

Influence of Arctic Sea-Ice Loss in Autumn Compared to that in Winter on the Atmospheric Circulation

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Key Points:

- Coupled ocean-atmosphere model experiments are forced with different seasonal cycles of Arctic sea-ice loss.
- Year-round sea-ice loss causes an equatorward jet shift and a negative North Atlantic Oscillation response in winter.
- Autumn sea-ice loss does not affect the winter atmospheric circulation, implying winter response is driven by winter ice loss.

18 **Abstract**

19 There is growing evidence that Arctic sea-ice loss affects the large-scale atmospheric circulation.
20 Some studies suggest that reduced autumn sea ice may be a precursor to severe midlatitude
21 winters. Here we use coupled ocean-atmosphere model experiments to investigate the extent to
22 which the winter atmospheric circulation response to Arctic sea-ice loss is driven by sea-ice loss
23 in preceding months. We impose different seasonal cycles of sea ice by using various
24 combinations of sea-ice albedo parameters. Year-round sea-ice loss causes an equatorward
25 migration of the eddy-driven jet and a shift towards the negative phase of the North Atlantic
26 Oscillation in winter. However, these circulation changes are not found when sea ice is reduced
27 only in late summer and autumn, despite high latitude warming persisting into the winter. Our
28 results imply that the winter atmospheric circulation response to sea-ice loss is primarily driven
29 by sea-ice loss in winter rather than in autumn.

30 **Plain Language Summary**

31 Arctic sea-ice loss is already affecting the inhabitants and wildlife of the Arctic. There is also
32 concern that sea-ice loss might be impacting weather and climate elsewhere. Past studies have
33 proposed that Arctic sea-ice loss can affect the jet stream, which has a big influence on weather
34 and climate in mid-latitudes. It remains unclear however, if the jet stream is more strongly
35 affected by sea-ice loss in autumn or by sea-ice loss in winter. This is an important question, as if
36 winter weather was strongly affected by autumn sea ice, severe winters might be predictable a
37 few months in advance. We have run experiments with a climate model in which we artificially
38 reduce the sea ice in order to study the effects of sea-ice loss on the jet stream. An experiment
39 with autumn and winter sea-ice loss shows a weakening and southward shift of the jet stream in
40 mid-latitudes. However, these changes are not seen in an experiment with sea-ice loss in autumn

41 but not in winter. We conclude that the sea-ice loss in winter has a bigger effect on the jet stream
42 than does sea-ice loss in autumn.

43 **1 Introduction**

44 One of the most striking features of recent climate change is the rapid reduction of Arctic sea ice
45 cover (Stroeve et al., 2012). There is growing evidence that sea-ice loss, and the warming it
46 causes, has the potential to impact the atmospheric circulation in mid-latitudes, particularly in
47 winter (Cohen et al., 2014; Vavrus, 2018). A common approach to isolate the impact of sea-ice
48 loss on the mid-latitude atmospheric circulation is to perform model experiments in which sea
49 ice is artificially reduced. While there is disagreement between such experiments run with
50 different models and different experimental designs, some common responses have emerged
51 (Screen et al., 2018). Robust responses include a weakening of the zonal wind on the poleward
52 side of the mid-latitude jet and a shift towards the negative phase of the North Atlantic
53 Oscillation (NAO) during winter.

54
55 An open question is to what extent these winter atmospheric circulation changes are a lagged
56 response to sea-ice loss in the summer and autumn, or whether they are caused by concurrent
57 sea-ice loss in winter. This has implications for understanding the underlying physical
58 mechanisms and for seasonal predictions. Autumn Arctic sea ice has been shown to be a
59 potential predictor of the winter NAO in both dynamical (Scaife et al., 2014) and statistical
60 forecasts (Hall et al., 2017; Wang et al., 2017). Francis et al., (2009) identified links between
61 observed September sea ice and the large-scale atmospheric circulation and precipitation patterns
62 during winter. They proposed that the winter atmosphere ‘remembers’ the September sea ice
63 through changes in lower troposphere stability, cloud cover and changes in poleward thickness

64 gradients. However, these statistical links between autumn sea ice and winter atmospheric
65 circulation cannot isolate cause and effect. Several studies have isolated the impacts of low
66 September sea ice on autumn atmospheric circulation in model experiments (Blüthgen et al.,
67 2012; Porter et al., 2012; Strey et al., 2010), but few have examined the lagged response into
68 winter.

69

70 Sun et al. (2015) compared the response to autumn (September-November) sea-ice loss versus
71 year-round sea-ice loss in atmosphere-only model experiments. They found that autumn sea ice
72 had little effect on early and mid-winter atmospheric circulation, but did cause a negative NAO
73 response in late winter via a stratospheric mechanism. The experiments of Sun et al. (2015) had
74 prescribed ocean surface boundary conditions and therefore, neglect coupling between the
75 atmosphere and ocean that has been shown to modify the atmospheric response to sea-ice loss
76 (Blackport & Kushner, 2018; Deser et al., 2015, 2016). Considering the potential for a lagged
77 winter response to autumn sea-ice loss, coupling to the ocean may allow for additional
78 mechanisms for delayed responses to sea-ice loss. Warming caused by sea-ice loss in late
79 summer and autumn may persist into the winter, through feedbacks with the ocean and sea ice
80 (Holland et al., 2010; Serreze & Francis, 2006; Stroeve et al., 2012), which could in turn impact
81 the atmospheric circulation.

82

83 In this study, we explore the question of whether sea-ice loss in late summer and autumn plays a
84 role in driving the wintertime atmospheric circulation response to sea-ice loss, using coupled
85 atmosphere-ocean climate model simulations. We use different combinations of sea ice albedo
86 parameter modifications to conduct two experiments with differing seasonal cycles of sea-ice

87 loss: One with year-round sea-ice loss and the other with sea ice extent (SIE) reduction only in
88 later summer and autumn. This allows us to cleanly isolate the impact the influence of late
89 summer and autumn sea-ice loss on the winter atmospheric circulation.

90 **2 Model and Experiments**

91 We use the HadGEM2-ES (Martin et al., 2011) coupled ocean-atmosphere model, which was
92 part of the Coupled Model Intercomparison Project 5 (CMIP5). The atmospheric model is the
93 Unified Model version 6.6.3 which has a horizontal resolution of 1.25° latitude by 1.875°
94 longitude and 38 vertical levels up to 10hPa. The ocean model is NEMO with a horizontal
95 resolution of approximately 1°C (increasing to 0.3° at the equator) and has 40 vertical levels.

96
97 We have performed four large ensemble model experiments: a present-day control ensemble, a
98 2°C global warming ensemble and the two aforementioned ensembles with reduced sea ice. The
99 present-day control ensemble consists of 400 realisations of 5 years in length, differing only in
100 their initial conditions, and forced with the RCP8.5 emissions scenario from 2008-2012. This
101 period was chosen as it is when the global mean temperature in the model matched the observed
102 global mean temperature in 2011-2015 from HadCRUT4. Initial conditions were generated by
103 branching 16 realisations from available HadGEM2-ES CMIP5 simulations at year 1990 and
104 forcing them with historical and then RCP8.5 forcing until 2008. Each of these 16 realisations
105 were branched off into 25 realisations on 1st January 2008 by initialising the atmosphere with
106 conditions from Jan 1st to Jan 25th. Due to the longer time scales of ocean variability, each of
107 these 25 ensemble members may not be independent of each other, but the 16 initial ocean states
108 should be. We also performed an ensemble similar to the present-day ensemble, but with RCP8.5
109 forcing from years 2036-2040 – when this model reaches 2°C warming above pre-industrial

110 levels. Here this ensemble, which we call “2C”, is only used to set the target for the ensembles
111 with reduced sea ice.

112

113 Next, we performed two additional ensembles that were identical to the present-day control
114 ensemble, but with modified sea ice albedo. Sea ice albedo reduction has been previously used to
115 examine the impacts of sea-ice loss on the climate (Blackport & Kushner, 2016, 2017; Scinocca
116 et al., 2009); however, the modifications could be unphysical (Screen et al., 2018) and result in
117 an unrealistic seasonal cycle with too much ice-loss in summer and too little ice-loss in winter
118 (Deser et al., 2015). To minimize this issue and to achieve different seasonal cycles of sea-ice
119 loss, we modify two albedo parameters (albedo of cold deep snow on top of sea ice and albedo of
120 snow-free ice), which have different impacts on the seasonal cycle of sea ice extent. While
121 lowering each parameter results in more sea-ice loss in summer compared to winter, the seasonal
122 difference is far greater for the snow-free ice albedo. These differences likely arise because there
123 is less snow cover on sea ice during the summer than winter.

124

125 In the first sea-ice loss ensemble, which we call “2Cice”, we decreased the albedo of cold deep
126 snow on top of sea ice from 0.80 to 0.05 and increased the albedo of snow-free ice from 0.61 to
127 0.66. This results in year-round reduction in SIE highly similar to that projected in the 2C
128 ensemble. For the second ensemble, which we call “2CiceASO”, we increased the albedo of cold
129 deep snow on top of the sea ice from 0.80 to 0.88 and decreased the albedo of snow-free ice from
130 0.61 to 0.10. This results in a reduction in SIE during August, September and October (ASO)
131 that is very close to the 2Cice ensemble, but yields little ice reduction the rest of the year. Our
132 choice of these months was primarily motivated by previous studies suggesting links between

133 September and October sea ice and the winter atmospheric circulation (Francis et al., 2009; Hall
134 et al., 2017; Wang et al., 2017), but was also constrained by what was achievable using the
135 albedo reduction method.

136

137 Our simulations consist of many short simulations, so they do not capture the adjustment
138 associated with the deep ocean response that occurs on decadal and longer timescales (Wang et
139 al., 2018). As our focus is on the winter season (December-February; DJF), we use the four full
140 winters from our five year-long simulations, which results in 1600 years in each experiment.
141 This results in an 11-month spin up period (only 7 months for the response during ASO), and all
142 results and conclusions remain the same if we add an additional year of spin-up by discarding the
143 first year (not shown). In all analysis and figures, we find the response by subtracting the mean
144 in each of the sea-ice loss ensembles from the mean in the present-day control ensemble.
145 Statistical significance is calculated using a two-sided student's t-test.

146 **3 Results**

147 **3.1 Sea Ice Response**

148 The seasonal cycle of the SIE response is shown in Figure 1a. In the 2Cice experiment, there is a
149 reduction in SIE throughout the year, with the largest changes occurring during summer and
150 autumn, but with a reduction of about 1 million km² averaged over DJF. Compared to the target
151 SIE reduction in the 2C experiment, there is too much sea-ice reduction from May-June and too
152 little in winter, however it is much closer to the seasonal cycle of ice loss from global warming
153 compared to previous sea-ice albedo reduction experiments (Blackport & Kushner, 2016, 2017).
154 In the 2CiceASO experiment, there is similar reduction in SIE in ASO (2.92 vs 2.88 million
155 km²), but little reduction the rest of the year. In July and November there is some ice reduction,

156 with 59 % and 45 % reduction in SIE compared to the 2Cice simulation, respectively. During
157 winter, there is little change in SIE with only 18 % of the reduction seen in the 2Cice simulation.

158

159 The spatial extent of the sea-ice loss in the two experiments during ASO are similar, but there are
160 subtle differences (Figure 1b,e). During winter, the 2Cice simulation has reductions in SIC in all
161 marginal seas, while the 2CiceASO experiment shows little ice reduction (Figure 1c, f). While
162 the 2CiceASO experiment shows little reduction in SIC during winter, SIE reductions in autumn
163 do impact sea thickness in winter (Figure 1d, g). The spatial patterns of the reductions in
164 thickness differ in the two experiments, which reflect the different spatial patterns of the SIC
165 reductions during ASO, but both show similar magnitudes of sea ice thickness reduction
166 averaged over the Arctic Ocean.

167 3.2 Temperature Response

168 The near surface air temperature (SAT) response is plotted in Figure 2. During ASO, the 2Cice
169 experiment shows warming that extends to lower latitudes, while in the 2CiceASO experiment,
170 the warming is mostly confined to the Arctic Ocean. As both simulations have similar sea-ice
171 loss during ASO, these differences reflect the persistence of the sea surface temperature
172 anomalies from sea-ice loss in the preceding months in the 2Cice experiment (Figure S1). Not
173 surprisingly, during winter near the ice edge, the warming is much stronger in the 2Cice
174 experiment than in the 2CiceASO experiment due to the larger reductions in SIC in the former.
175 However, over the Arctic Ocean, despite the little change in SIE and SIC, there is still a SAT
176 response in the 2CiceASO experiment. Averaged north of 80 °N, the warming in the 2CiceASO
177 experiment is over half the magnitude of that of 2Cice (1.7° C vs 3.1° C). This is likely attributed
178 to the reductions in ice thickness in the 2CiceASO experiment, as Labe et al. (2018) and Lang et

179 al. (2017) find similar SAT responses to imposed reductions in sea ice thickness. Neither
180 experiment shows evidence of cooling over the midlatitude continents.

181 3.3 Atmospheric Circulation Response

182 Figure 3 shows the zonal mean, zonal wind response in both sea-ice loss experiments for
183 December, January and February. In response to year-round sea-ice loss in the 2Cice
184 experiment, there is weakening westerly winds at $\sim 55^\circ\text{N}$ and smaller increase at around 30°N ,
185 reflecting a weakening and equatorward shift of the eddy-driven jet and small strengthening of
186 the sub-tropical jet, respectively (Figure 3a-c). This is consistent with previous coupled model
187 experiments using a range of models and experiment protocols (Screen et al., 2018). The
188 response in the 700 hPa zonal winds (Figure S2) shows that the weakening and equatorward shift
189 in the eddy-driven jet are primarily found in the Atlantic Basin. Within the winter season, the
190 response looks qualitatively similar in each month, but the strongest response occurs in
191 December. In the stratosphere, we see a small weakening of the stratospheric polar vortex in
192 December, which is weaker in magnitude and statistically insignificant in January and February.
193 In contrast, in the 2CiceASO experiment, the zonal wind response is very weak throughout the
194 winter months (Figure 3d-f). The only month with statistically significant weakening of the zonal
195 winds on the poleward side of the eddy-driven jet is in December, and it is substantially smaller
196 magnitude than in the 2CiceASO experiment. In both experiments, the responses found during
197 winter continue into early spring (not shown).

198

199 As with the zonal mean wind, the sea level pressure (SLP) response to year-round sea-ice loss
200 has many similarities with previous coupled model experiments (Hay et al., 2018; Screen et al.,
201 2018; Sun et al., 2018). These include a negative NAO response, a low pressure response over

202 Hudson Bay and Northeastern Canada during each winter month, and a high pressure response
203 over Northern Eurasia during February (Figure 4 a-c). The biggest discrepancy between our
204 results and those synthesised by Screen et al. (2018), is the lack of an Aleutian Low response.
205 This can potentially be explained by our 5-year long simulations not capturing the decadal time-
206 scale response of the tropical ocean and associated teleconnections to the North Pacific (Tomas
207 et al., 2016; Wang et al., 2018). Similar to the zonal wind response, the SLP response is
208 substantially weaker in the 2CiceASO experiment than in the 2Cice experiment (Figure 4 d-f).
209 There is a weak negative NAO response in December, but not in January or February. The 500
210 hPa geopotential height responses (Figure S3) are similar to the SLP, but also included increased
211 heights over the polar cap in the 2Cice experiment.

212

213 The time evolution of the polar cap geopotential height (PCH; averaged from 65-90 °N) response
214 is shown in Figure S4. In response to year-round sea-ice loss, there are increased PCHs
215 throughout the troposphere during the entire autumn and winter seasons, which primarily reflects
216 the baroclinic warming response to sea-ice loss, but also includes a barotropic component related
217 to the NAO response in winter. In the stratosphere, weak but statistically significant increases in
218 PCH are found in December and early January, consistent with the reduced stratospheric zonal
219 wind near 60 °N in Figure 3a. In the 2CiceASO experiment, there are much weaker tropospheric
220 anomalies from October to December, consistent with the weaker warming response. Similar to
221 the response to year-round ice loss, there are weak increases in PCH in the stratosphere during
222 late December and early January in the 2CiceASO experiment, followed by a decrease in heights
223 at the end of January and into February, however these aspects of the response are not

224 statistically significant. The weak stratospheric responses are consistent with no statistically
225 significant change in eddy heat flux at 100hPa in either experiment (not shown).

226

227 Taken together, Figures 3-4 and S2-4 show a clear winter atmospheric circulation response to
228 year-round sea ice, but little winter circulation change in response to sea-ice loss only in ASO.

229 In the 2CiceASO experiment there are small, but statistically significant responses in December,
230 but these likely occur in direct response to the small SIE reductions in November and December
231 in the 2CiceASO experiment. The circulation responses found in both experiments appear to be
232 primarily via the troposphere, but we cannot rule out the possibility that the stratosphere, driven
233 by reduced ice in late autumn or early winter, plays a minor role in the February response as
234 shown by Sun et al., (2015) and Peings & Magnusdottir, (2014).

235 **4 Discussion**

236 It is important to note that our model does not have particularly high vertical resolution in the
237 stratosphere or a high model top (it is a so-called “low top model”). It is unclear whether low top
238 models are able to properly represent the stratospheric pathway through which autumn sea ice
239 can affect the winter circulation (Nakamura et al., 2016; Sun et al., 2015; Zhang et al., 2017,
240 2018). However, there are two reasons that lead us to believe that our conclusions would be
241 unaffected by improved stratospheric resolution. First, the winter circulation response to year-
242 round sea-ice loss we see in our simulations is nearly identical to that of Smith et al. (2017), who
243 used a version from the same model family as us, but with better stratospheric resolution (a so
244 called “high top model”). In fact, the winter circulation response in our simulation is slightly
245 larger than that in Smith et al (2017), when scaled by the amount of sea-ice loss. Second,
246 although Sun et al. (2015) found substantial differences in the stratosphere response to year-

247 round sea-ice loss in a low-top model compared to a high-top model, the stratospheric response
248 in our simulations bears closer resemblance to that in their high-top model simulations than in
249 their low-top model simulations. This suggests that the stratospheric response to sea ice loss and
250 its downward influence on the troposphere may not only depend on the stratospheric resolution
251 or how high the model top is. Nevertheless, the model used in this study has reduced
252 stratospheric variability compared to observations (Osprey et al., 2013), so it is possible that
253 inadequate representation of the stratosphere may contribute to the weak response to autumn sea-
254 ice loss in our simulations. More generally, we are cognisant that our conclusions could be
255 model dependent and therefore, encourage similar experiments with different models.

256

257 Unlike Sun et al. (2015), we used a coupled climate model which allows for additional
258 mechanisms by which autumn sea-ice loss could drive winter atmosphere circulation. We do
259 indeed find that autumn sea-ice loss results in a high-latitude warming response over the Arctic
260 Ocean in winter by reducing ice thickness. This mechanism could not be captured without
261 coupling between the atmosphere, ocean and ice. However, despite this lagged warming
262 response, we still find only a weak winter atmospheric circulation response to autumn sea-ice
263 loss. We speculate that because the winter warming response to autumn sea-ice loss is confined
264 to the high latitudes over the Arctic Ocean it has a weaker influence on the jet stream. In
265 contrast, the winter warming response to year-round sea-ice loss reaches lower latitudes and has
266 a larger effect on the jet. This is consistent with previous work from idealized model experiments
267 which has shown that the jet speed and location are insensitive to warming at high-latitudes, and
268 their sensitivity to warming increases when the warming is closer to the jet (Baker et al., 2017).
269 The absence of a winter response to autumn sea-ice loss, in spite of reduced ice thickness in

270 winter, suggests that the winter atmospheric circulation is more sensitive to reductions in sea ice
271 concentration than in sea ice thickness, in agreement with Labe et al. (2018).

272

273 In the context of seasonal prediction, our results imply that autumn sea ice may provide only
274 limited predictability for the winter atmospheric circulation. However, there are some caveats to
275 this conclusion. First, even though we find no direct causal link between autumn sea ice and
276 winter atmospheric circulation, there could still be statistical links that provide predictive skill.
277 These links could come from autumn sea ice anomalies persisting into winter, which could in
278 turn influence the atmospheric circulation, or from a common driver. Second, previous work has
279 shown that the stratospheric response to year-round sea-ice loss in the Pacific and Atlantic
280 sectors can oppose each other, resulting in a weak response to pan-arctic sea-ice loss (McKenna
281 et al., 2017; Sun et al., 2015), similar to the weak stratospheric response we find here. Thus
282 regional autumn sea ice, particularly over the Barents-Kara Sea, could still contribute to skillful
283 predictions of the winter atmospheric circulation, to the extent that sea ice anomalies in the
284 Pacific and Atlantic sector vary independently.

285 **5 Conclusions**

286 We have investigated to what extent the winter atmospheric circulation response to sea-ice loss is
287 driven by autumn sea-ice loss compared to winter sea-ice loss, using coupled ocean-atmosphere
288 climate model experiments. We modified different combinations of sea ice albedo parameters to
289 impose different seasonal cycles of sea-ice loss. In response to year-round sea-ice loss, we find a
290 robust weakening and equatorward migration of the jet and a phase shift of the NAO towards its
291 negative phase in all winter months. These aspects are consistent with previous coupled model
292 experiments. However, we find that the winter atmospheric circulation response to sea-ice loss in

293 late summer and autumn is very weak, despite the high latitude warming persisting into the
294 winter. Thus, we conclude that the winter atmospheric circulation response to sea-ice loss is
295 mostly driven by concurrent sea-ice loss during winter as opposed to a delayed response to sea-
296 ice loss in autumn. Assuming our model captures the relevant mechanisms, our results suggest
297 that the observed correlation between Autumn sea ice and the winter atmospheric circulation
298 arises either due to persistence of autumn sea ice anomalies into winter, which then impact the
299 winter circulation, or that the observed relationship is non-causal and arises due to a common
300 driver.

301

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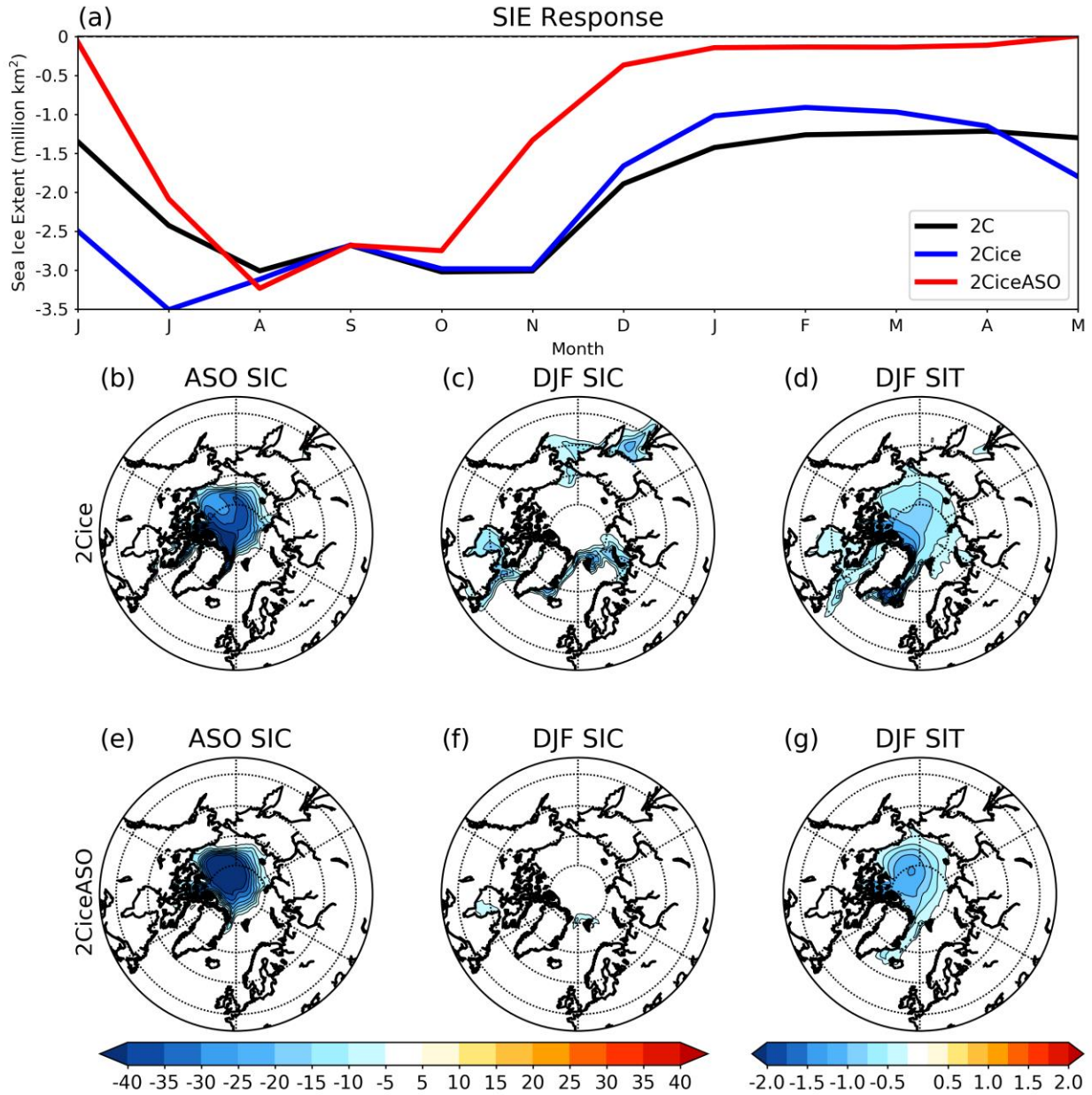
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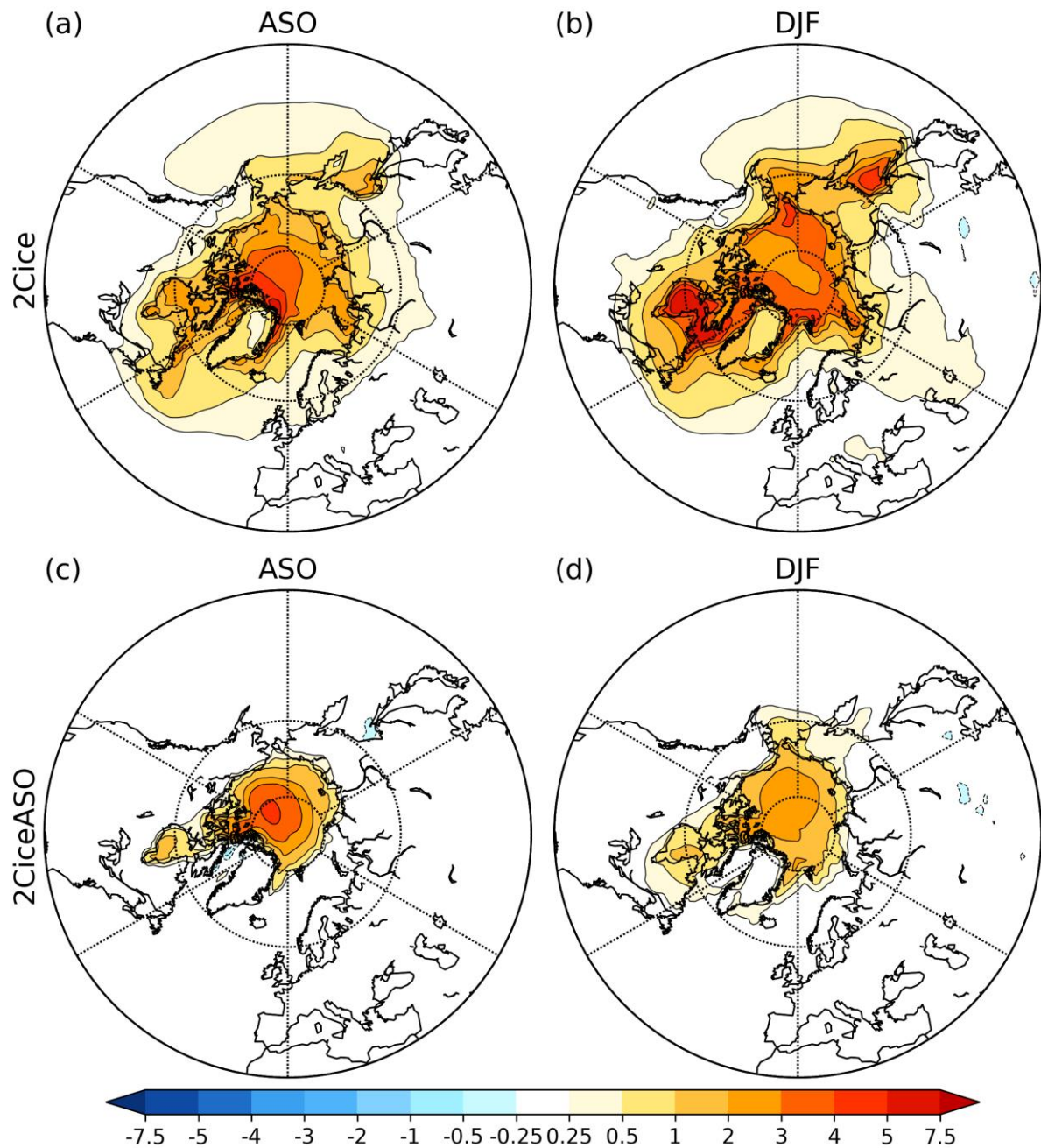
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419
 420 **Figure 1.** (a) The seasonal cycle of the SIE response (million km²) in the 2C (black), 2Cice
 421 (blue) and 2CiceASO (red) experiments. (b) The SIC response (%) during August-October in
 422 2Cice experiment. (c) As in (b) but during DJF. (d) As in (c) but for sea ice thickness (m). (e)-(f)
 423 As in (b)-(d) but for the 2CiceASO experiment.

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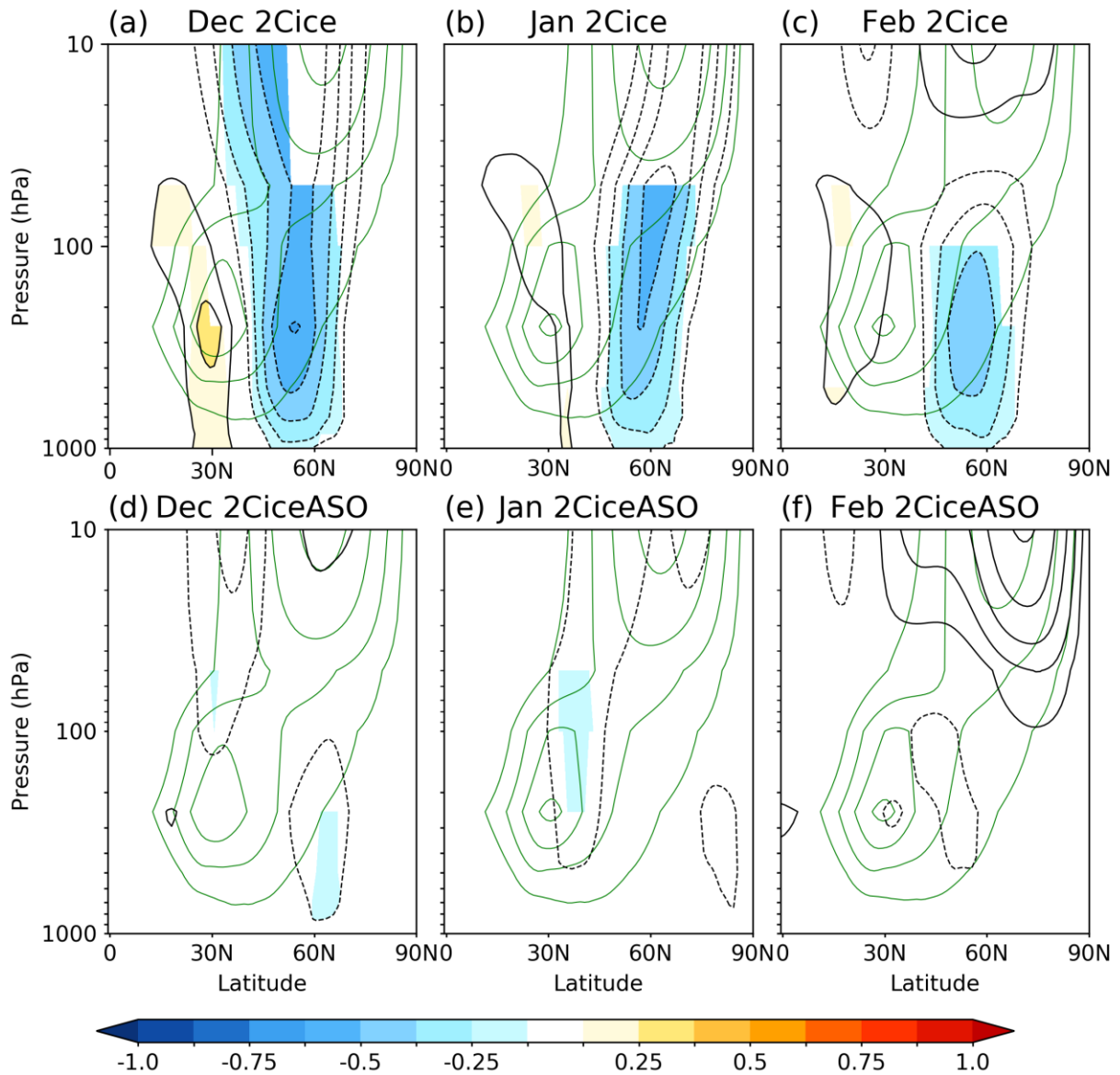
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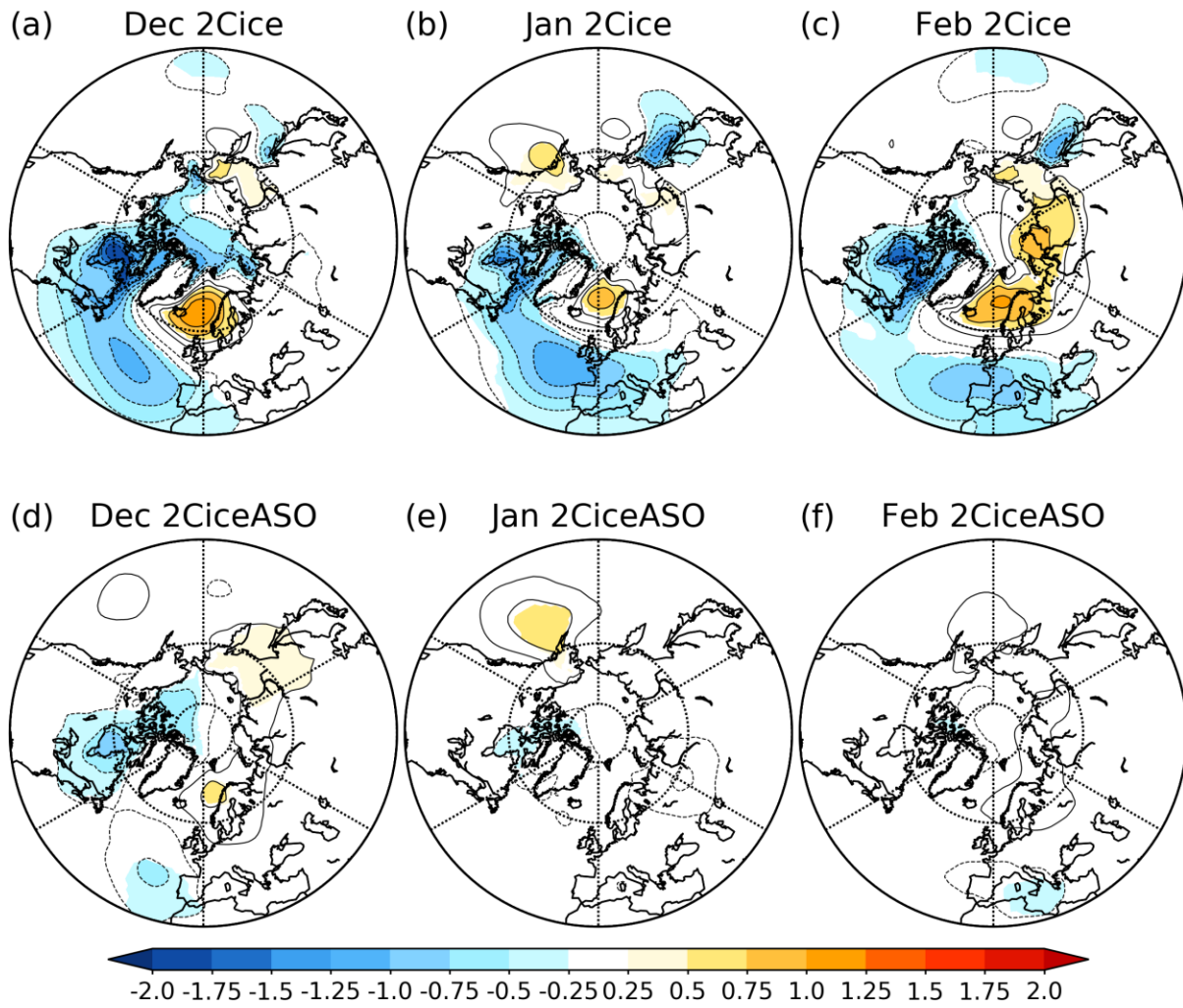
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Figure 2. (a) The SAT response during ASO in the 2Cice experiment. (b) As in (a) but during DJF. (c)-(d) As in (a)-(b) but for the 2CiceASO experiment. Shading is only shown for points that are statistically significant at the 95% confidence level.



429
 430 **Figure 3.** (a)-(c) The zonal mean, zonal wind response (m s⁻¹) in the 2Cice experiment for (a)
 431 December, (b) January and (c) February. (d)-(f) As in (a)-(c) but for the 2CiceASO experiment.
 432 Shading is only shown for points that are statistically significant at the 95% confidence level.
 433 Green contours show the baseline climatology from the present-day control simulation (10 m s⁻¹
 434 contour levels).



435
436 **Figure 4.** As in Figure 3 but for SLP (hPa).

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