

Causes and consequences of Arctic amplification elucidated by coordinated multimodel experiments

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21

22

23

24 Abstract

25

26 Human-induced warming is amplified in the Arctic, but its causes and consequences are not precisely
27 known. Here, we review scientific advances facilitated by the Polar Amplification Model
28 Intercomparison Project. Surface heat flux changes and feedbacks triggered by sea-ice loss are critical
29 to explain the magnitude and seasonality of Arctic amplification. Tropospheric responses to Arctic sea-
30 ice loss that are robust across models and separable from internal variability have been revealed,
31 including local warming and moistening, equatorward shifts of the jet stream and storm track in the
32 North Atlantic, and fewer and milder cold extremes over North America. Whilst generally small
33 compared to simulated internal variability, the response to Arctic sea-ice loss comprises a non-
34 negligible contribution to projected climate change. For example, Arctic sea-ice loss is essential to
35 explain projected North Atlantic jet trends and their uncertainty. Model diversity in the simulated
36 responses has provided pathways to observationally constrain the real-world response.

37

38

39 Introduction

40

41 Polar amplification describes the phenomenon that the polar regions warm at a faster rate than the global
42 average in response to increased greenhouse gases¹⁻³. It has long been attributed to the surface albedo
43 feedback: diminishing snow and sea ice reflects less incoming solar radiation, promoting warming and
44 further snow and sea-ice loss. This intuitive explanation, however, is not the full picture for a few
45 fundamental reasons. Firstly, polar amplification occurs in climate models even without any loss of ice
46 or snow, albeit with reduced magnitude⁴. Second, feedback analysis of climate model output
47 consistently highlights the lapse rate feedback, which characterises the sensitivity to the vertical
48 temperature structure, as the single most important driver of polar amplification². Lastly, while sea-ice
49 loss is greatest in late summer, polar amplification is most pronounced in winter⁵. We now understand
50 that polar amplification is a coupled atmosphere-ocean-ice phenomenon that operates across the
51 seasonal cycle^{6,7}. It is important to note that the framework through which polar amplification is viewed
52 can lead to different conclusions about the importance of different processes, as the relevant feedbacks
53 are interconnected, but interact in complex ways, with the impact of individual feedbacks potentially
54 enhanced through synergistic interactions⁸⁻¹⁰. Thus, although the processes and feedbacks leading to
55 polar amplification are reasonably well understood, how they interact, their physical interpretation, their
56 relative contributions, and how they lead to differences in the character of amplification between the
57 hemispheres and seasons are not precisely known^{6,7}.

58

59 Polar amplification may trigger remote climate responses in other parts of the world. For example, a
60 direct consequence of Arctic amplification is a reduction in the near-surface meridional temperature

61 gradient at high latitudes, which implies a weaker jet stream through thermal wind balance¹¹. A weaker
62 jet stream may in turn affect the propagation of weather disturbances across the Northern Hemisphere
63 midlatitudes, impacting regional climate¹²⁻¹⁴. However, there is a lack of scientific consensus on the
64 details of any potential influence on midlatitudes^{11,13}. Major challenges here are to separate cause from
65 effect, and forced changes from internal variability^{15,16}.

66

67 Climate models are useful tools to probe questions of causality and physical mechanisms, as they allow
68 for controlled experiments to isolate and quantify specific forcings or processes. For example, an
69 atmospheric model can be provided with different sea ice conditions to isolate the atmospheric response
70 to sea-ice loss. Myriad sea ice perturbation experiments have been conducted, but often with apparently
71 conflicting results^{12,13,17}. For example, models seemingly disagree on the sign of regional winter
72 temperature changes over midlatitudes in response to sea-ice loss¹⁷⁻¹⁹. Some of the apparent differences
73 between models could relate to sampling uncertainty or be due to varying aspects of the experimental
74 design. However, even absent these factors, the forced response may still be model dependent.
75 Understanding if and why models differ is important to constrain projections of future climate change²⁰.

76

77 To address these questions, the Polar Amplification Model Intercomparison Project (PAMIP) provided
78 a framework for the scientific community to produce and analyse coordinated model experiments²⁰.
79 The PAMIP experiments broadly fall into two categories (**Fig. 1**): experiments with perturbed sea ice
80 cover (prescribed in atmosphere-only experiments and nudged in coupled experiments) but baseline sea
81 surface temperatures (SST), and experiments with perturbed SST but baseline sea ice. Differencing
82 these experiments allows for the quantification of the simulated responses to sea ice, separately in the
83 Arctic and Antarctic, or SST change, absent other factors (Fig. 1). The ‘Tier 1’ time-slice simulations
84 have been most widely run and utilised. These are year-long simulations with prescribed SST and sea
85 ice representing preindustrial, present, or future time periods, each with at least 100 ensemble members
86 (i.e., repeated simulations), where ensemble members differ only by very small changes in their initial
87 conditions. Such a large sample size ensures a more robust quantification of the simulated response to
88 sea ice and SST change in the face of internal variability. This, in turn, allows for a comparison of the
89 forced response across models to quantify model uncertainty and, through the identification of emergent
90 relationships across models and the application of observational constraints, to potentially narrow
91 uncertainties in the real-world response.

92

93 The purpose of this Perspective is to synthesise recent advances in understanding the causes and
94 consequences of polar amplification facilitated by the PAMIP. It is not our intention to provide a
95 comprehensive review of polar amplification, which can be found elsewhere^{6,7,12,13}. Instead, we draw
96 upon and summarise the latest developments in the field (focussing on work published since the

97 inception of PAMIP in 2019) to identify key advances, remaining questions and pathways to address
98 these, including the need for new coordinated model experiments.

99

100 **Causes of Arctic amplification**

101

102 The PAMIP experiments serve as an ideal testbed to further understand the processes responsible for
103 Arctic amplification. Jenkins et al. (2024) used the PAMIP experiments to show the roles of Arctic sea-
104 ice loss and global SST change in contributing to different local feedbacks and remote processes²¹.
105 Arctic warming in response to sea-ice loss maximises in winter, due to greatly enhanced oceanic heat
106 release. This produces lower tropospheric Arctic warming and triggers positive lapse rate, Planck, and
107 cloud feedbacks, leading to large Arctic amplification (**Fig. 2a,b**). Despite strong albedo feedback in
108 summer, atmospheric warming is muted in that season. In contrast, in response to global SST warming
109 absent sea-ice loss, enhanced atmospheric energy convergence into the Arctic is the dominant
110 contributor to Arctic warming, although Arctic amplification is relatively small compared to that in
111 response to sea-ice loss (**Fig. 2c,d**). Here, the lapse rate feedback is of diminished importance consistent
112 with SST-induced warming being larger aloft than at the surface. In all cases, the water vapor feedback
113 contributes to Arctic warming but opposes amplification due to larger tropical than Arctic moistening
114 under SST-induced warming with fixed Arctic sea-ice. These results reinforce that changes in surface
115 fluxes and feedbacks triggered by sea-ice loss are critical to explain the magnitude and seasonality of
116 Arctic amplification, while increased poleward energy transport produces weaker amplification in the
117 absence of sea-ice-related feedbacks. We emphasise that Fig. 2 presents a diagnostic decomposition of
118 the contributions to Arctic amplification and in reality, the effects of sea-ice loss and SST warming act
119 in combination and interact.

120

121 While the magnitude and seasonality of polar amplification are controlled by local processes and
122 feedbacks (**Fig. 2**), disproportionately large Arctic warming is a fundamental response of a moist
123 atmosphere to an increase in greenhouse gases^{22,23}. A preferential increase in tropical humidity, which
124 occurs due to the Clausius-Clapeyron relation, provokes an increase in poleward atmospheric latent
125 energy transport. This process explains polar amplification in the absence of sea ice and related polar
126 feedbacks^{4,24}, and the greater amplification when local and remote drivers combine²². PAMIP has
127 expanded understanding of these poleward energy transport changes by linking them to the processes
128 of sea-ice loss and SST changes. Audette et al. (2021) shows that Arctic sea-ice loss reduces northward
129 eddy-driven energy transport into the Arctic in all the PAMIP models, owing to the reduced near-surface
130 temperature gradient, that is balanced by a similar magnitude increase of latent energy transport due to
131 SST warming²⁵. This opposition in total energy transport mainly arises in the annual mean as the
132 influence of Arctic sea-ice loss is greatest in winter while that of SST warming is greatest in summer²⁶.
133 Hence, there is growing appreciation that different aspects of the poleward energy transport exhibit

134 different efficacies, and that the polar-cap-averaged energetic perspective risks obscuring the role of
135 remote processes in driving polar amplification.

136

137 Precipitation changes are also amplified in the Arctic relative to lower latitudes²⁷. The PAMIP
138 experiments have shown that sea-ice loss and SST warming both increase Arctic precipitation, but
139 through predominantly different mechanisms. SST warming increases precipitation in the Arctic²⁸,
140 consistent with the increase in moisture convergence in the same experiments^{25,26}, while sea-ice loss
141 also increases precipitation through increased evaporation^{21,28,29}. Since SST warming alone leads to
142 larger wetting at lower than higher latitudes, it is sea-ice loss that is critical for amplified wetting in the
143 Arctic²⁹.

144

145 **Robust remote responses to sea-ice loss**

146

147 Prior to the PAMIP, the precise nature of the remote circulation response to sea ice loss, including the
148 effect on the jetstream, storm tracks and dominant modes of variability (e.g., North Atlantic Oscillation,
149 Northern Annular Mode), as well as the mechanisms involved were elusive^{13,20}. This is due to a variety
150 of factors, including, but not limited to, inter-model differences, differences in experimental design,
151 and sampling errors due to large internal variability. The PAMIP has facilitated like-for-like comparison
152 across models (owing to identical boundary conditions) and better separation of the forced response
153 from internal variability (by requiring a minimum of 100 ensemble members), although even larger
154 ensembles appear to be necessary to confidently capture the stratospheric response³⁰⁻³² and changes in
155 regional weather extremes³³⁻³⁵, as discussed later. One important advance from the PAMIP has been to
156 identify robust large-scale troposphere circulation responses to future Arctic³⁶ and Antarctic sea-ice
157 loss³⁷. More specifically, the PAMIP experiments impose changes in sea ice concentration (hence, areal
158 coverage; Fig. 1) throughout the year and so, include shifts in the seasonal cycle, but not changes in sea
159 ice thickness.

160

161 Smith et al. (2022) examined the PAMIP ‘present-day’ baseline and future Arctic sea ice experiments
162 from 16 atmospheric models and showed a robust equatorward shift of the tropospheric westerly jet in
163 response to future Arctic sea-ice loss, albeit of varying magnitudes between models³⁶. A similar
164 equatorward shift of the wintertime jet was found in the southern hemisphere in response to future
165 Antarctic sea-ice loss, also robust in sign but of varying magnitude across models³⁷. The mechanisms
166 that lead to an equatorward jet shift are shown schematically in **Fig. 3**. Briefly, Arctic warming induced
167 by sea-ice loss reduces the high-latitude meridional temperature gradient (step 1 in **Fig. 3**), reducing
168 wind speed on the poleward flank of the jet (step 2; following the thermal wind relationship). The
169 weakened temperature gradient also reduces baroclinic eddy activity, weakening the storm track and in
170 turn, reducing the upward wave activity flux from the surface (consistent with reduced eddy-driven

171 poleward heat transport). An anomalous meridional circulation develops with ascent around 40–50°N,
172 poleward flow in the mid to upper troposphere, descent around 65–75°N, and equatorward flow near
173 the surface (step 3). Adiabatic cooling of the ascending branch acts to enhance the latitudinal
174 temperature gradient on the equatorward side of the jet, which strengthens the wind to the south of the
175 jet core (step 4). Taken together, the weakened westerlies to the north and strengthened westerlies to
176 the south imply an equatorward shift of the jet and storm activity (step 5). The shifted storm activity
177 leads to wave flux anomalies that reinforce the jet shift, through positive eddy feedback (step 6). The
178 magnitude of the response across models appears to depend on the strength of this atmospheric eddy
179 feedback, in both hemispheres^{36,37}. This zonal-mean perspective applies also for the Atlantic basin. In
180 the Pacific, while the anomalies are broadly similar, the climatological jet is located farther south, so
181 the westerly wind anomalies act to strengthen the Pacific jet rather than shift it equatorward³⁸.

182

183 Regionally, the winter North Atlantic jet shifts equatorward in response to Arctic sea-ice loss in most
184 models, with a few models showing a negligible response^{35,30,40}. However, models disagree on the sign
185 of simulated changes in the speed and tilt of the North Atlantic jet with most models showing negligible
186 change^{35,39,40}. In contrast, the North Pacific jet is simulated to strengthen in response to future Arctic
187 sea-ice loss, on average across models^{38,41}. The contrasting jet speed responses in the North Atlantic
188 and North Pacific can be understood by the more equatorward climatological position of the North
189 Pacific jet, such that the strengthened westerly wind in response to sea-ice loss occurs in the core of the
190 jet in the Pacific rather than on the equatorward flank, as simulated in the Atlantic^{38,42}.

191

192 Accompanying the jet shift is a weakening and equatorward shift of the North Atlantic storm
193 track^{34,38,43,44}. An eastward shift or extension of the North Pacific storm track is consistent with a
194 strengthened and extended jet^{38,41}. Across the whole Northern Hemisphere, in response to future Arctic
195 sea-ice loss there are fewer individual storms simulated, those storms are weaker, they propagate more
196 slowly, and have longer lifetimes⁴³, which can be understood as an energetic response to change in
197 surface albedo and weakened poleward atmospheric energy transport⁴⁵. However, over North America,
198 weather systems do not appear to stagnate, although they tend to be weaker³³. Other weather system
199 responses to Arctic sea-ice loss identified using the PAMIP experiments include an increase in winter
200 Scandinavian blocking^{35,46}, a reduction in cut-off-lows over Southern Europe⁴⁷, enhanced tropical
201 cyclone genesis over the eastern North Pacific⁴⁸, and shifts in the predominant locations of atmospheric
202 rivers⁴⁹, albeit with varying degrees of confidence (Fig. 4).

203

204 Drying over Northwest Europe and wetting over central Europe are found in response to future Arctic
205 sea-ice loss, closely linked to storm track changes^{34,35,39,50}. Warmer and fewer cold air outbreaks over
206 central and western North America are connected to the strengthened and extended North Pacific jet⁴¹.
207 Reduced meridional winds are linked to increased surface temperature persistence⁵¹. In addition to these

208 dynamically driven responses, advection across the weakened meridional temperature gradient causes
209 a reduction in day-to-day temperature variability and more rapid warming of cold extremes than of the
210 average temperature⁵², consistent with earlier findings⁵³. Cold days, which typically occur under
211 northerly flow, warm faster than the seasonal mean (and hot days), as northerly flow advects Arctic air
212 masses that are significantly warmed by sea-ice loss to lower latitudes⁵². Lo et al. (2023) found the 1-
213 in-20-year extreme cold events over northern mid-to-high latitudes warmed by up to 2.5°C for eastern
214 Canada and the northeast United States⁵⁴.

215

216 The varied and widespread responses to Arctic sea-ice loss, summarised visually in **Fig. 4**, have been
217 predominantly identified in winter, although some responses have been reported in summer^{48,55-58}. The
218 larger magnitude responses in winter than summer^{9,28,43}, arise due to the seasonality of the Arctic surface
219 energy budget response to sea-ice loss^{9,59}. Anomalous energy transfer from the ocean to atmosphere
220 maximises in the winter, as does the Arctic warming response, which is the trigger for the subsequent
221 effects on the atmospheric circulation and midlatitude weather and climate.

222

223 **Reducing and exploiting uncertainty**

224

225 Atmospheric internal variability has emerged as a common challenge in understanding the character of
226 the forced response to sea-ice loss, especially for applications involving regional climate and
227 extremes^{33-35,41,49,60} and the stratospheric polar vortex^{30-32,61,62}. The PAMIP protocol recommended a
228 minimum ensemble size of 100 members. However, Peings et al. (2021) found substantial
229 inconsistencies in the atmospheric circulation response to Arctic sea-ice loss among three separate 100-
230 member ensembles, indicating that ensembles of this size still contain a substantial imprint of internal
231 variability³⁰. Similarly, Sun et al. (2022) showed that the stratospheric polar vortex response in PAMIP
232 simulations is small compared to its internal variability³¹. Even the sign of the stratospheric circulation
233 response to sea-ice loss is uncertain³⁶, for reasons that remain unclear but are likely to include low
234 signal-to-noise and state dependence^{32,62,63}, and in turn influences the magnitude of the tropospheric
235 circulation response^{31,32,62,63}. Ye et al. (2024) is unique in conducting very large ensembles (~2000
236 members) with two models following the PAMIP protocol and found that several hundred members (>
237 400) are needed to robustly estimate the seasonal-mean large-scale circulation response, and a thousand
238 or more members for regional climate extremes³⁴. This could imply the real-world response to sea-ice
239 loss is weak^{15,36,37,63}. However, the weak simulated responses in the PAMIP experiments could be a
240 symptom of a broader signal-to-noise problem in models⁶⁴ and thus, the real-world response may be
241 larger than models suggest.

242

243 Internal variability appears insufficient to fully explain the model spread in the magnitude of the
244 tropospheric circulation response^{36,37,63}, suggesting this response is model dependent. One factor that

245 may lead to model dependence is the strength of atmospheric eddy feedback, which describes the
246 reinforcing interaction of transient eddies on the time-mean flow. Models exhibiting stronger eddy
247 feedback simulate a stronger tropospheric circulation response to Arctic and Antarctic sea-ice loss^{36,37}.
248 Understanding the causes of model spread is valuable not only for interpreting model responses but also
249 for reducing uncertainty in projections through an emergent constraint—an inter-model relationship
250 linking an observable aspect of the climate to the response to sea-ice loss. One example is the
251 relationship between the simulated eddy feedback and the jet response to sea-ice loss across the PAMIP
252 models^{36,37}. The observed estimate of eddy feedback is larger than any of the modelled values, which
253 suggests that models systematically underestimate the atmospheric circulation response to Arctic sea-
254 ice loss. While there are suggestions that simulated eddy feedback is too weak owing to coarse model
255 resolution⁶⁵, it remains unclear if the response to sea-ice loss is dependent on model resolution⁶¹.
256 Constraining by the observed eddy feedback increases the equatorward jet shift in response to Arctic
257 sea-ice loss by 40% compared to the multimodel mean, becoming of larger magnitude than the
258 simulated poleward shift in response to SST warming³⁷.

259
260 Additionally, differences in models' unperturbed climate - often referred to as the basic state - can also
261 influence the response to sea-ice loss^{62,63,66}. The basic state of the winds in the so-called “neck region”,
262 located in the upper troposphere-lower stratosphere between the latitudes of the subtropical jet and polar
263 jet, determines whether the stratospheric pathway is active, and thereby affects the magnitude of the
264 tropospheric circulation response to Arctic sea-ice loss^{62,63,67}. Sigmond and Sun (2025) propose that the
265 jet latitude response to future sea-ice loss can be constrained by the observed neck region winds, more
266 than halving the model uncertainty⁶³. The neck wind constraint yields an estimated real world jet shift
267 that closely matches the unconstrained multi-model mean response, implying that models do not
268 systematically underestimate the jet shift⁶³, unlike the constraint based on observed eddy feedback^{36,37}.
269 These contrasting findings underscore the need to test the robustness of such emergent constraints using
270 independent ensembles. Stratosphere-troposphere coupling also plays a central role in mid-tropospheric
271 Arctic warming in response to sea-ice loss⁶⁸, and this deep warming, can further enhance the
272 tropospheric circulation response⁶⁹.

273
274 Slow modes of natural climate variability can alter the ‘basic state’ and thereby, modulate the response
275 to sea-ice loss. Labe et al. (2019) found that the atmospheric circulation response to Arctic sea-ice loss
276 was stronger during the easterly phase of the Quasi-Biennial Oscillation (QBO) than its westerly
277 phase⁷⁰. This led one group, the UK Met Office, to perform separate PAMIP ensembles for different
278 QBO phases. The stratospheric polar vortex weakened in response to Arctic sea-ice loss during easterly
279 QBO but not during westerly QBO^{32,71,72}. The different QBO states across the PAMIP models may
280 contribute to the model differences in the responses of the stratospheric polar vortex³². There is also
281 evidence that the phase of the El Niño-Southern Oscillation (ENSO), Pacific (Inter-) Decadal

282 Variability (PDV), and Atlantic Multidecadal Variability (AMV) all influence the atmospheric response
283 to Arctic sea-ice loss^{30,72-76}. These modes of variability rely on coupling between the ocean and
284 atmosphere. A recent study by Cvijanovic et al. (2025) suggests that the North Pacific response to Arctic
285 sea-ice loss is strongly influenced by ocean–atmosphere coupling in the tropics⁷⁷. Models that prescribe
286 tropical SSTs — thereby lacking ocean-atmosphere coupling - tend to simulate a strengthened Aleutian
287 Low over the North Pacific in response to sea-ice loss³⁶, as do many coupled model experiments¹⁷, but
288 in the study of Cvijanovic et al. (2025), the inclusion of coupling resulted in weakened Aleutian Low⁷⁷.
289 We will return to the potential importance of ocean coupling and the limitations of prescribing
290 climatological SST (i.e. lacking internal ocean variability) later.

291

292 **Interpreting climate projections**

293

294 Confidence in climate projections is increased when the underpinning physical mechanisms are well
295 understood. Since sea-ice loss and SST warming may affect the atmospheric circulation in different
296 ways and through different mechanisms, it is of value therefore, to consider the responses to these
297 factors separately, which the PAMIP experiments has facilitated. The effect of SST warming dominates
298 over most of the globe, outside the Arctic^{9,28} (**Fig. 5**). However, the effect of sea-ice loss is as important,
299 if not more, than SST warming for response of the winter North Atlantic circulation^{28,35,38} (**Fig. 5**) and
300 East Asian summer monsoon⁵⁸.

301

302 Separation of the responses to SST warming and sea-ice loss has been particularly useful to uncover
303 the mechanisms driving the extratropical circulation changes. Using the PAMIP experiments, Yu et al.
304 (2024) demonstrated a significant regional weakening of the westerlies over the high-latitude North
305 Atlantic and strengthening over the midlatitude North Atlantic in response to Arctic sea-ice loss²⁸,
306 consistent with the zonal-mean response³⁶, while ocean warming led to a broadly opposite response²⁸
307 (**Fig. 5**). This regional ‘tug-of-war’ in the Atlantic is also seen for storm track activity^{38,50}, but not in the
308 Pacific^{28,38,41}. Hay et al (2025) showed that more equatorward average location of the Pacific jet and the
309 geography of the North Pacific results in circulation responses to sea-ice loss and ocean warming that
310 reinforce rather than oppose each other³⁸, in contrast to the zonally-averaged response³⁶.

311

312 The role of Arctic sea-ice loss on cold winter extremes, in the context of a warming climate, has been
313 the subject of debate for the past few decades¹²⁻¹⁵. The PAMIP has facilitated a clearer picture on the
314 relative roles of SST warming and Arctic sea-ice loss on mid-latitude extreme cold events. While Arctic
315 sea-ice loss leads to more frequent or severe cold extremes in some simulations in limited midlatitude
316 regions^{19,54}, these changes are small and overwhelmed by strong warming of extreme cold events over
317 the midlatitudes in response to ocean warming^{46,54}. However, sea-ice loss plays a more dominant role
318 than SST warming in the reduction of temperature variability over North America⁵².

319

320 It is worth noting that the PAMIP experiments are based upon one scenario of sea-ice loss and SST
321 warming, but model projections suggest a range of outcomes. In the PAMIP experiments, comparing
322 the annual-mean future and present-day states, there is a loss of 3.0 million km² of sea ice cover for a
323 global SST warming of 1.4 C, equating to approximately 2.1 million km² of sea-ice loss per degree
324 Celsius of global SST warming. Model projections show sea-ice sensitivities of less than 1 to more than
325 4 million km² per degree of global SST warming³⁵. Under the assumptions of linear additivity and
326 scalability²⁹, the PAMIP-derived responses to sea-ice loss and SST warming can be scaled and summed
327 to illustrate different storylines. Storylines are a concept to help communicate uncertainty in climate
328 change⁷⁸ and describe distinct but possible, physically self-consistent pathways. Here, the storylines
329 describe plausible combinations of future global warming and sea-ice loss (**Fig. 6**), which are closely
330 related to model uncertainty in the magnitude of Arctic amplification, expressed in terms of the
331 magnitude of sea-ice loss per degree of global warming. The high sensitivity case describes a future
332 with greater sea-ice loss relative to global warming, and the low sensitivity case describe a world with
333 less sea-ice loss relative to global warming. Arctic warming, Arctic amplification (2.7 and 4.2 in low
334 and high sensitivity cases, respectively) and Arctic wetting (0.12 and 0.18 mm/day, respectively)
335 increase with greater sea-ice sensitivity to global warming (**Fig. 6**). The magnitude and pattern of the
336 circulation response at lower latitudes are also sensitive to the storyline. For example, the North Atlantic
337 jet shifts marginally poleward (0.1° latitude) in the low sea-ice sensitivity storyline and equatorward (-
338 0.5°) in the high sea-ice sensitivity storyline. Given that models appear to underestimate the observed
339 sea-ice sensitivity⁷⁹, the high sea-ice sensitivity storyline may be the most plausible.

340

341 **Future directions**

342

343 To close, we highlight some future research opportunities.

344

345 **Hemispheric asymmetry.** First, polar amplification exhibits notable hemispheric asymmetry, with the
346 Arctic experiencing markedly stronger warming than the Antarctic². Several mechanisms underpinning
347 this disparity have been proposed, including a buffering effect by the presence of a deep and cold
348 Southern Ocean, which limits surface warming through effective oceanic heat uptake⁸⁰, and high
349 topography in the Antarctic that inhibits temperature longwave feedbacks¹. At a longer timescale,
350 oceanic heat transport contributes to this hemispheric asymmetry, as the AMOC facilitates poleward
351 heat transfer and local feedbacks in the Northern Hemisphere⁸¹, whereas analogous mechanisms are
352 weaker in the Southern Hemisphere. Beyond temperature change, Arctic precipitation amplification -
353 driven by increased moisture availability and enhanced poleward moisture transport that remains
354 energetically constrained^{27,82} - enhances Arctic hydrological sensitivity and serves as another
355 manifestation of polar amplified climate change. In sum, the interplay between sea-ice feedbacks, ocean

356 dynamics, and atmospheric processes leads to pronounced and hemispherically asymmetric polar
357 climate responses. We urge more process-based analysis to improve our understanding of asymmetries
358 in the two poles and their implications for global climate. This need is particularly urgent given the
359 unprecedented Antarctic sea-ice loss since 2016, which may signal a transition to a new Antarctic
360 climate regime⁸³⁻⁸⁵, for which the associated atmospheric response, both locally and globally, remains
361 relatively unknown^{86,87}. Advancing our understanding of these processes is critical for anticipating
362 future climate impacts.

363

364 **Experimental protocols.** Within the framework of the PAMIP, a variety of experimental strategies have
365 been employed to advance the understanding of polar climate processes and their remote influences,
366 including prescribing ocean surface boundary conditions (in atmosphere-only experiments) and
367 nudging or albedo reduction techniques (in coupled atmosphere-ocean-ice experiments). Ocean
368 coupling appears to modulate the response to sea-ice loss and aspects of the response may be
369 underestimated by prescribing sea ice and thereby inhibiting ocean-ice-atmosphere interaction^{42,44,86,88-}
370 ⁹¹. The PAMIP coupled experiments simulate enhanced weakening of the winter storm tracks in
371 response to sea-ice loss, compared to the uncoupled experiments⁴⁴, and deeper Arctic warming and
372 enhanced strengthening of the Siberian High⁹¹. However, concerns have been raised that the methods
373 used to constrain sea ice in coupled modes might lead to spurious responses⁹²⁻⁹⁵. New methods for
374 addressing these issues are necessary for developing protocols for the next phase of the PAMIP. For
375 example, the climate impacts of spurious heating associated with current nudging techniques can be
376 quantified, and hence removed, through additional model simulations⁹³ or through post processing via
377 pattern scaling⁹⁵. Alternatively, regional CO₂ forcing may offer a pathway for isolating Arctic change
378 with fewer unintended consequences and is technically more straightforward to implement across all
379 climate models than nudging^{96,97}. Other methods, such as those involving modifications to sea ice and
380 snow-over-sea-ice parameters^{77,85,98} or atmosphere-ocean-ice coupling⁹⁹, have been proposed and may
381 reduce any spurious responses. The most utilised experiments, the year-long atmosphere-only
382 simulations, not only omit ocean coupling, but also lack ocean internal variability (as climatological
383 boundary conditions are prescribed) and processes acting on interannual timescales. Transient
384 experiments, although more costly to run, allow for better sampling of internal variability and response
385 timescales. Additionally, considering different initial states in the presence of sea ice forcings, such
386 sampling opposite phases of the QBO, ENSO, AMV or PDV, would further enhance our understanding
387 of the state dependency (i.e. nonlinearity) of responses to sea-ice loss⁷⁰⁻⁷⁶. Greater coordination of
388 atmospheric and ocean initial conditions across modelling protocols may help to explain apparent model
389 discrepancies that remain hard to reconcile, for example, the divergent stratospheric polar vortex
390 responses across models³².

391

392 ***New models and experiments.*** High-resolution models, either globally or with regional grid refinement,
393 better capture fine-scale processes and therefore further improve the representation of sea-ice-
394 atmosphere interactions and feedbacks^{29,100} and simulate stronger circulation responses to SST
395 anomalies¹⁰¹. However, whether the atmospheric response to sea-ice loss is sensitive to model resolution
396 remains unclear^{29,32,61} and warrants further investigation. Additionally, saving more diagnostic variables
397 at high temporal frequency (daily or 6-hourly), would provide opportunities to examine processes at
398 the scale of weather events. New experiments with different prescribed boundary conditions (e.g., larger
399 global warming and sea-ice loss to increase the signal-to-noise ratio, and different storylines of sea ice
400 and SST change) may also yield important insights. Repeating the existing experiments with newer
401 models, including at higher resolution, would be valuable to test the robustness of emergent constraints
402 with independent ensembles. Idealized simulations also continue to serve as a useful tool for conceptual
403 understanding, providing controlled environments to disentangle nonlinear interactions and benchmark
404 model behaviour across scales^{1,4,21,22,24,45,51,67,94,102}. Such modelling experiments offer opportunities to
405 target remaining questions regarding the causes of polar amplification, such as the interpretation of the
406 lapse rate feedback in polar regions. More recently, Artificial Intelligence and machine learning-based
407 climate models¹⁰³ offer new avenues to simulate complex climate dynamics with enhanced
408 computational efficiency, although their capacity to fully capture sea-ice thermodynamics and large-
409 scale coupling remains under assessment.

410
411 ***Enhanced collaboration.*** We encourage the use of PAMIP simulations for novel and varied
412 applications. Examples include interpreting the implications of incomplete Arctic sea-ice recovery
413 under CO₂ removal¹⁰⁴, exploring the role of sea-ice-related feedbacks in sustaining Barents Sea ice
414 loss¹⁰⁵, identifying the surface signature of stratospheric variability¹⁰⁶, and quantifying the effects of
415 projected sea-ice loss on cold-related mortality¹⁰⁷, Greenland ice sheet mass balance⁵⁷, Yangtze River
416 Basin heatwaves¹⁰⁸ and eastern Siberian wildfires¹⁰⁹, amongst others. Expanding collaborations with
417 other research communities will be critical for the next phase of PAMIP. Coordination between future
418 PAMIP and other model intercomparison projects could enhance process-based understanding. Joint
419 efforts with the climate feedback, atmosphere-ocean-ice dynamics, and polar process communities
420 could further enrich the interpretation of results. Side-by-side analysis of modelling experiments within
421 dynamical and radiative feedback frameworks will provide deeper insights into the processes and
422 mechanisms by which a climate response to sea ice loss is provoked. Closer ties with the polar
423 observational community would support robust model–observation comparisons, which likely needs
424 better experimental designs and additional high-frequency model outputs.

425

426 In summary, the PAMIP has facilitated a plethora of studies (not all are cited here), but arguably the
427 biggest collective advance has been to reveal robust tropospheric responses to Arctic sea-ice loss, that
428 whilst generally small compared to simulated internal variability, comprise a non-negligible, and for

429 some regions and variables, large (relative to that of SST warming), contribution to projected climate
430 change. Further, it has uncovered and explained responses that are dependent on model physics and/or
431 background states, which provide pathways to constrain the real-world response. Looking forward,
432 there are opportunities, through novel analyses of existing experiments, new simulations and model
433 versions, and enhanced collaborations, to gain further insights into the causes and consequences of polar
434 amplification.

435

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451

452 **Data availability**

453 All PAMIP data analysed here is freely available at the Earth System Grid Federation
454 (<https://esgf.github.io>).

455

456 **Author Contributions**

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473

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475

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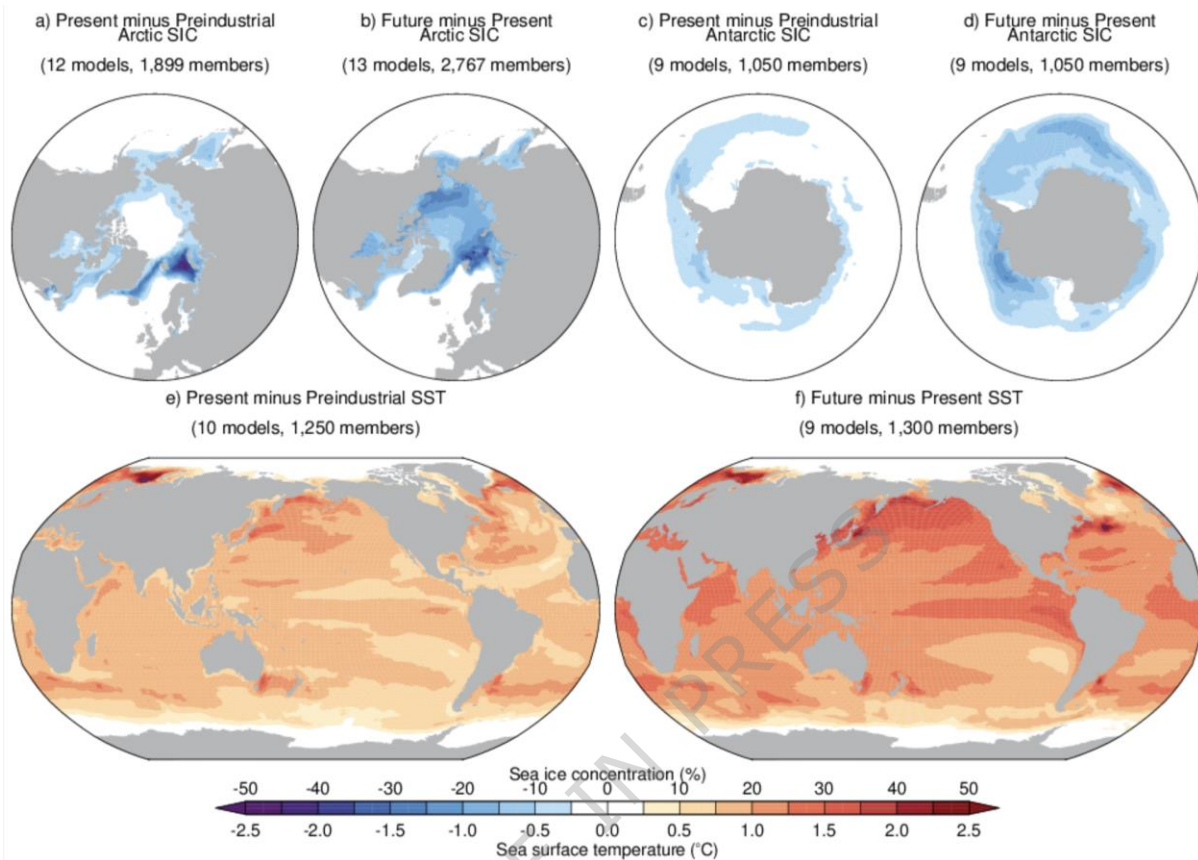
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843 **Figures**

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846 **Figure 1: Differences in the specified sea ice and SST between selected PAMIP experiments.**

847 Differences in the prescribed annual-mean sea ice concentration (SIC) and sea surface temperature

848 (SST) between PAMIP experiments to quantify the effects of (a) past and (b) future Arctic sea-ice loss;

849 (c) past and (d) future Antarctic sea-ice loss; and (e) past and (f) future SST change. The number of

850 models providing each experiment combination and the total number of members, for each year-long

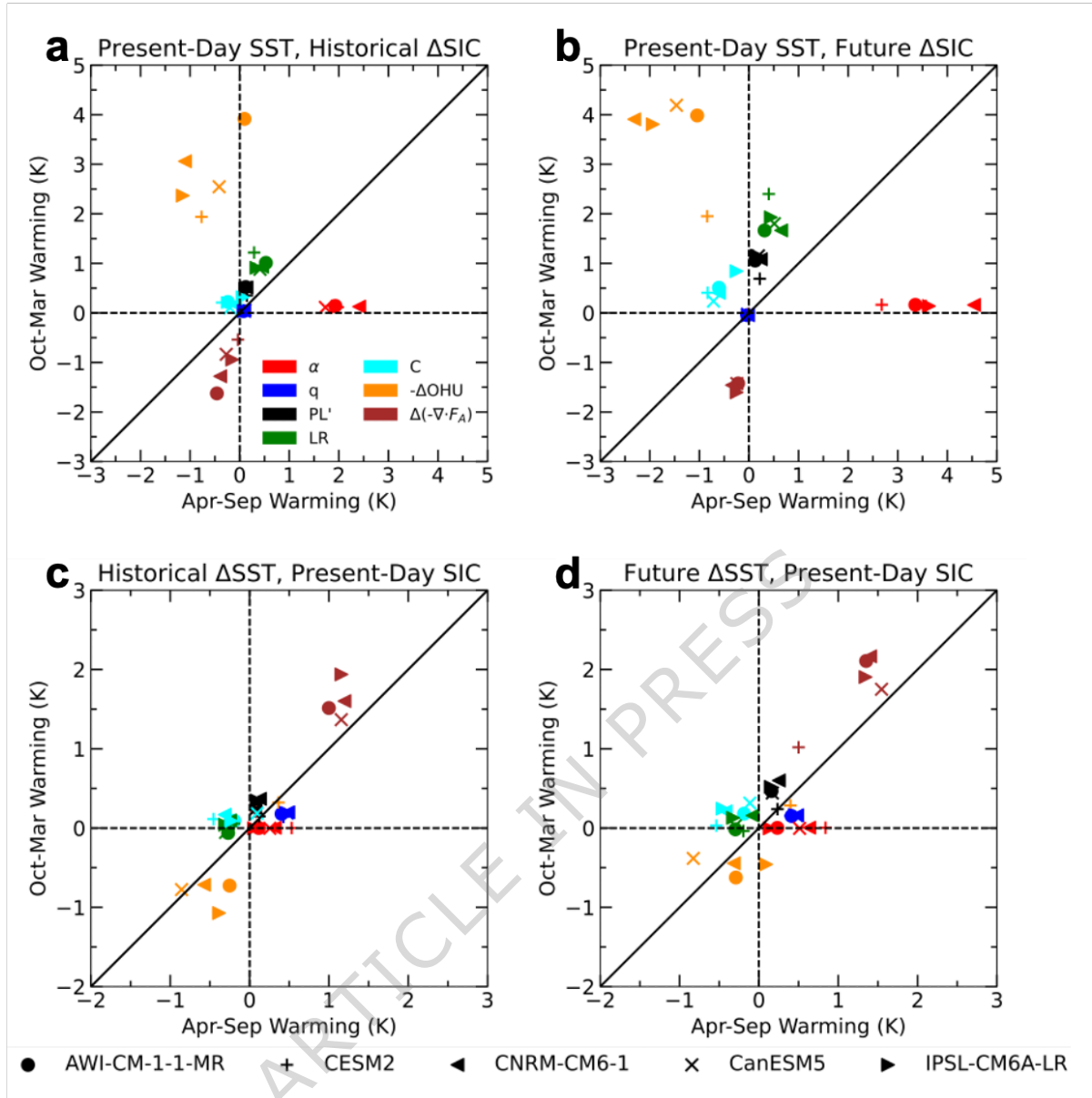
851 time-slice experiment, across all models (publicly available on the Earth System Grid Federation) are

852 provided. The present-day SIC and SST are representative of the period 1979-2008. The pre-industrial

853 and future periods correspond to when the global mean temperature was 0.6°C cooler and 1.4°C warmer854 than present-day (2°C warmer than preindustrial), respectively.

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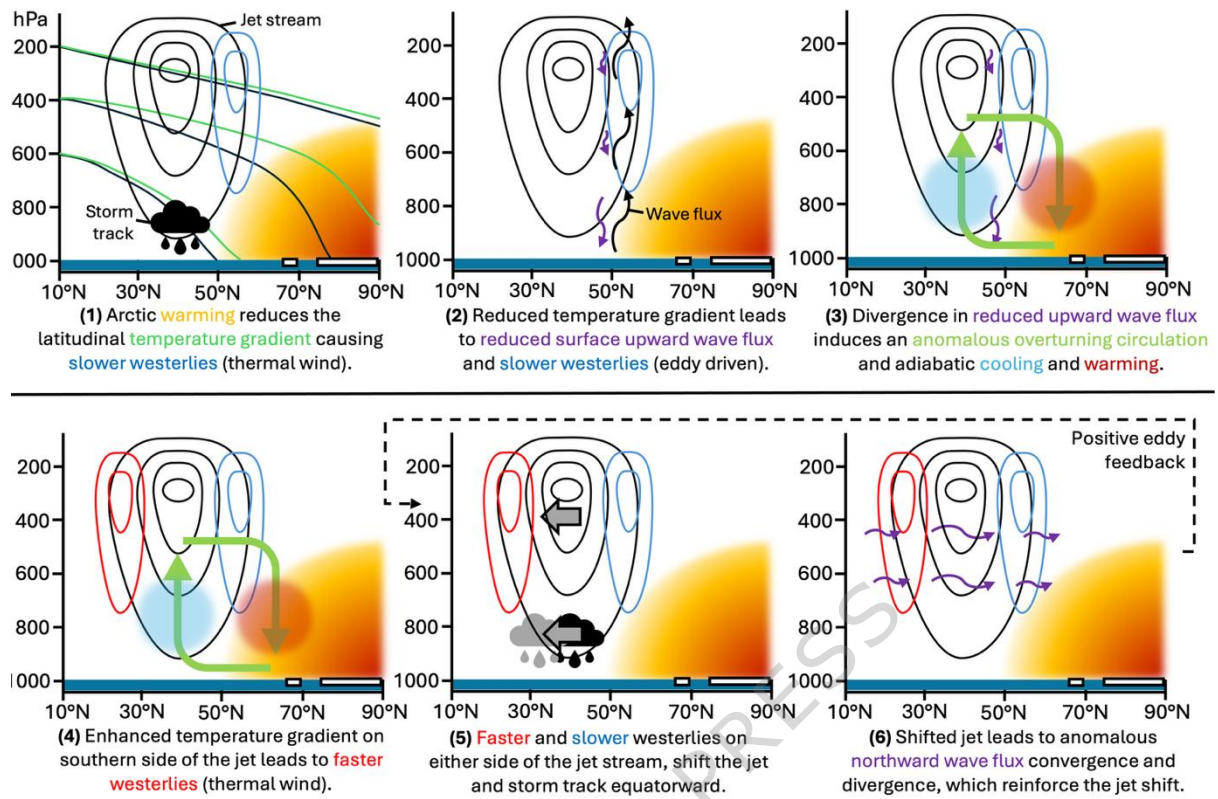
858 **Figure 2: Contributions to seasonal Arctic warming from various processes and feedbacks.** Arctic

859 warming contributions (in K) in the warm half-year (April-September) vs. cold half-year (October-

860 March) from the surface albedo (α , red), water vapor (q ; blue), Planck (PL' ; black), lapse rate (LR;861 green) and cloud (C ; cyan) feedbacks, and changes in oceanic heat release ($-\Delta OHU$; orange) and862 atmospheric energy convergence ($\Delta(-\nabla \cdot F_A)$; maroon) in response to (a) past and (b) future Arctic sea-863 ice loss, and (c) past and (d) future SST warming. Adapted from Jenkins et al. (2024)²¹.

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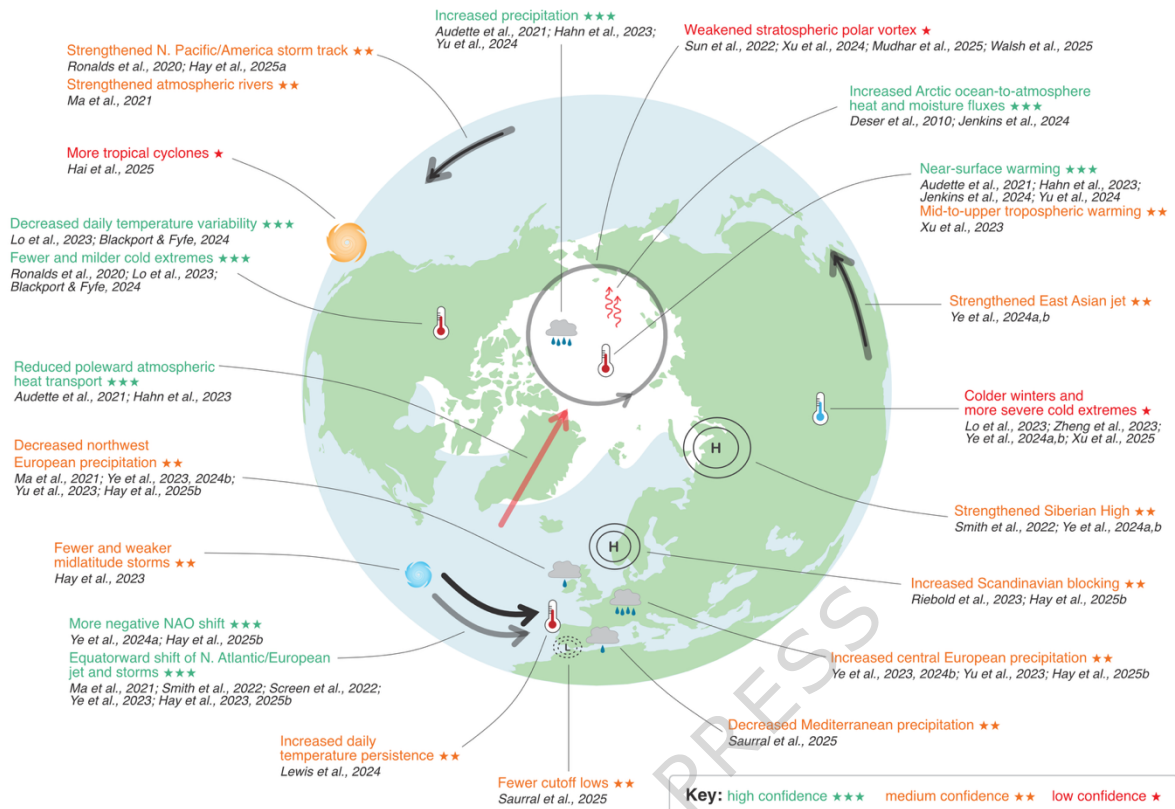


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867 **Figure 3: Schematic representation of the mechanisms of the jet shift in response to Arctic sea-**
 868 **ice loss.** Features depicted in black represent the climatological state whereas those shown in colour
 869 represent the response to sea-ice loss. See Smith et al. (2022)³⁶ for further details.

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873 **Figure 4: Regional effects of Arctic sea-ice loss.** Visual summary of the predominantly wintertime

874 effects of Arctic sea-ice loss across the Northern Hemisphere, as simulated in the PAMIP experiments.

875 The assessed confidence is based on expert judgement, considering the level of consistency between

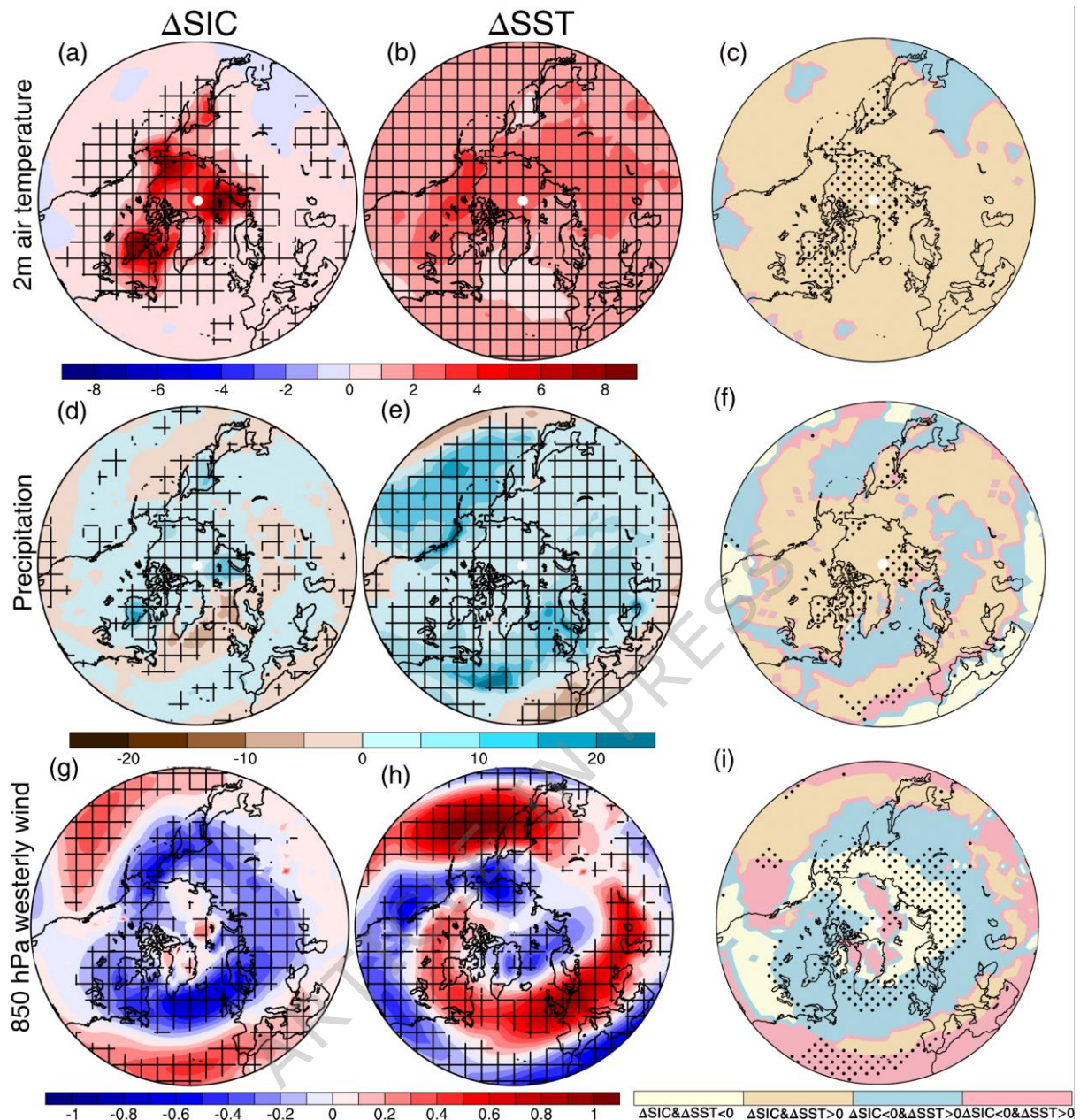
876 studies/models/experiments, knowledge of the mechanisms involved, and evidence that the simulated

877 response is representative of that in the real world. The locations of features are approximate. The

878 supporting references are examples and are not intended to provide a comprehensive list of all studies

879 that have reported on each effect.

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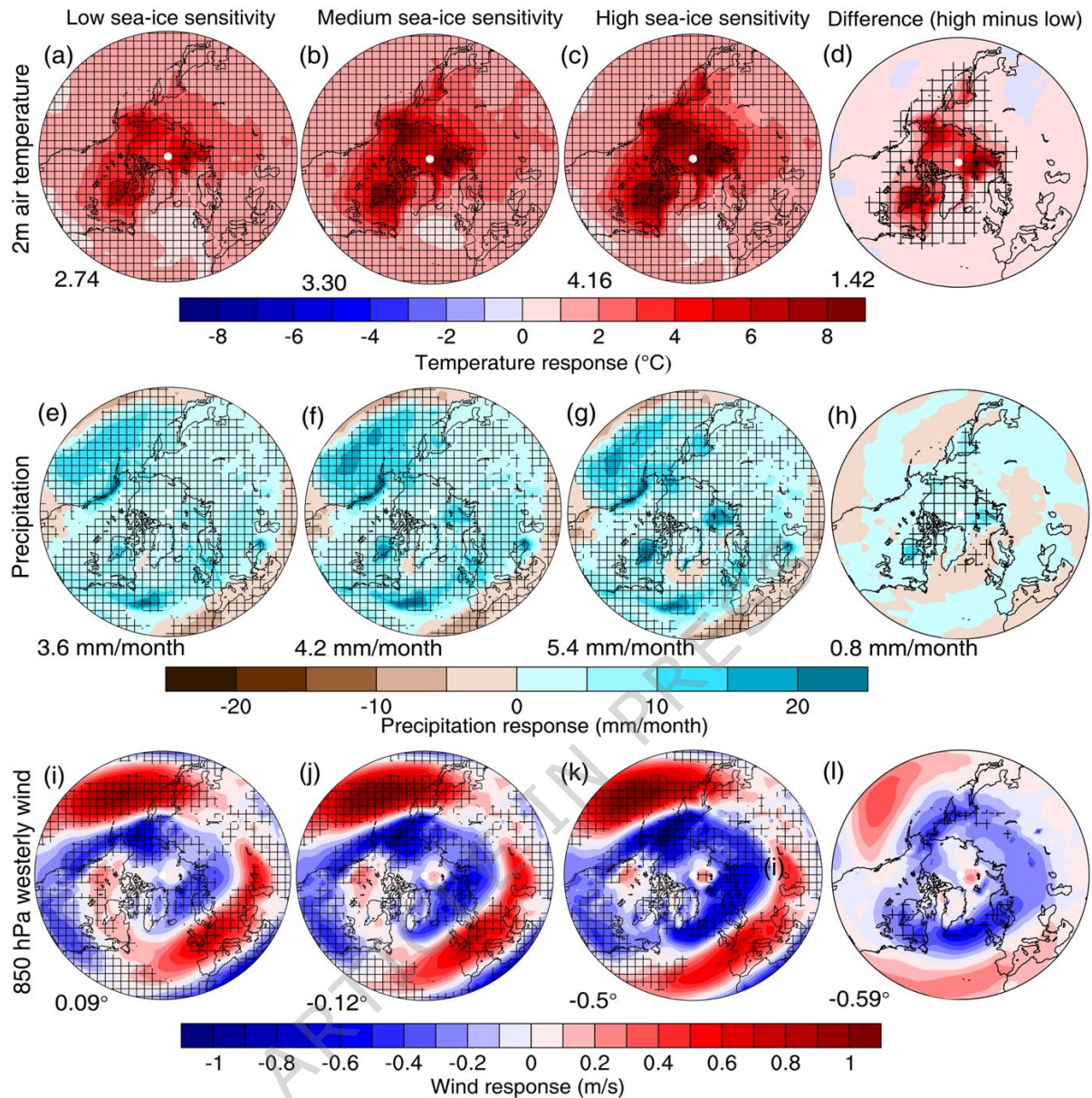
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Figure 5. Distinct responses to sea-ice loss and SST warming. Multimodel-mean winter near-surface air temperature response to (a) future Arctic sea-ice loss and (b) future SST warming, and (c) their relative signs and magnitudes. Hatching denotes statistical significance at the 90% confidence level. In (c), yellow and orange colors denote the responses reinforce each other, whereas blue and red colors denote the responses oppose each other, and stippling shows where the response to sea-ice loss is of greater magnitude than that to SST warming. (d-f) As a-c, but for precipitation. (g-i) As a-c, but for 850 hPa westerly wind. Adapted from Yu et al. (2024)²⁸.



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891 **Figure 6. Storylines of projected climate change.** (a-c) Summed multimodel winter near-surface air
 892 temperature responses to future Arctic sea-ice loss and SST warming, for three different storylines: low
 893 sea-ice sensitivity (1.5 million square kilometers of sea-ice loss per degree Celsius of global-mean SST
 894 warming), medium sea-ice sensitivity (2.7 million $\text{km}^2/\text{°C}$) and high sea-ice sensitivity (3.8 million
 895 $\text{km}^2/\text{°C}$). The low and high sensitivity storylines are calculated by linearly scaling the PAMIP responses
 896 prior to their summation; the medium sea-ice sensitivity storyline uses the unscaled PAMIP responses.
 897 (d) The difference between the high and low sensitivity storylines. (e-h) As a-d, but for precipitation.
 898 (i-l) As a-d, but for 850 hPa westerly wind. Hatching denotes statistical significance at the 90%
 899 confidence level. Numbers in the lower left corner denote Arctic amplification in a-c, Arctic-mean
 900 precipitation change in e-g, and the North Atlantic jet latitude change in i-k. Adapted from Yu et al.
 901 (2024)²⁸ and Hay et al. (2025)³⁵.

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Editorial summary:

The Polar Amplification Model Intercomparison Project reveals robust jet stream and storm track responses to Arctic sea-ice loss that are separable from internal variability, and the model diversity provides pathways to constrain the real-world response.

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