1   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

34   rejects simple cause-and-effect pathways, notes diagnostic challenges in interpreting atmospheric

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

39   Various metrics indicate that the recent period of disproportionate Arctic warming relative to

40   midlatitudes—referred to as Arctic Amplification (AA)—emerged from the noise of natural

41   variability in the late 1990s[1]. This signal will strengthen as human activities continue to raise

42   greenhouse gas concentrations[2]. The assessment of the potential for AA to influence broader

43   hemispheric weather (referred to as linkages) is complex and controversial[3-6]. Yet with

44   intensifying AA, we argue that the key question is not whether the melting Arctic will influence

45   midlatitude weather patterns over the next decades, but rather what is the nature and magnitude

46   of this influence relative to non-Arctic factors, and is it limited to specific regions, seasons, or

47   types of weather events[7]?

48

49   Although studies arguing for linkages often highlight a single causal pathway, the complexity of

50   atmospheric dynamics implies that such singular linkage pathways are unlikely. Nonlinearities in

51   the climate system are particularly important in the Arctic and subarctic[8,9,10]. The climate change

52   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

56   reflected in observationally based studies that have struggled to find robust linkages[11,12]. Further,

57   multiple runs of the same model with similar but slightly different initial conditions, termed

58   ensemble members, show linkages in some subsets of ensemble runs but not in others[13]. This

59   failure to detect direct connections is sometimes interpreted as evidence against linkages. Four

60   properties (limitations) that contribute to the complexity of attribution of linkages are developed

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 sea-

64   surface temperature anomalies in the tropics, midlatitudes and Arctic], and *state dependence* [a

65   response dependent on the prior state of the atmospheric circulation, e.g., the phase of the Arctic

66   Oscillation (AO) atmospheric circulation index or the strength of the stratospheric vortex].

67

68   We propose a system-level approach that recognizes multiple simultaneous processes, internal

69   instabilities, and feedbacks. Progress in understanding Arctic/midlatitude linkages will require

70   the use of probabilistic model forecasts that are based on case studies and high-resolution,

71   ensemble solutions to the equations of motion and thermodynamics. Community coordinated

72   model experiments and diagnostic studies of atmospheric dynamics are essential to resolve

73   controversy and benefit efforts to communicate the impacts of linkages and uncertainties with a

74   broad public.

75

Arctic warming is unequivocal, substantial, and ongoing

Changes in Arctic climate in the last two 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 highest annual mean surface air temperatures since 1900. AA is also manifested in 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 fall/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 spring snow loss has occurred progressively earlier[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 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 CO_2 assure mid-century AA and global

100   warming.

101

102   **Living with an uncertain climate system**

103   The task of unraveling cause and effect of mechanisms linking changes in the large scale

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

107   which responses are not directly proportional to the change in forcing[8,10,22]. Further, when

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

110   can lead to confusion because only sufficient causes have deterministic predictive power[23,24].

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

113   least implicitly assume quasi-linear, sufficient causal connections[5,7,25-37]. While this approach has

114   been helpful in elucidating relevant linkage mechanisms, we provide a view at the system level

115   that can mask simple cause and effect.

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

126   anomalies in the Arctic may increase the persistence of weather systems [20,38]. Further,

127   troposphere-stratosphere connections can trigger changes in the regional wind patterns[39].

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

133   states can persist through nonlinear mechanisms[10,22]. Fig. 1(a, b) illustrates two configurations of

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

137   north-south wavy flow pattern. Although the phrase *polar vortex* is formally reserved for the

138   stratosphere, it is a useful term for discussing tropospheric geopotential height/wind

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

143   height pattern are part of the seemingly random, internal variability of atmospheric circulation. A

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

149   into the western hemisphere. The wavier jet stream case has two warm and two cold anomaly

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

152   patterns have occurred in the last decade[40,41].

153

154   Multiple studies [42,43,44] illustrate the paradigm of itinerancy in describing the physical

155   mechanisms driving shifts in atmospheric circulation. Atmospheric circulation can fluctuate

156   between multiple states (referred to as local attractors) in irregular transitions, resulting in

157   chaotic-like behavior on monthly, seasonal, and interannual time scales[42]. Chaos theory argues

158   that the climate system can destabilize and suddenly shift into a new stable state[45,46]. On decadal

159   timescales, increasing variability within a time series is a possible early-warning signal of a

160   critical transition to a different state[47].

161

162   Do observations indicate a recent increase in these types of sudden shifts in the atmospheric

163   circulation? Although one might expect decreased sub-seasonal variability as the temperature

164   contrast across the jet stream declines with AA[48], recent observations suggest contrary evidence

165   of stable or larger circulation variability and new extremes in several circulation indices. For

166   example, an enhanced magnitude of both positive and negative excursions of the AO circulation

167   index is evident in the last decade during Decembers based on data from 1950-2014[49]. Cohen[50]

168   notes an increase in midlatitude intraseasonal winter temperature variability from 1988/89 to

169   2014/15. Periods of relative persistence as well as increases in interannual variability have been

170   noted in other related winter climate indices–such as the North Atlantic Oscillation (NAO),

171   Greenland Blocking Index (GBI), and jet latitude metrics–although stability is more evident at

172   other times of the year[51,52,53]. Observations from the next decade should reveal much about

173   whether increasing variability and weather extremes are ongoing features of climate change or

174   whether circulation-related extremes are damped by AA.

175

176   The ability of state-of-the-art climate models to correctly simulate the interplay between thermal

177   and dynamical processes producing itinerancy on different spatial scales is limited. One

178   manifestation of this is the continuing tendency for climate models to underestimate the

179   frequency of blocking (a regional slowing of tropospheric winds)[54]. Also the signal to noise in

180   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,

184   evident at some times and not at others, or the same response arising from different combinations

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

188   of how the climate will respond to the ongoing AA and loss of sea ice[48,58]. For example, climate

189   model studies have reported shifts towards both the positive or negative phases of the AO and/or

190   NAO, or no apparent shift, in response to AA[13,19,34,39,59]. Analyses that involve averaging over

191   large areas, long time periods, and/or many ensemble members may not reveal specific

192   atmospheric responses to AA, such as enhanced jet-stream ridges and troughs that occur in

193   specific locations. Despite some clear hypotheses for linkages, it remains difficult to prove that

194   Arctic change has already had or not had an impact on midlatitude weather based on

195   observations alone because of the short period since AA has become apparent[5].

196

197   One approach to overcome the signal-to-noise problem is to use model simulations[59]. Large

198   ensembles of climate simulations have been run with observed sea ice loss as the only forcing

199   factor. In such large ensembles it is possible to answer the question: how many years of

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

204   noise of internal variability. Thermodynamic responses may be detected sooner than dynamical

205   responses[59,60]. It may be that regional sea-ice loss will elicit robust signals in a shorter period.

206

207   The Arctic climate system is especially sensitive to external forces that can fundamentally alter

208   climate and ecosystem functioning[62]. Nonlinear threshold behavior of the Arctic climate system

209   to the loss of sea ice has been discussed[63]. There are qualitative hypotheses for the coupled

210   Arctic/subarctic climate system[64] and new approaches such as nonlinear auto-regressive

211   modeling for constructing linear and non-linear dynamical models (e.g. NARMAX)[65,66]. So far,

212   NARMAX has been used to discern changing effects of glaciological, oceanographic and

213   atmospheric conditions on Greenland iceberg numbers over the last century[67]. Novel methods to

214 distinguish between statistical and causal relationships[68], the application of artificial intelligence

215 such as evolutionary algorithms[69], and a Bayeasian Hierarchical Model approach may enable

216 progress.

217

218 Evidence of systematic midlatitude responses to Arctic warming is beginning to emerge[28-38].

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

222 linkages shape the overall picture, considered individually they are subject to intermittency in

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

225 Scandinavia) can lead to cold continental Asian temperatures[33,70-74]. A doubled probability of

226 severe winters in central Eurasia with increased regional sea ice loss has been reported[75]. This

227 singular linkage mechanism may be the exception rather than the rule[7]. Intermittency implies that

228 frameworks allowing for multiple necessary causal factors may be required to accurately

229 describe linkages in multiple locations.

230

231 *Multiple influences*

232 Whilst a more consistent picture of linkages may emerge in future scenarios as AA strengthens,

233 one needs to remember that sea ice loss is only one factor of many that influences, and is

234 influenced by, climate change. For example, eastern North American weather is affected by sea-

235 surface temperature patterns in the North Pacific and tropical Pacific[76-79] and also by sea ice loss

236 in the Pacific sector of the Arctic[32,33]. The so-named Snowmageddon blizzard that hit eastern

237 North America in February 2010 was strengthened by the coincidence of moist, warm air

238 associated with El Niño colliding with frigid air originating from Canada. Downstream

239 influences on the Barents/Kara Sea region, noted for initiating sea ice linkages with eastern Asia,

240 have been connected to the western North Atlantic[80].

241

242 The Arctic can also be influenced by variability from midlatitudes. January through May 2016,

243 for example, set new records for globally averaged temperatures along with the lowest recorded

244 sea ice extent in those months since 1880. Extensive Arctic temperature anomalies of over 7°C

245 were associated with strong southerly winds and warm air originating from the North Pacific,

246 southwestern Russia and the northeastern Atlantic; anomalies for January 2016 are shown in Fig.

247 3. In contrast, the large scale wind pattern also resulted in a severe, week-long cold surge over

248 eastern Asia during January 2016, evident as the blue region in Fig. 3.

249

250 On a hemispheric scale, the relative importance of Arctic versus non-Arctic forcing on

251 atmospheric circulation patterns is uncertain. While models generally suggest that AA and sea

252 ice loss favor a weakened and equatorward-shifted midlatitude storm track, warming of the

253 tropical upper troposphere favors the opposite response[81]. Recent work suggests that Arctic

254 influences may have started to exceed tropical influences in explaining subarctic variability[50,82].

255 In the long term, the direct warming effect of raised greenhouse gas concentrations favors warm

256 anomalies over cold anomalies, leading to an overall hemispheric tendency for warmer winters[4].

257

258 *State dependence*

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

11

260   vapor, changes in clouds) can either reinforce or counteract the amplitude of regional

261   geopotential height fields[60,83]. This response can depend on preexisting atmosphere-ocean

262   conditions and the intensity of the index cycle[49] (state dependence), and can be considered a

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

269   Variability in the wintertime Arctic stratospheric is another mechanism for state dependence. In

270   winter, planetary waves propagate between the troposphere and stratosphere, and the impacts of

271   this propagation are sensitive to the state of the stratospheric polar vortex[84]. While a strong

272   vortex is characterized by relatively fast-moving westerly winds and a cold core, sudden

273   stratospheric warmings can occur, in which temperatures can increase by over 40° C in a matter

274   of days[85]. These events can weaken, or even reverse, the stratospheric winds, leading to an

275   eventual downward propagation of the circulation feature into the troposphere[86] and a tendency

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

278   lagged transfer of wave-induced disturbances involving the stratosphere[39]. Only models with

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

285 dynamics, and the study of linkages remains an unfinished puzzle. Handorf and Dethloff[87] report

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

298 processes that act sometimes separately, sometimes interactively in a framework based on the

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

303 Studies of linkages are motivated by the potential that a better understanding will benefit

304 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:

307

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

Summary

328

329 Many recent studies of linkages have focused on direct effects attributed to specific changes in

330 the Arctic, such as reductions in sea ice and snow cover. Disparate conclusions have been

331 reached owing to the use of different data, models, approaches, metrics, and interpretations. Low

332 signal-to-noise ratios and the regional, episodic, and state-dependent nature of linkages further

333 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

345 Wintertime cold spells, summer heatwaves, droughts and floods–and their connections to natural

346 variability and forced change–will be topics of active research for years to come. We recommend

347 that the meteorological community "embrace the chaos" as a dominant component of linkages

348 between a rapidly warming Arctic and the midlatitude atmospheric circulation. Scientists should

349 capitalize on and seek avenues to improve the realism and self-consistency of the physical

350 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 toward 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 midlatitudes, 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.

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624   **Author Contributions & Competing Financial Interests statement**

625   JEO was the coordinating author and all other authors contributed ideas, analyses, and text.

626   There are no competing financial interests.

627

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.

648

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

661   that the response to sea-ice loss is state dependent. Green hatching denotes responses that are

662   statistically significant at the 95% (p=0.05) confidence level.

663

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

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

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

667   international cooperation of individual researchers.

668

669   **Figures**
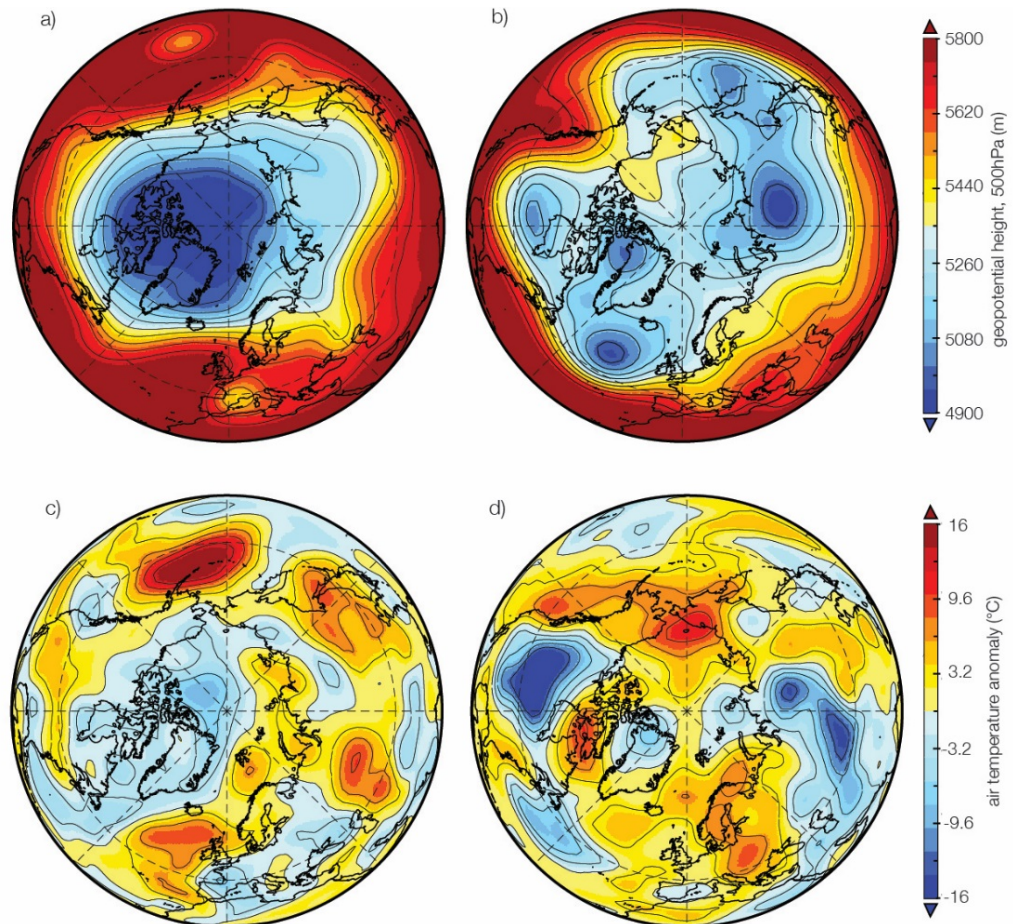
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the northern hemisphere's polar jet stream where height lines are closely spaced. Winds of the jet
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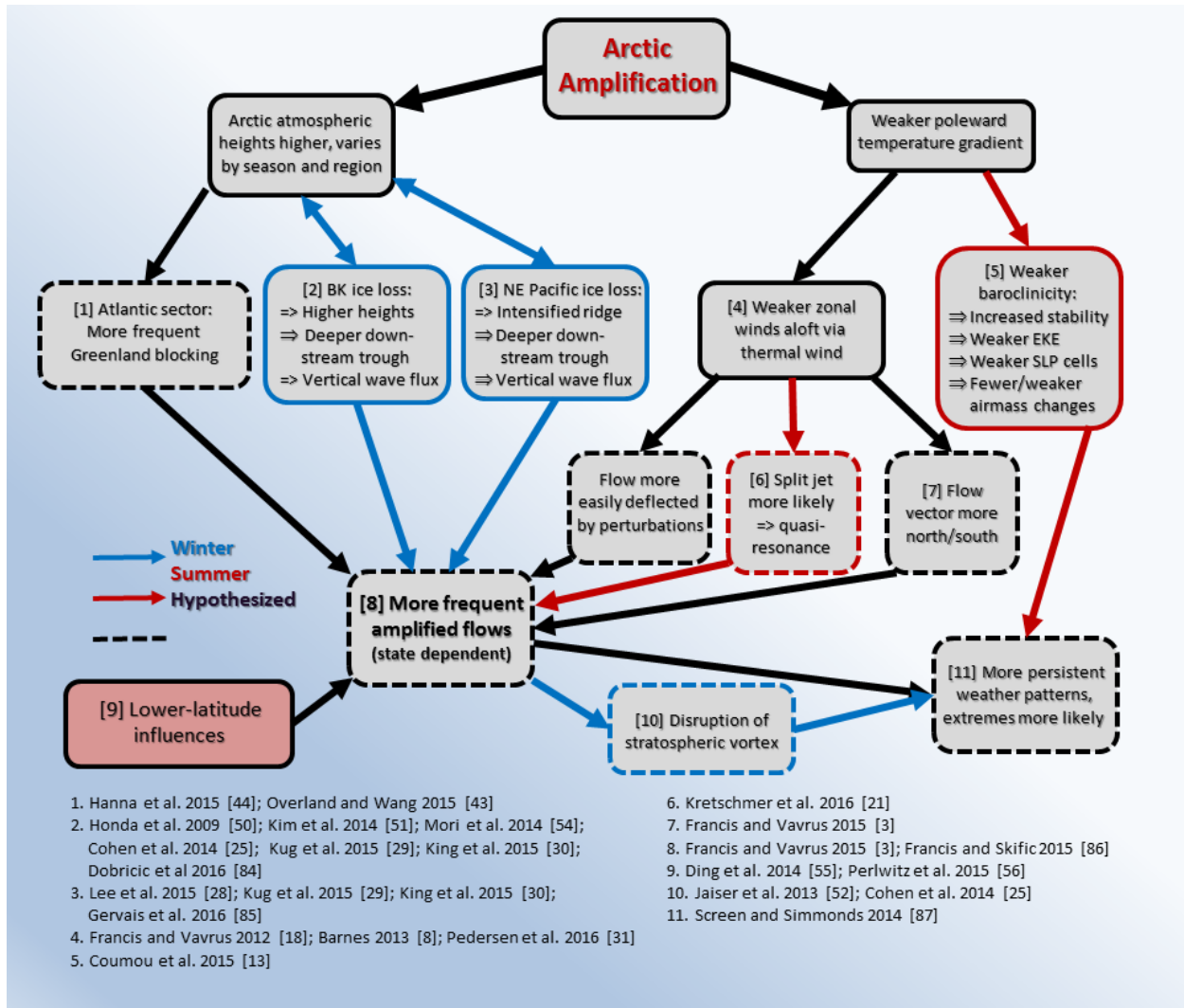
680

Figure 2: A complex web of pathways that summarize examples of potential mechanisms that contribute to more frequent amplified flow and more persistent weather patterns in mid-latitudes. Numbers 1-11 refer to original literature listed below diagram, and [ ] refer to these citations in the current reference list. BK is Barents/Kara Seas area, EKE is eddy kinetic energy, and SLP is sea-level atmospheric pressure. For details on processes consult the original references.

687

January 2016   L-OTI(°C) Anomaly vs 1951-1980   1.13

−4.1 −4.0 −2.0 −1.0 −0.5 −0.2 0.2 0.5 1.0 2.0 4.0 12.9
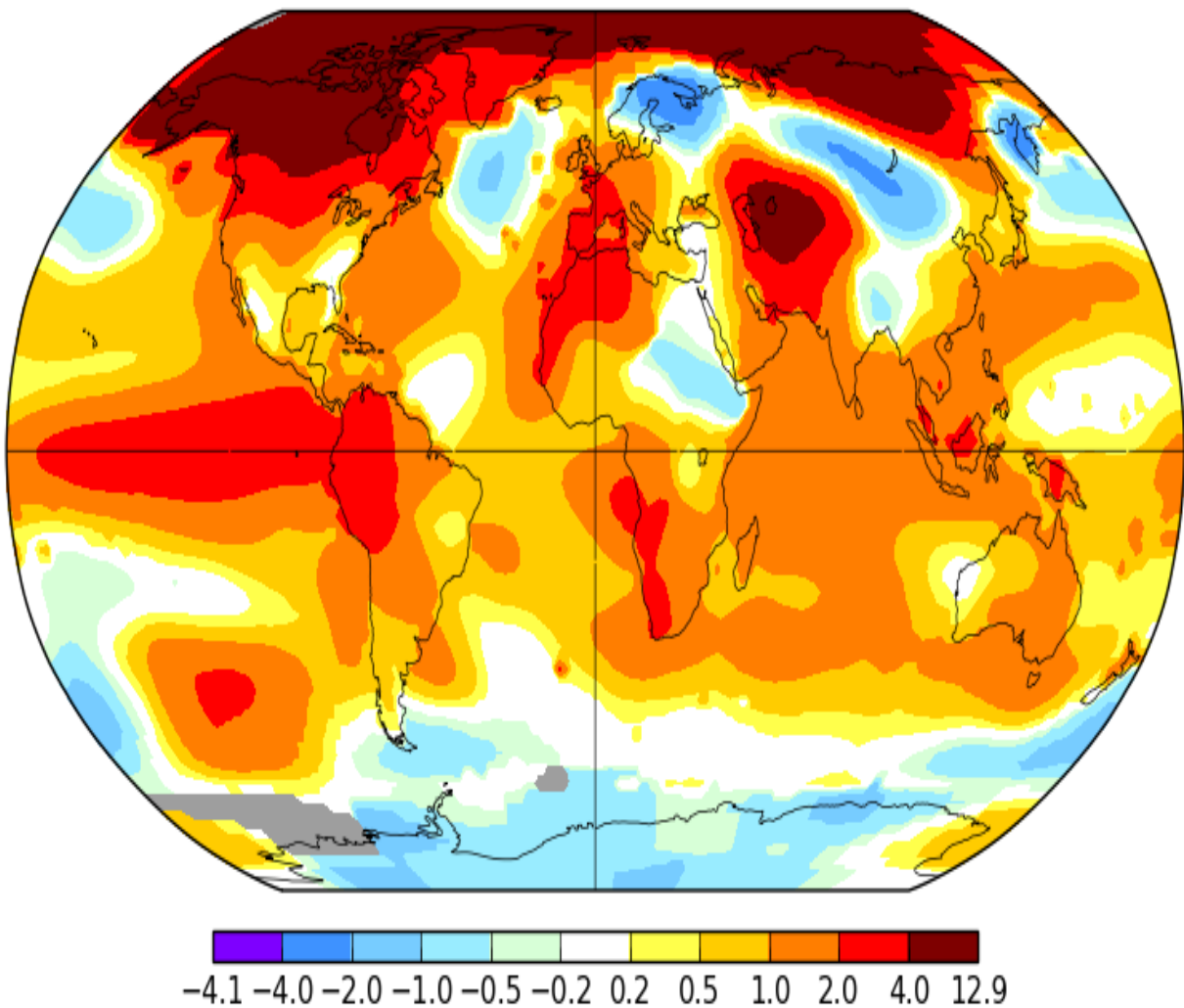
688

689   Figure 3. Global air temperatures anomalies (°C) for January 2016 were the highest in the
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691   contributed to the largest anomalies in the Arctic (+7° C). Note the cold anomaly (blue) over
692   Asia. Source: NASA.

693

a) Experiment *A* - *B*   **b)** Experiment *C* - *D*
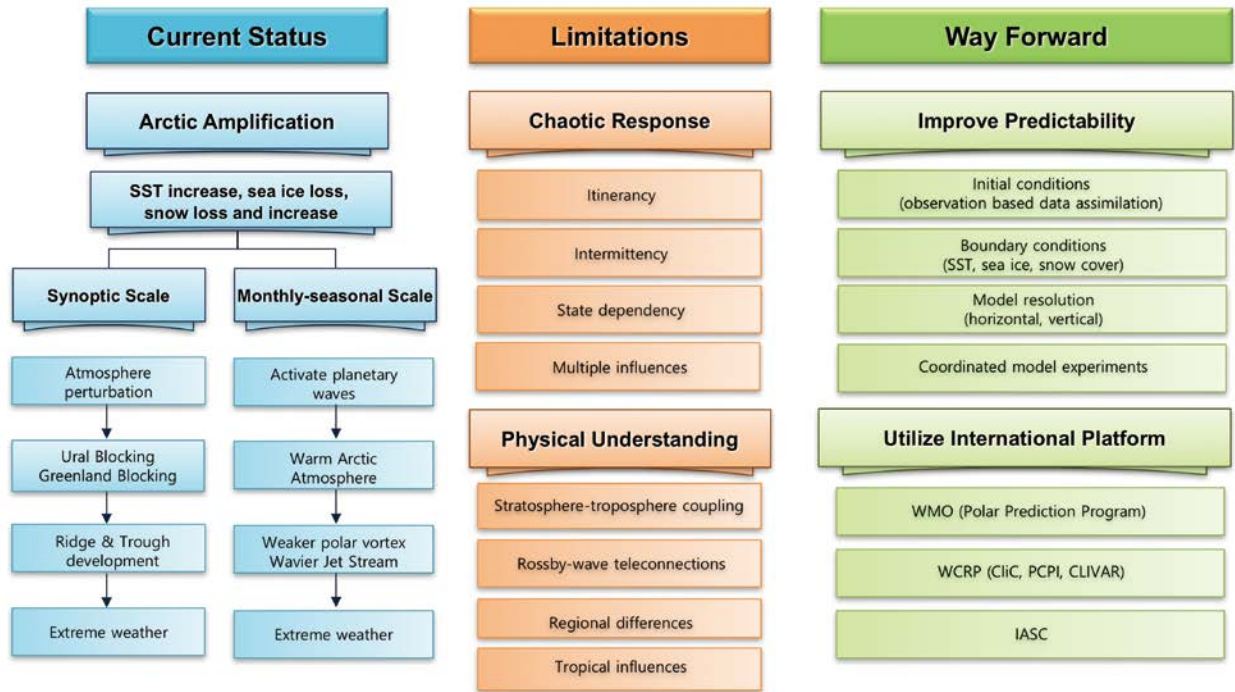
500 hPa geopotential height (m)
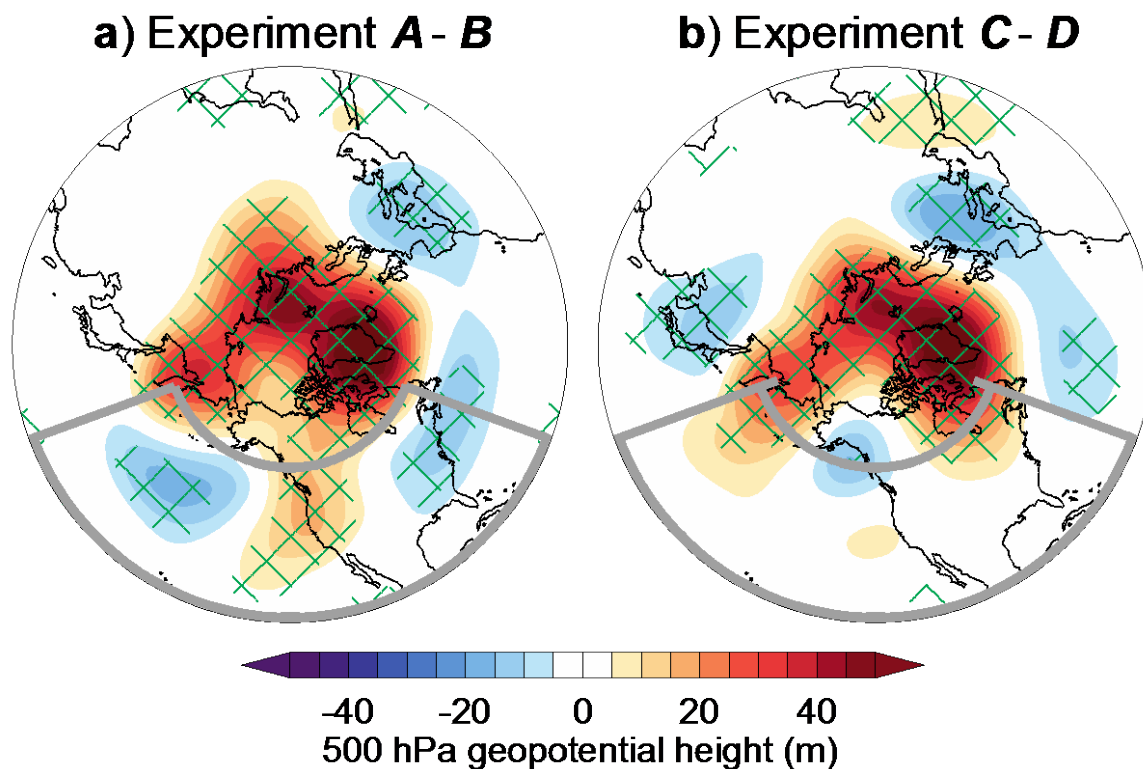
694

695   Figure 4:

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698   states. The responses are estimated from four 100-yr long atmospheric model simulations, with
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700   identical below-average sea ice conditions. Experiments *B* and *D* have identical above-average
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706   highlights the midlatitude Pacific-American region, where a wave-train response to sea-ice loss
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708   that the response to sea-ice loss is state dependent. Green hatching denotes responses that are
709   statistically significant at the 95% (*p*=0.05) confidence level.

710

Current Status	Limitations	Way Forward
Arctic Amplification	**Chaotic Response**	**Improve Predictability**
SST increase, sea ice loss, snow loss and increase	Itinerancy	Initial conditions (observation based data assimilation)
	Intermittency	Boundary conditions (SST, sea ice, snow cover)
Synoptic Scale — **Monthly-seasonal Scale**	State dependency	Model resolution (horizontal, vertical)
	Multiple influences	Coordinated model experiments
Atmosphere perturbation — Activate planetary waves	**Physical Understanding**	**Utilize International Platform**
Ural Blocking Greenland Blocking — Warm Arctic Atmosphere	Stratosphere-troposphere coupling	WMO (Polar Prediction Program)
Ridge & Trough development — Weaker polar vortex Wavier Jet Stream	Rossby-wave teleconnections	WCRP (CliC, PCPI, CLIVAR)
Extreme weather — Extreme weather	Regional differences	IASC
	Tropical influences	

711

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 (center). (Right) A way forward is through improved data, models, and international cooperation of individual researchers.

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a) Experiment *A - B / C - D*   b) Experiment *A - C / B - D*

Sea ice concentration (%)

Sea surface temperature (℃)
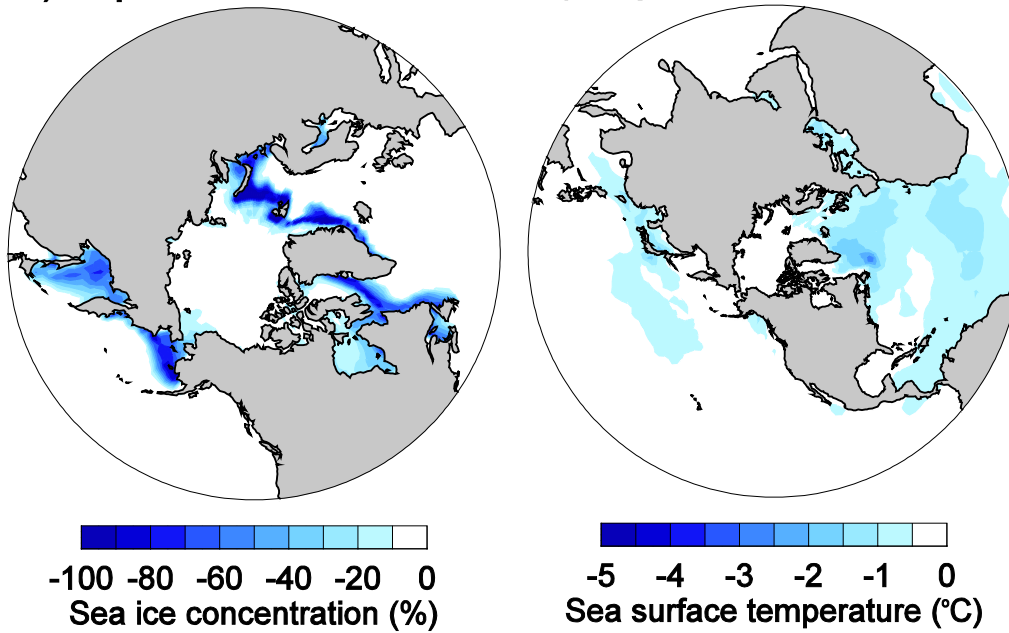
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719   Figure S1: Prescribed surface boundary conditions. Differences in prescribed winter sea ice
720   concentrations (**a**) and sea surface temperatures (**b**) between the experiments presented in
721   Figure 4 of the main material. Experiments *A* and *C* have identical below-average sea ice
722   conditions whilst experiments *B* and *D* have identical above-average sea ice conditions, and the
723   difference between these is presented in (**a**). Experiments *A* and *B*, and *C* and *D*, have identical
724   sea surface temperatures, but the two pairs have different sea surface temperatures from one
725   another, with this difference shown in (**b**).

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