Nonlinear response of mid-latitude weather to the changing Arctic

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Accepted Version

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3   James E. Overland[1,*], Klaus Dethloff[2], Jennifer A. Francis[3], Richard J. Hall[4], Edward Hanna[4],

4   Seong-Joong Kim[5], James A. Screen[6], Theodore G. Shepherd[7], and Timo Vihma[8]

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6   [1]Pacific Marine Environmental Laboratory, NOAA, Seattle, Washington, USA
7   [2]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Potsdam, Germany
8   [3]Department of Marine and Coastal Sciences, Rutgers University, New Jersey, USA
9   [4]Department of Geography, University of Sheffield, UK
10 [5]Korea Polar Research Institute, Korea
11 [6]College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK
12 [7]Department of Meteorology, University of Reading, UK
13 [8]Finnish Meteorological Institute, Helsinki, Finland
14
15
16
17 [*]Corresponding author: James Overland
18 NOAA/PMEL
19 7600 Sand Point Way NE
20 Seattle WA 98115
21 1-206-526-6795
22 james.e.overland@noaa.gov
23
24
25
26   Final Revision Submitted to Nature Climate Change: Perspectives

27

28   22 July 2016

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1

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

76 **Arctic warming is unequivocal, substantial, and ongoing**

77 Changes in Arctic climate in the last two decades are substantial. Since 1980 Arctic temperature

78 increases have exceeded those of the Northern Hemisphere average by at least a factor of two[14].

79 Over land north of 60°N, 12 of the past 15 years have exhibited the highest annual mean surface

80 air temperatures since 1900. AA is also manifested in loss of sea ice, glaciers, snow and

81 permafrost, a longer open-water season, and shifts in Arctic ecosystems. Sea ice has undergone

82 an unprecedented decline over the past three decades with a two-thirds reduction in volume[2].

83 Comparable decreases in snow cover have occurred during May and June. AA is strongest in

84 fall/winter with largest values over regions of sea ice loss[15], while the areas of greatest warming

85 in summer are located over high-latitude land where spring snow loss has occurred progressively

86 earlier[16].

87

88 This amplification of warming in the Arctic occurs for several reasons, all based on fundamental

89 physical processes[17,18]. Among these are feedbacks related to albedo owing to a loss of snow and

90 sea ice along with increases in heat-trapping water vapor and clouds. Increasing temperatures in

91 the lower atmosphere elevate the height of mid-level pressure surfaces (geopotential height),

92 leading to changes in poleward and regional gradients and, consequently, wind patterns[19,20,21].

93

94 Based on over 30 climate model simulations presented in the most recent Intergovernmental

95 Panel on Climate Change (IPCC) Assessment Report, future winter (November-March) surface

96 temperatures in the Arctic (60-90°N) are projected to rise ~4°C by 2040, with a standard

97 deviation of 1.6 °C, relative to the end of the previous century (1981-2000)[2]. This is roughly

98 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

6

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

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**

12

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

328 **Summary**

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

351 processes and internal instabilities. Use of multiple ensembles is essential. Coordination efforts

352 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 billions of people living in northern midlatitudes, these priorities have been identified by national

355 and international agencies, such as: the WMO/Polar Prediction Program (PPP), WCRP Climate

356 and Cryosphere (CliC), WCRP Polar Climate Predictability Initiative (PCPI), the International

357 Arctic Science Committee (IASC), the International Arctic Systems for Observing the

358 Atmosphere (IASOA), the US National Science Foundation, NOAA, and the US CLIVAR

359 Arctic-midlatitude working group.

360

361 **References**

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　　　　*Dynam.* **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. *Nature* **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

419   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   midlatitudeweather-patterns.

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).

431   29   Jung, T. *et al.* Polar lower-latitude linkages and their role in weather and climate

432   prediction. *Bull. Am. Meteorol. Soc.* **96,** ES197–ES200, doi:10.1175/BAMS-D-15-

433   00121.1 (2015).

434   30   Hopsch, S., Cohen, J. & Dethloff, K. Analysis of a link between fall Arctic sea ice

435   concentration and atmospheric patterns in the following winter. *Tellus A* **64,** 18624,

436   doi:10.3402/tellusa.v64i0.18624 (2012).

437 31 Lee, M.-Y., Hong, C.-C. & Hsu, H.-H. Compounding effects of warm SST and reduced

438   sea ice on the extreme circulation over the extratropical North Pacific and North America

439   during the 2013–2014 boreal winter. *Geophys. Res. Lett.* **42,** 1612–1618,

440   doi:10.1002/2014GL062956 (2015).

441 32 Kug, J.-S. *et al.* Two distinct influences of Arctic warming on cold winters over North

442   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

444   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).

449 35 Tang, Q., Zhang, X. Yang, X. & Francis, J. A. Cold winter extremes in northern

450   continents linked to Arctic sea ice loss. *Environ. Res. Lett.* **8,** 014036, doi:10.1088/1748-

451   9326/8/1/014036 (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   *Sci.* **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   *Roy. Soc. A* **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-15-

487   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,**

490   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. Roy. 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   *Clim. Dyn.* **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).

544   72   Jaiser, R., Dethloff, K. & Handorf, D. Stratospheric response to Arctic sea ice retreat and

545   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).

550   74   Luo, D. *et al.* Impact of Ural blocking on winter warm Arctic–cold Eurasian anomalies.

551   Part I: Blocking-induced amplification. *J. Clim.* **29**, 3925–3947, doi:10.1175/JCLI-D-15-

552   0611.1 (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   *Dyn.,* 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. *Nature Clim. Change* **4,** 704–709, doi:10.1038/nclimate2271

611   (2014).

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613 To whom correspondence and requests for materials should be addressed:

614 James Overland james.e.overland@noaa.gov

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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.

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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.

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**
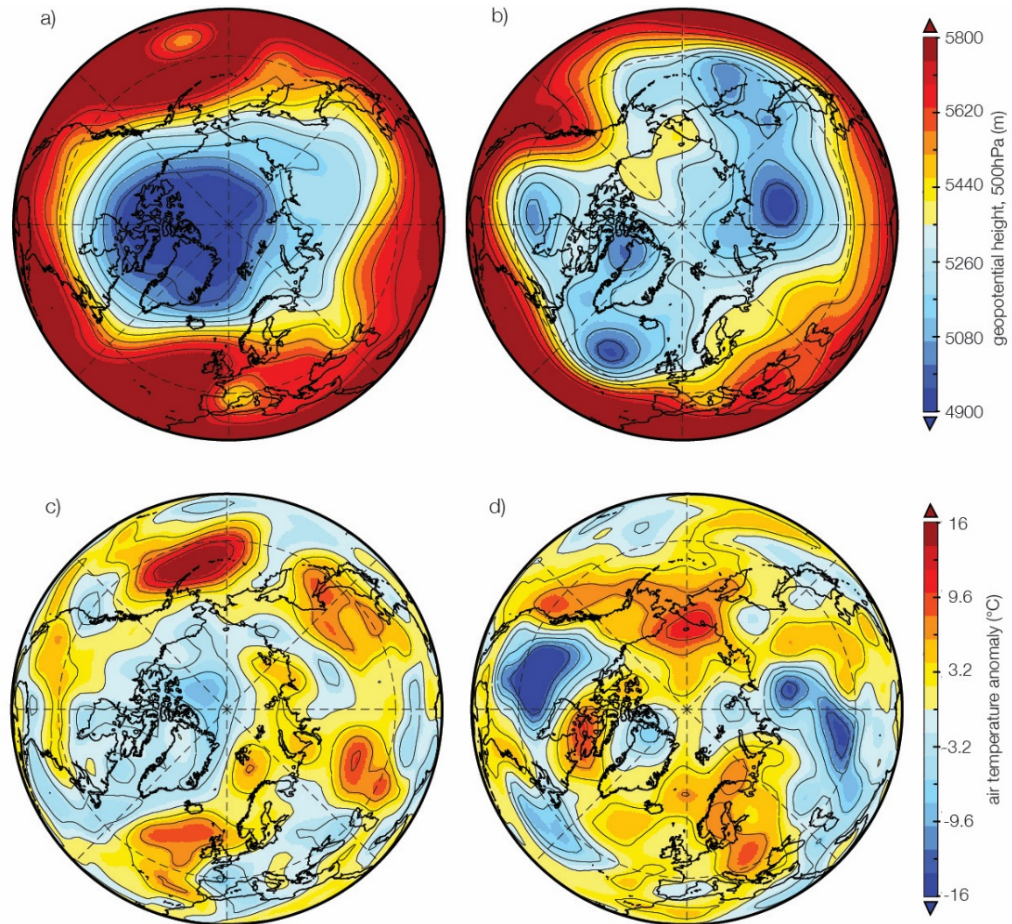
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Figure 1. (a, b) Geopotential height (units of meters) of the 500 hPa pressure surface, illustrating
the northern hemisphere's polar jet stream where height lines are closely spaced. Winds of the jet
stream follow the direction parallel to contours, forming the persistent vortex that circulates
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relatively circular pattern **(**a, for 15 November 2013**)** or a wavy one **(**b, for 5 January 2014**)**. The
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same days at a lower atmospheric level (850 hPa).
679
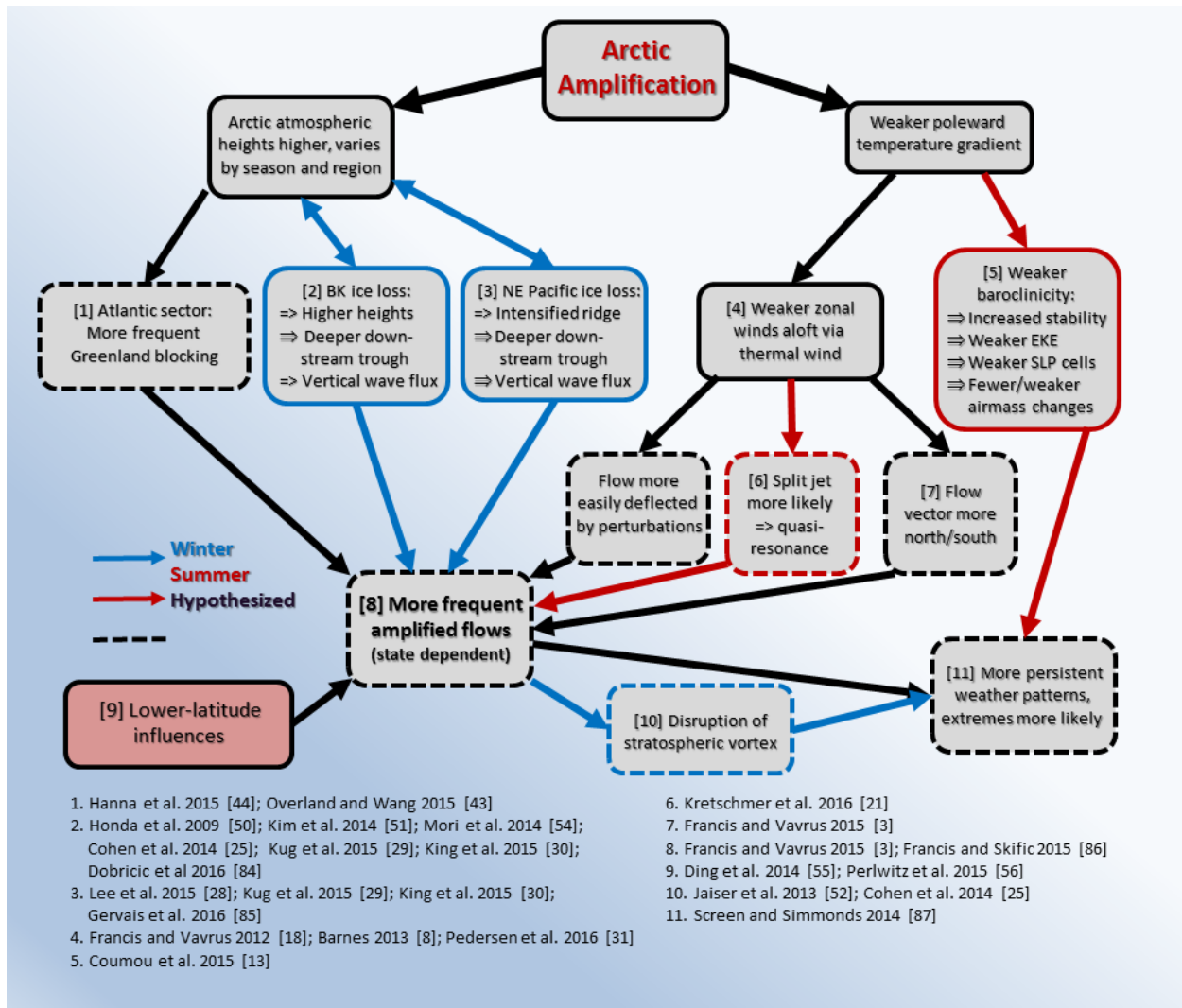
1. Hanna et al. 2015 [44]; Overland and Wang 2015 [43]
2. Honda et al. 2009 [50]; Kim et al. 2014 [51]; Mori et al. 2014 [54];
   Cohen et al. 2014 [25]; Kug et al. 2015 [29]; King et al. 2015 [30];
   Dobricic et al 2016 [84]
3. Lee et al. 2015 [28]; Kug et al. 2015 [29]; King et al. 2015 [30];
   Gervais et al. 2016 [85]
4. Francis and Vavrus 2012 [18]; Barnes 2013 [8]; Pedersen et al. 2016 [31]
5. Coumou et al. 2015 [13]
6. Kretschmer et al. 2016 [21]
7. Francis and Vavrus 2015 [3]
8. Francis and Vavrus 2015 [3]; Francis and Skific 2015 [86]
9. Ding et al. 2014 [55]; Perlwitz et al. 2015 [56]
10. Jaiser et al. 2013 [52]; Cohen et al. 2014 [25]
11. Screen and Simmonds 2014 [87]

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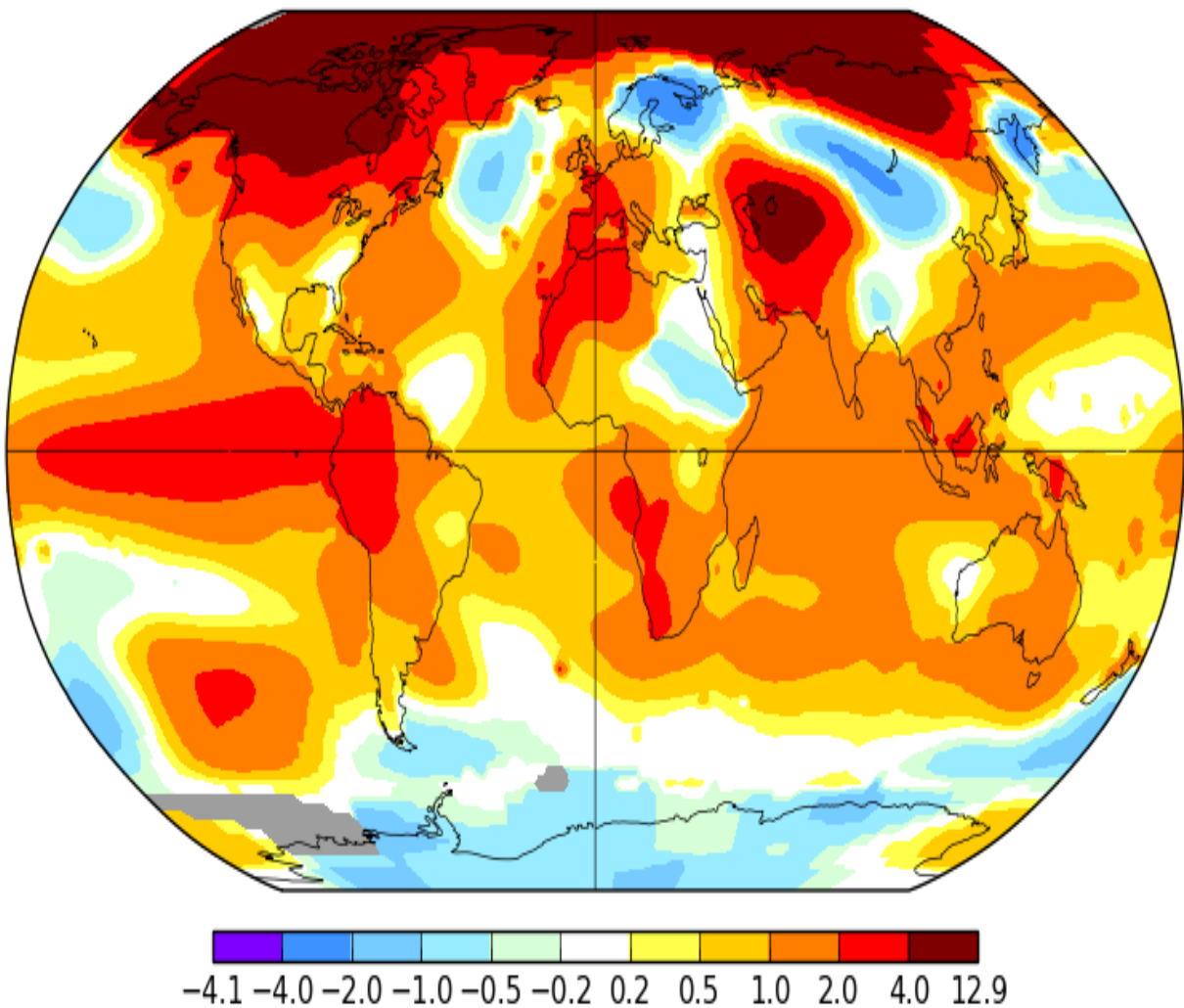
−4.1 −4.0 −2.0 −1.0 −0.5 −0.2 0.2 0.5 1.0 2.0 4.0 12.9
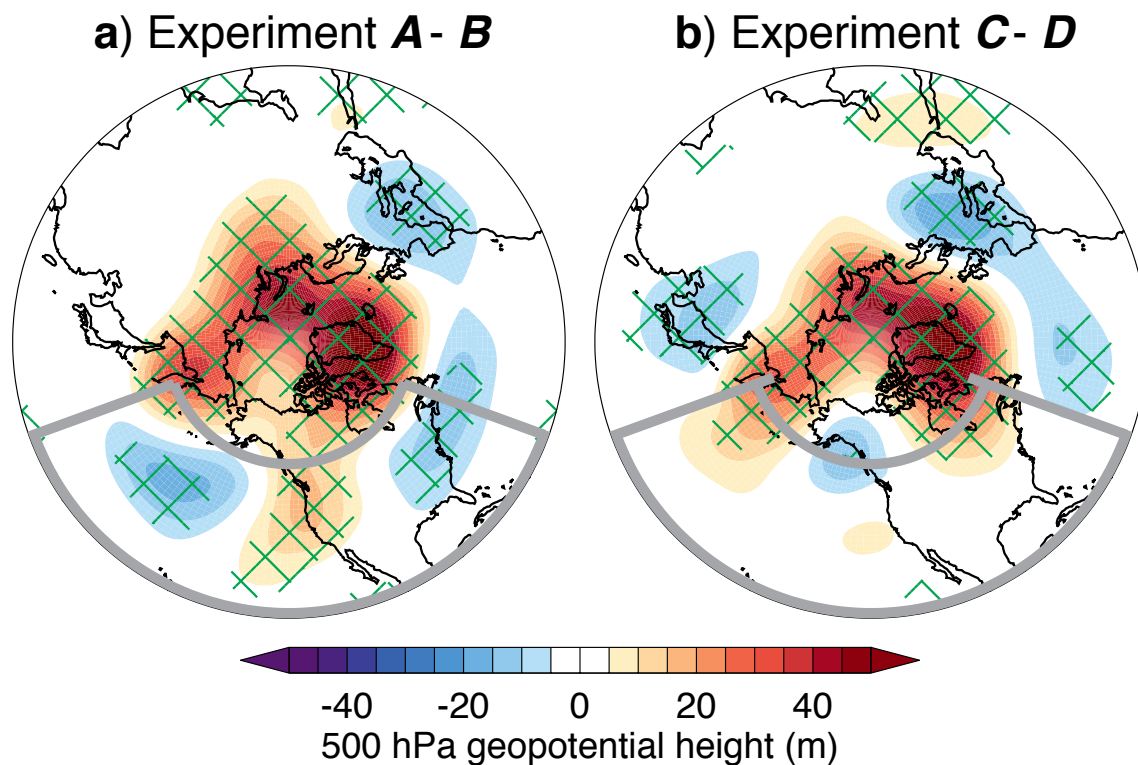
688

Figure 3. Global air temperatures anomalies (°C) for January 2016 were the highest in the historical record for any January beginning in 1880. Southerly winds from northern midlatitudes contributed to the largest anomalies in the Arctic (+7° C). Note the cold anomaly (blue) over Asia. Source: NASA.

693

a) Experiment _A_ - _B_   **b) Experiment _C_ - _D_**

-40   -20   0   20   40
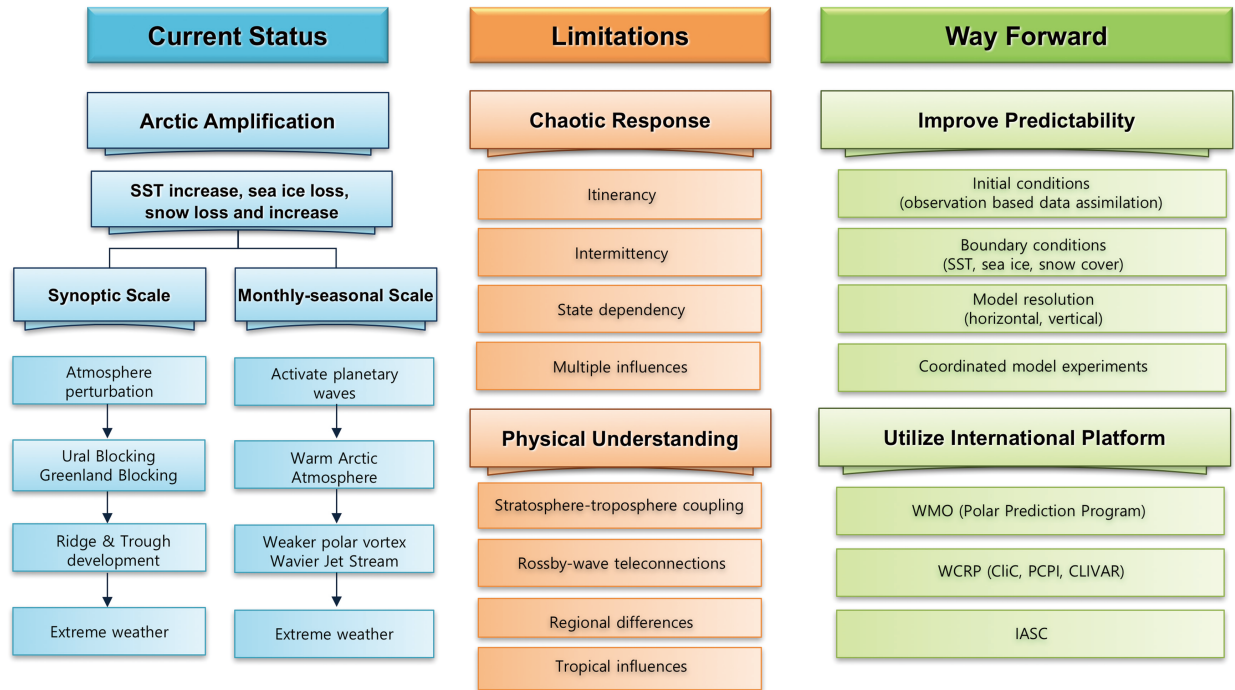500 hPa geopotential height (m)

694

695   Figure 4:

696   State dependence of the atmospheric response to Arctic sea-ice loss. Model simulated wintertime
697   500 hPa geopotential height responses to Arctic sea ice loss for two different surface ocean
698   states. The responses are estimated from four 100-yr long atmospheric model simulations, with
699   prescribed sea ice concentrations and sea surface temperatures. Experiments _A_ and _C_ have
700   identical below-average sea ice conditions. Experiments _B_ and _D_ have identical above-average
701   sea ice conditions. Experiments _A_ and _B_, and _C_ and _D_, have identical sea surface temperatures,
702   but the two pairs have different sea surface temperatures from one another (i.e., _A_ and _B_ differ
703   from _C_ and _D;_ see Supplementary Figure 1), capturing opposite phases of the Atlantic
704   Multidecadal Oscillation (AMO). The response to sea-ice loss, under different surface ocean
705   states, is estimated by contrasting experiments (**a**) _A_ and _B_, and (**b**) _C_ and _D_. The grey box
706   highlights the midlatitude Pacific-American region, where a wave-train response to sea-ice loss
707   is simulated for one SST state (**a**; negative AMO) but not the other (**b**; positive AMO), implying
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.
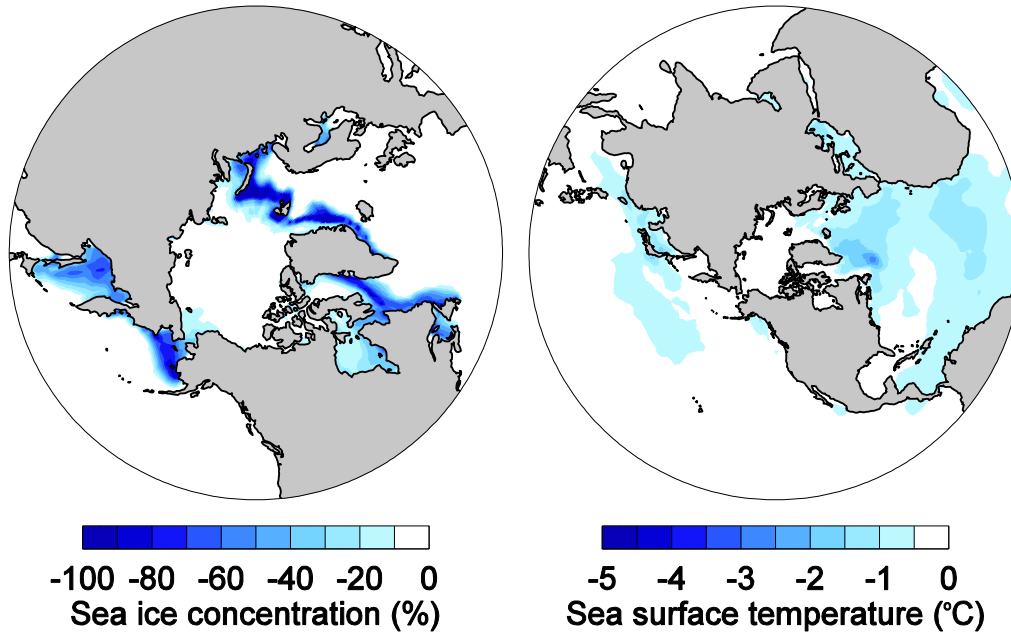
710

Current Status

Arctic Amplification

SST increase, sea ice loss, snow loss and increase

Synoptic Scale — **Monthly-seasonal Scale**

Atmosphere perturbation → Ural Blocking Greenland Blocking → Ridge & Trough development → Extreme weather

Activate planetary waves → Warm Arctic Atmosphere → Weaker polar vortex Wavier Jet Stream → Extreme weather

Limitations

Chaotic Response

Itinerancy

Intermittency

State dependency

Multiple influences

Physical Understanding

Stratosphere-troposphere coupling

Rossby-wave teleconnections

Regional differences

Tropical influences

Way Forward

Improve Predictability

Initial conditions (observation based data assimilation)

Boundary conditions (SST, sea ice, snow cover)

Model resolution (horizontal, vertical)

Coordinated model experiments

Utilize International Platform

WMO (Polar Prediction Program)

WCRP (CliC, PCPI, CLIVAR)

IASC

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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*

-100 -80 -60 -40 -20 0
Sea ice concentration (%)

-5 -4 -3 -2 -1 0
Sea surface temperature (℃)

Figure S1: Prescribed surface boundary conditions. Differences in prescribed winter sea ice concentrations (**a**) and sea surface temperatures (**b**) between the experiments presented in 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**).