014GL059637 (2014).
504	56	Eade, R. et al. Do seasonal-to-decadal climate predictions underestimate the
505		predictability of the real world? Geophys. Res. Lett. 41, 5620-5628,
506		doi:10.1002/2014GL061146 (2014).
507	57	Stockdale, T. N. et al. Atmospheric initial conditions and the predictability of the Arctic
508		Oscillation. Geophys. Res. Lett. 42, 1173–1179, doi:10.1002/2014GL062681 (2015).
509	58	Barnes, E. A. & Polvani, L. M. CMIP5 projections of Arctic amplification, of the North
510		American/North Atlantic Circulation, and of their relationship. J. Clim. 28, 5254–5271,
511		doi:10.1175/JCLI-D-00589.1 (2015).
512	59	Screen, J. A., Deser, C., Simmonds, I. & Tomas, R. Atmospheric impacts of Arctic sea-
513		ice loss, 1979–2009: Separating forced change from atmospheric internal variability.
514		<i>Clim. Dyn.</i> 43, 333–344, doi:10.1007/s00382-013-1830-9 (2014).
515	60	Shepherd, T. G. Atmospheric circulation as a source of uncertainty in climate change
516		projections. Nature Geosci. 7, 703-708, doi:10.1038/ngeo2253 (2014).
517	61	Hinzmann, L. et al. Trajectory of the Arctic as an integrated system. Ecol. Appl. 23,
518		1837–1868, doi:10.1890/11-1498.1 (2013).
519	62	Carstensen, J. & Weydmann, A. Tipping points in the Arctic: Eyeballing or statistical
520		significance? AMBIO 41, 34–43 (2012).

521	63	Eisenman, I. & Wettlaufer, J. S. Nonlinear threshold behavior during the loss of Arctic
522		sea ice. Proc. Natl. Acad. Sci. USA 106, 28-32, doi:10.1073/pnas.0806887106 (2009).
523	64	Mysak, L. A. & Venegas, S. A. Decadal climate oscillations in the Arctic: A new
524		feedback loop for atmosphere-ice-ocean interactions. Geophys. Res. Lett. 25, 3607–3610,
525		(1998).
526	65	Billings, S. A., Chen, S. & Korenberg, M. J. Identification of MIMO non-linear systems
527		using a forward-regression orthogonal estimator. Int. J. Control 49, 2157–2189,
528		doi:10.1080/00207178908559767 (1989).
529	66	Billings, S. A. Nonlinear System Identification: NARMAX Methods in the Time,
530		Frequency, and Spatio-Temporal Domains (Wiley, 2013).
531	67	Bigg, G. R. et al. A century of variation in the dependence of Greenland iceberg calving
532		on ice sheet surface mass balance and regional climate change. Proc. R. Soc. A 470,
533		20130662, doi:10.1098/rspa.2013.0662 (2014).
534	68	Kretschmer, M., Coumou, D., Donges, J. & Runge, J. Using causal effect networks to
535		analyze different Arctic drivers of midlatitude winter circulation. J. Clim. 29, 4069–4081
536		doi:10.1175/JCLI-D-15-0654.1 (2016).
537	69	Stanislawska, K., Krawiec, K. & Kundzewicz, Z.W. Modeling global temperature
538		changes with genetic programming. Comput. Math. Appl. 64, 3717–3728 (2012).
539	70	Honda, M., Inoue, J. & Yamane, S. Influence of low Arctic sea-ice minima on
540		anomalously cold Eurasian winters. Geophys. Res. Lett. 36, L08707,
541		doi:10.1029/2008GL037079 (2009).

- 542 71 Kim, B.-M. *et al.* Weakening of the stratospheric polar vortex by Arctic sea-ice loss.
- 543 *Nature Commun.* 5, 4646, doi:10.1038/ncomms5646 (2014).
- Jaiser, R., Dethloff, K. & Handorf, D. Stratospheric response to Arctic sea ice retreat and
 associated planetary wave propagation changes. *Tellus A* 65, 19375,
- 546 doi:10.3402/tellusa.v65i0.19375 (2013).
- 547 73 Handorf, D., Jaiser, R., Dethloff, K., Rinke, A. & Cohen, J. Impacts of Arctic sea-ice and
 548 continental snow-cover changes on atmospheric winter teleconnections. *Geophys. Res.*
- 549 *Lett.* **42**, 2367–2377 doi:10.1002/2015GL063203 (2015).
- Luo, D. *et al.* Impact of Ural blocking on winter warm Arctic–cold Eurasian anomalies.
 Part I: Blocking-induced amplification. *J. Clim.* 29, 3925–3947, doi:10.1175/JCLI-D-150611.1 (2016).
- 553 75 Mori, M. Watanabe, M., Shiogama, H., Inoue, J. & Kimoto, M. Robust Arctic sea-ice
 554 influence on the frequent Eurasian cold winters in past decades. *Nature Geosci.* 7, 869–
 555 873, doi:10.1038/ngeo2277 (2014).
- 556 76 Ding, Q. *et al.* Tropical forcing of the recent rapid Arctic warming in northeastern
 557 Canada and Greenland. *Nature* 509, 209–212, doi:10.1038/nature13260 (2014).
- 558 77 Perlwitz, J., Hoerling, M. & Dole, R. Arctic tropospheric warming: Causes and linkages
 559 to lower latitudes. *J. Clim.* 28, 2154–2167 (2015).
- 560 78 Hartmann, D. L. Pacific sea surface temperature and the winter of 2014. *Geophys. Res.*
- 561 *Lett.* **42**, 1894–1902, doi:10.1002/2015GL063083 (2015).
- 562 79 Screen J. & Francis, J. Contribution of sea-ice loss to Arctic amplification regulated by
 563 Pacific Ocean decadal variability. *Nature Clim. Change*, accepted (2016).

564	80	Sato, K., Inoue, J. & Watanabe, M. Influence of the Gulf Stream on the Barents Sea ice
565		retreat and Eurasian coldness during early winter. Environ. Res. Lett. 9, 084009 (2014).
566	81	Harvey, B. J., Shaffrey, L. C. & Woollings, T. Deconstructing the climate change
567		response of the Northern Hemisphere wintertime storm tracks. Clim. Dynam. 45, 2847–
568		2860 (2015).
569	82	Feldstein, S. B. & Lee, S. Intraseasonal and interdecadal jet shifts in the Northern
570		Hemisphere: The role of warm pool tropical convection and sea ice. J. Clim. 27, 6497-
571		6518, doi:10.1175/JCLI-D-14-00057.1 (2014).
572	83	Trenberth, K. E., Fasullo, J. T. & Shepherd, T. G. Attribution of climate extreme events.
573		Nature Clim. Change 5, 725–730, doi:10.1038/nclimate2657 (2015).
574	84	Sigmond, M. & Scinocca, J. F. The influence of the basic state on the Northern
575		Hemisphere circulation response to climate change. J. Clim. 23, 1434–1446 (2010).
576	85	Butler, A. H. et al. Defining sudden stratospheric warmings. Bull. Am. Meteorol. Soc. 96,
577		1913–1928, doi:10.1175/BAMS-D-13-00173.1 (2015).
578	86	Sigmond, M., Scinocca, J. F., Kharin, V. V. & Shepherd, T. G. Enhanced seasonal
579		forecast skill following stratospheric sudden warmings. Nature Geosci. 6, 98-102,
580		(2013).
581	87	Handorf, D. & Dethloff, K. How well do state-of-the-art atmosphere-ocean general
582		circulation models reproduce atmospheric teleconnection patterns? Tellus A 64, 19777,
583		doi:10.3402/tellusa.v64i0.19777 (2012).

584	88	Byrkjedal, Ø., Esau, I. N. & Kvamstø, N. G. Sensitivity of simulated wintertime Arctic
585		atmosphere to vertical resolution in the ARPEGE/IFS model. Clim. Dynam. 30, 687–701,
586		doi:10.1007/s00382-007-0316-z (2008).
587	89	Wu, Y. & Smith, K. L. Response of Northern Hemisphere midlatitude circulation to
588		Arctic amplification in a simple atmospheric general circulation model. J. Clim. 29,
589		2041-2058, doi:10.1175/JCLI-D-15-0602.1 (2016).
590	90	Anstey, J. A. et al. Multi-model analysis of Northern Hemisphere winter blocking: Model
591		biases and the role of resolution. J. Geophys. Res. Atmos. 118, 3956-3971,
592		doi:10.1002/jgrd.50231 (2013).
593	91	Inoue, J. et al. Additional Arctic observations improve weather and sea-ice forecasts for
594		the Northern Sea Route. Sci. Rep. 5, 16868, doi:10.1038/srep16868, (2015).
595	92	Schlichtholz, P. Empirical relationships between summertime oceanic heat anomalies in
596		the Nordic seas and large-scale atmospheric circulation in the following winter. Clim.
597		<i>Dyn.,</i> doi:10.1007/s00382-015-2930-5 (2016).
598	93	Lindsay, R., Wensnahan, M., Schweiger, A. & Zhang, J. Evaluation of seven different
599		atmospheric reanalysis products in the Arctic. J. Clim. 27, 2588–2606, doi:10.1175/JCLI-
600		D-13-00014.1 (2014).
601	94	Handorf, D., Dethloff, K., Marshall, A. G. & Lynch, A. Climate regime variability for
602		past and present time slices simulated by the Fast Ocean Atmosphere Model. J. Clim. 22,
603		58–70, doi:10.1175/2008 JCLI2258.1 (2009).

604	95	Gervais, M., Atallah, E., Gyakum, J. R. & Tremblay, L. B., Arctic air masses in a
605		warming world. J. Clim. 29, 2359–2373, doi:10.1175/JCLI-D-15-0499.1. (2016).
606	96	Francis, J. & Skific, N. Evidence linking rapid Arctic warming to mid-latitude weather
607		patterns. Philos. Trans. R. Soc. Lond. Ser. A 373, 20140170, doi.10.1098/rsta.2014.0170
608		(2015).
609	97	Screen, J. A. & Simmonds, I. Amplified mid-latitude planetary waves favour particular
610		regional weather extremes. <i>Nature Clim. Change</i> 4 , 704–709, doi:10.1038/nclimate2271
611		(2014).
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625	JEO wa	as the coordinating author and all other authors contributed ideas, analyses, and text.
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628	Figure captions
629	Figure 1: (a, b) Geopotential height (units of meters) of the 500 hPa pressure surface, illustrating
630	the northern hemisphere's tropospheric polar jet stream where height lines are closely spaced.
631	Winds of the jet stream follow the direction parallel to contours, forming the persistent vortex
632	that circulates counterclockwise around the North Pole. The primarily west-to-east wind flow
633	can adopt a relatively circular pattern (a, for 15 November 2013) or a wavy one (b, for 5 January
634	2014). The lower panels (c, d) show the corresponding air temperature anomaly patterns (units of
635	°C) for the same days at a lower atmospheric level (850 hPa).
636	
637	Figure 2: A complex web of pathways that summarize examples of potential mechanisms
638	that contribute to more frequent amplified flow and more persistent weather patterns in mid-
639	latitudes. Numbers 1-11 refer to original literature listed below diagram, and [] refer to
640	these citations in the current reference list. BK is Barents/Kara Seas area, EKE is eddy
641	kinetic energy, and SLP is sea-level atmospheric pressure. For details on processes consult
642	the original references.
643	
644	Figure 3: Global air temperatures anomalies (°C) for January 2016 were the highest in the
645	historical record for any January beginning in 1880. Southerly winds from midlatitudes
646	contributed to the largest anomalies in the Arctic (+7° C). Note the cold anomaly (blue) over
647	Asia. Source: NASA.

649 Figure 4: State dependence of the atmospheric response to Arctic sea-ice loss. Model simulated 650 wintertime 500 hPa geopotential height responses to Arctic sea ice loss for two different surface 651 ocean states. The responses are estimated from four 100-yr long atmospheric model simulations, 652 with prescribed sea ice concentrations and sea surface temperatures. Experiments A and C have 653 identical below-average sea ice conditions. Experiments B and D have identical above-average 654 sea ice conditions. Experiments A and B, and C and D, have identical sea surface temperatures, 655 but the two pairs have different sea surface temperatures from one another (i.e., A and B differ 656 from C and D; see Supplementary Figure 1), capturing opposite phases of the Atlantic 657 Multidecadal Oscillation (AMO). The response to sea-ice loss, under different surface ocean 658 states, is estimated by contrasting experiments (a) A and B, and (b) C and D. The grey box 659 highlights the midlatitude Pacific-American region, where a wave-train response to sea-ice loss 660 is simulated for one SST state (a; negative AMO) but not the other (b; positive AMO), implying that the response to sea-ice loss is state dependent. Green hatching denotes responses that are 661 662 statistically significant at the 95% (p=0.05) confidence level.

663

Figure 5: Current state of the science for selected linkages. Arctic amplification and some

international cooperation of individual researchers.

665 pathways are known (left), but chaotic instabilities and multiple external forcing sources are

noted under Limitations (center). (Right) A way forward is through improved data, models, and

667 668

669 Figures



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- 673 the northern hemisphere's polar jet stream where height lines are closely spaced. Winds of the jet
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- noted under Limitations (center). (Right) A way forward is through improved data, models, and
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717

719 Figure S1: Prescribed surface boundary conditions. Differences in prescribed winter sea ice

720 concentrations (a) and sea surface temperatures (b) between the experiments presented in

721 Figure 4 of the main material. Experiments A and C have identical below-average sea ice

conditions whilst experiments *B* and *D* have identical above-average sea ice conditions, and the

difference between these is presented in (a). Experiments A and B, and C and D, have identical

sea surface temperatures, but the two pairs have different sea surface temperatures from one

another, with this difference shown in (b).