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.

Abstract

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

Plain Language Summary

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

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

1 Introduction

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

An open question is to what extent these winter atmospheric circulation changes are a lagged response to sea-ice loss in the summer and autumn, or whether they are caused by concurrent sea-ice loss in winter. This has implications for understanding the underlying physical mechanisms and for seasonal predictions. Autumn Arctic sea ice has been shown to be a potential predictor of the winter NAO in both dynamical (Scaife et al., 2014) and statistical forecasts (Hall et al., 2017; Wang et al., 2017). Francis et al., (2009) identified links between observed September sea ice and the large-scale atmospheric circulation and precipitation patterns during winter. They proposed that the winter atmosphere 'remembers' the September sea ice through changes in lower troposphere stability, cloud cover and changes in poleward thickness gradients. However, these statistical links between autumn sea ice and winter atmospheric circulation cannot isolate cause and effect. Several studies have isolated the impacts of low September sea ice on autumn atmospheric circulation in model experiments (Blüthgen et al., 2012; Porter et al., 2012; Strey et al., 2010), but few have examined the lagged response into winter.

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

In this study, we explore the question of whether sea-ice loss in late summer and autumn plays a role in driving the wintertime atmospheric circulation response to sea-ice loss, using coupled atmosphere-ocean climate model simulations. We use different combinations of sea ice albedo parameter modifications to conduct two experiments with differing seasonal cycles of sea-ice loss: One with year-round sea-ice loss and the other with sea ice extent (SIE) reduction only in later summer and autumn. This allows us to cleanly isolate the impact the influence of late summer and autumn sea-ice loss on the winter atmospheric circulation.

2 Model and Experiments

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

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

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

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

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

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

3 Results

3.1 Sea Ice Response

The seasonal cycle of the SIE response is shown in Figure 1a. In the 2Cice experiment, there is a reduction in SIE throughout the year, with the largest changes occurring during summer and autumn, but with a reduction of about 1 million km^2 averaged over DJF. Compared to the target SIE reduction in the 2C experiment, there is too much sea-ice reduction from May-June and too little in winter, however it is much closer to the seasonal cycle of ice loss from global warming compared to previous sea-ice albedo reduction experiments (Blackport & Kushner, 2016, 2017). In the 2CiceASO experiment, there is similar reduction in SIE in ASO (2.92 vs 2.88 million km^2), but little reduction the rest of the year. In July and November there is some ice reduction, with 59 % and 45 % reduction in SIE compared to the 2Cice simulation, respectively. During winter, there is little change in SIE with only 18 % of the reduction seen in the 2Cice simulation.

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

3.2 Temperature Response

The near surface air temperature (SAT) response is plotted in Figure 2. During ASO, the 2Cice experiment shows warming that extends to lower latitudes, while in the 2CiceASO experiment, the warming is mostly confined to the Arctic Ocean. As both simulations have similar sea-ice loss during ASO, these differences reflect the persistence of the sea surface temperature anomalies from sea-ice loss in the preceding months in the 2Cice experiment (Figure S1). Not surprisingly, during winter near the ice edge, the warming is much stronger in the 2Cice experiment than in the 2CiceASO experiment due to the larger reductions in SIC in the former. However, over the Arctic Ocean, despite the little change in SIE and SIC, there is still a SAT response in the 2CiceASO experiment. Averaged north of 80 °N, the warming in the 2CiceASO experiment is over half the magnitude of that of 2Cice (1.7° C vs 3.1° C). This is likely attributed to the reductions in ice thickness in the 2CiceASO experiment, as Labe et al. (2018) and Lang et al. (2017) find similar SAT responses to imposed reductions in sea ice thickness. Neither experiment shows evidence of cooling over the midlatitude continents.

3.3 Atmospheric Circulation Response

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

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

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

The time evolution of the polar cap geopotential height (PCH; averaged from 65-90 °N) response is shown in Figure S4. In response to year-round sea-ice loss, there are increased PCHs throughout the troposphere during the entire autumn and winter seasons, which primarily reflects the baroclinic warming response to sea-ice loss, but also includes a barotropic component related to the NAO response in winter. In the stratosphere, weak but statistically significant increases in PCH are found in December and early January, consistent with the reduced stratospheric zonal wind near 60 °N in Figure 3a. In the 2CiceASO experiment, there are much weaker tropospheric anomalies from October to December, consistent with the weaker warming response. Similar to the response to year-round ice loss, there are weak increases in PCH in the stratosphere during late December and early January in the 2CiceASO experiment, followed by a decrease in heights at the end of January and into February, however these aspects of the response are not statistically significant. The weak stratospheric responses are consistent with no statistically significant change in eddy heat flux at 100hPa in either experiment (not shown).

Taken together, Figures 3-4 and S2-4 show a clear winter atmospheric circulation response to year-round sea ice, but little winter circulation change in response to sea-ice loss only in ASO. In the 2CiceASO experiment there are small, but statistically significant responses in December, but these likely occur in direct response to the small SIE reductions in November and December in the 2CiceASO experiment. The circulation responses found in both experiments appear to be primarily via the troposphere, but we cannot rule out the possibility that the stratosphere, driven by reduced ice in late autumn or early winter, plays a minor role in the February response as shown by Sun et al., (2015) and Peings & Magnusdottir, (2014).

4 Discussion

It is important to note that our model does not have particularly high vertical resolution in the stratosphere or a high model top (it is a so-called “low top model”). It is unclear whether low top models are able to properly represent the stratospheric pathway through which autumn sea ice can affect the winter circulation (Nakamura et al., 2016; Sun et al., 2015; Zhang et al., 2017, 2018). However, there are two reasons that lead us to believe that our conclusions would be unaffected by improved stratospheric resolution. First, the winter circulation response to year-round sea-ice loss we see in our simulations is nearly identical to that of Smith et al. (2017), who used a version from the same model family as us, but with better stratospheric resolution (a so called “high top model”). In fact, the winter circulation response in our simulation is slightly larger than that in Smith et al (2017), when scaled by the amount of sea-ice loss. Second, although Sun et al. (2015) found substantial differences in the stratosphere response to year-round sea-ice loss in a low-top model compared to a high-top model, the stratospheric response in our simulations bears closer resemblance to that in their high-top model simulations than in their low-top model simulations. This suggests that the stratospheric response to sea ice loss and its downward influence on the troposphere may not only depend on the stratospheric resolution or how high the model top is. Nevertheless, the model used in this study has reduced stratospheric variability compared to observations (Osprey et al., 2013), so it is possible that inadequate representation of the stratosphere may contribute to the weak response to autumn sea-ice loss in our simulations. More generally, we are cognisant that our conclusions could be model dependent and therefore, encourage similar experiments with different models.

Unlike Sun et al. (2015), we used a coupled climate model which allows for additional mechanisms by which autumn sea-ice loss could drive winter atmosphere circulation. We do indeed find that autumn sea-ice loss results in a high-latitude warming response over the Arctic Ocean in winter by reducing ice thickness. This mechanism could not be captured without coupling between the atmosphere, ocean and ice. However, despite this lagged warming response, we still find only a weak winter atmospheric circulation response to autumn sea-ice loss. We speculate that because the winter warming response to autumn sea-ice loss is confined to the high latitudes over the Arctic Ocean it has a weaker influence on the jet stream. In contrast, the winter warming response to year-round sea-ice loss reaches lower latitudes and has a larger effect on the jet. This is consistent with previous work from idealized model experiments which has shown that the jet speed and location are insensitive to warming at high-latitudes, and their sensitivity to warming increases when the warming is closer to the jet (Baker et al., 2017). The absence of a winter response to autumn sea-ice loss, in spite of reduced ice thickness in winter, suggests that the winter atmospheric circulation is more sensitive to reductions in sea ice concentration than in sea ice thickness, in agreement with Labe et al. (2018).

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

5 Conclusions

We have investigated to what extent the winter atmospheric circulation response to sea-ice loss is driven by autumn sea-ice loss compared to winter sea-ice loss, using coupled ocean-atmosphere climate model experiments. We modified different combinations of sea ice albedo parameters to impose different seasonal cycles of sea-ice loss. In response to year-round sea-ice loss, we find a robust weakening and equatorward migration of the jet and a phase shift of the NAO towards its negative phase in all winter months. These aspects are consistent with previous coupled model experiments. However, we find that the winter atmospheric circulation response to sea-ice loss in late summer and autumn is very weak, despite the high latitude warming persisting into the winter. Thus, we conclude that the winter atmospheric circulation response to sea-ice loss is mostly driven by concurrent sea-ice loss during winter as opposed to a delayed response to sea-ice loss in autumn. Assuming our model captures the relevant mechanisms, our results suggest that the observed correlation between Autumn sea ice and the winter atmospheric circulation arises either due to persistence of autumn sea ice anomalies into winter, which then impact the winter circulation, or that the observed relationship is non-causal and arises due to a common driver.

Acknowledgments

We thank two anonymous reviewers for their helpful suggestions. This work was supported by Natural Environment Research Council grant NE/P006760/1. Simulations were performed on the ARCHER UK national computing service. Data from the simulations are available at https://doi.org/10.24378/exe.963 .

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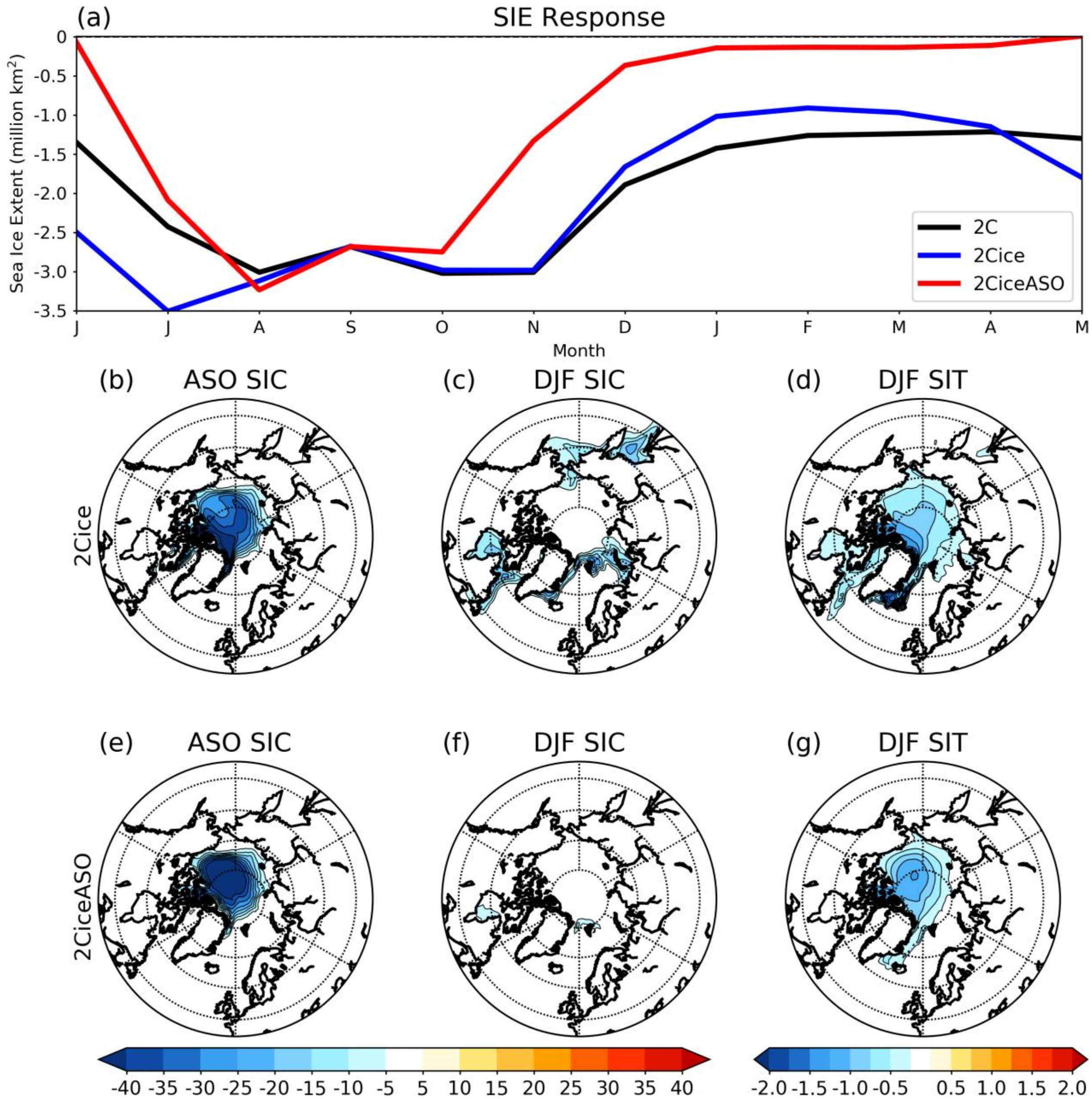

Figure 1. (a) The seasonal cycle of the SIE response (million km^2) in the 2C (black), 2Cice (blue) and 2CiceASO (red) experiments. (b) The SIC response (%) during August-October in 2Cice experiment. (c) As in (b) but during DJF. (d) As in (c) but for sea ice thickness (m). (e)-(f) As in (b)-(d) but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

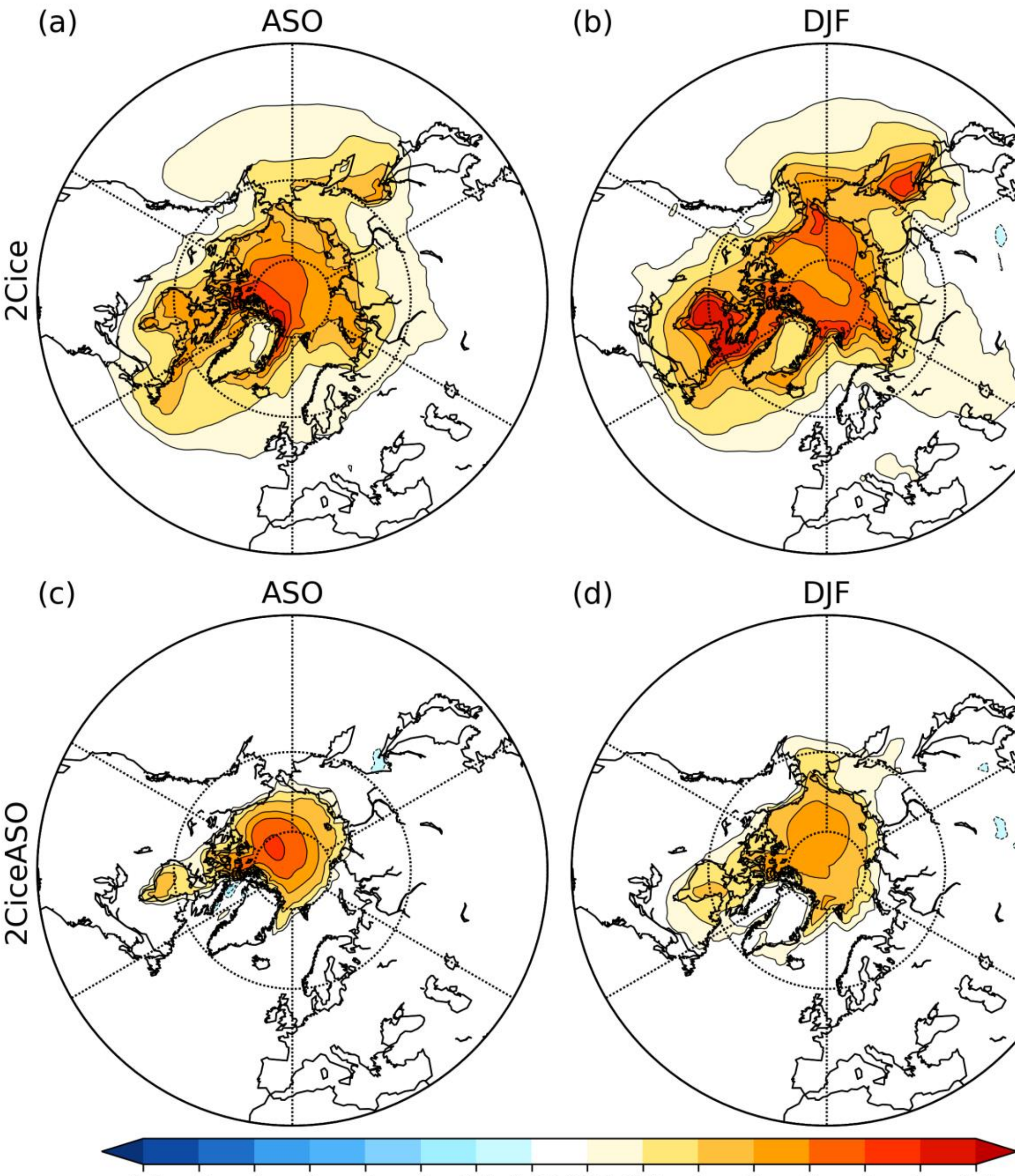

Figure 2. (a) The SAT response during ASO in the 2Cice experiment. (b) As in (a) but during DJF. (c)-(d) As in (a)-(b) but for the 2CiceASO experiment. Shading is only shown for points that are statistically significant at the 95% confidence level.

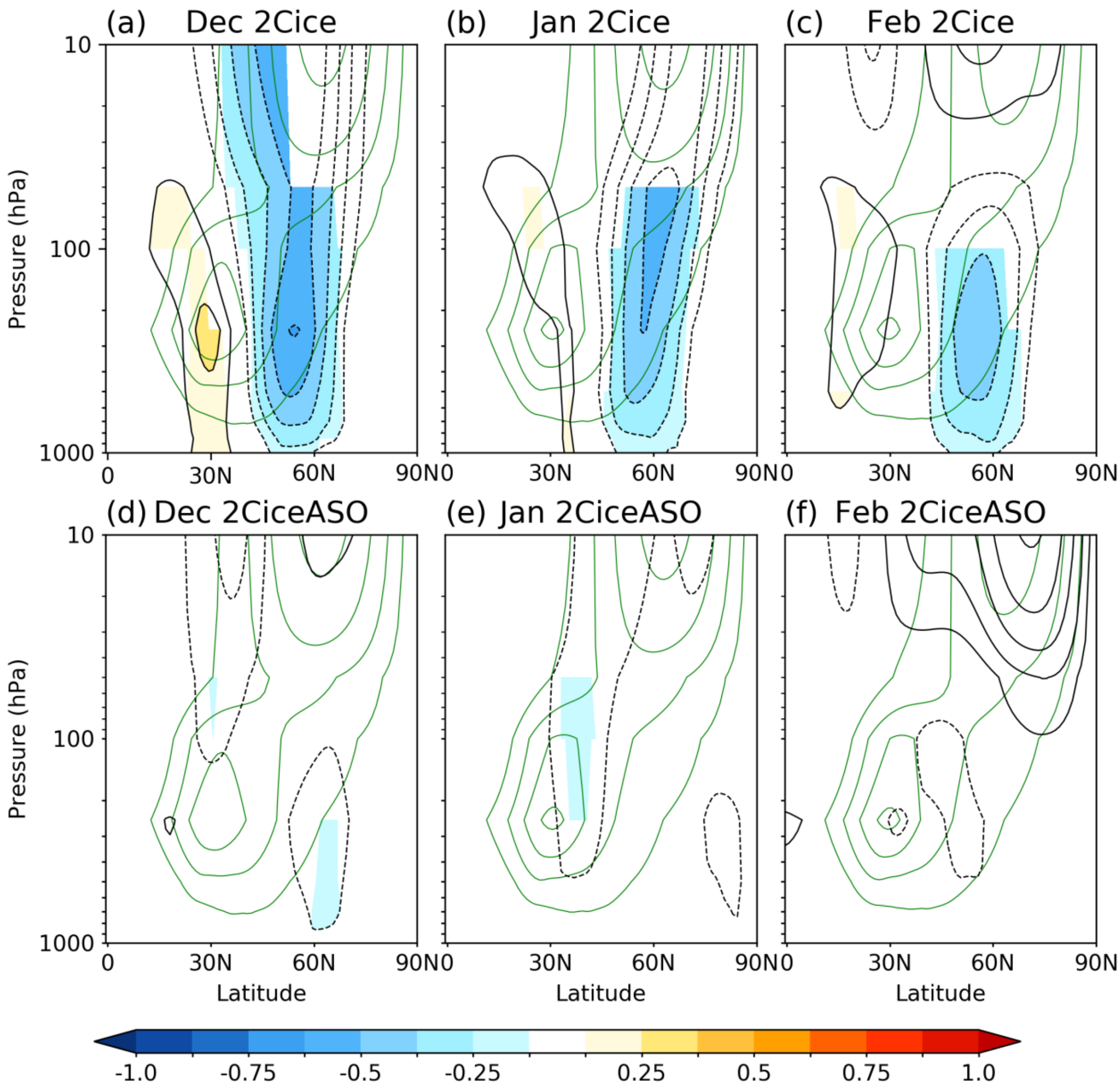

Figure 3. (a)-(c) The zonal mean, zonal wind response (m s^{-1}) in the 2Cice experiment for (a) December, (b) January and (c) February. (d)-(f) As in (a)-(c) but for the 2CiceASO experiment. Shading is only shown for points that are statistically significant at the 95% confidence level. Green contours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

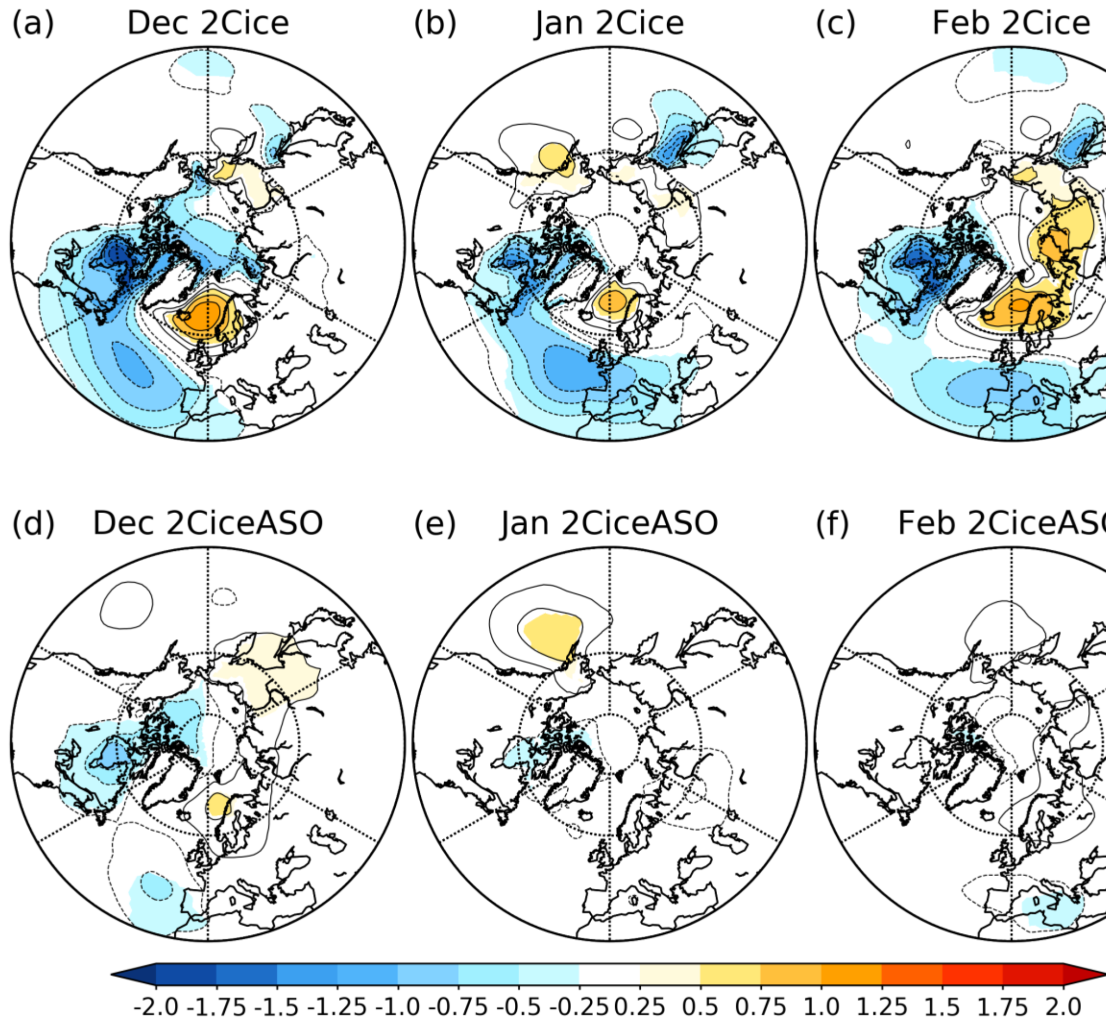

Figure 4. As in Figure 3 but for SLP (hPa).