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Consistent but more intense atmospheric circulation response to Arctic sea ice loss in CMIP6 experiments compared to PAMIP experiments

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Abstract. The atmospheric circulation response to Arctic sea ice loss may differ depending on the region of sea ice loss but also on the methodology used to study this impact. Examining the different possible atmospheric circulation responses to sea ice loss is essential, as the Arctic sea ice is not melting uniformly. In this study, we examine the atmospheric response in winter to regional sea ice loss using two different approaches across seven climate models. The sea ice anomaly areas are the pan-Arctic, the Barents-Kara Seas only, and the Sea of Okhotsk only. The first approach involves sensitivity experiments performed within the Polar Amplification Model Intercomparison Project (PAMIP), while the second approach entails a composite analysis in long pre-industrial control simulations from CMIP6. Our results reveal that both approaches lead to consistent atmospheric circulation responses to pan-Arctic sea ice loss, characterized by a negative phase in the North Atlantic Oscillation and a weakening of the stratospheric polar vortex. Similar responses to BK sea ice loss are simulated, albeit with more spread in the PAMIP experiments. The responses to Okhotsk sea ice loss differ and are uncertain in both approaches. Furthermore, larger changes are detected in the composite analysis than in the sensitivity experiments, likely due to a different background state and the presence of confounding factors in the composite analysis. We also find that the atmosphere-ocean coupling does not imply larger circulation changes or a better representation of the eddy momentum feedback in the climate response. These results highlight that sea ice loss in sensitivity experiments yields a weaker atmospheric circulation response compared to the pre-industrial simulations in CMIP6 where the sea ice loss is governed by internal climate variability. A quantification of the role played by factors related to sea ice loss that amplifies the response should be further investigated.

1 Introduction

The decrease in Arctic sea ice extent over the satellite era is a significant indicator of ongoing climate change (Meredith et al., 2019). This decline has displayed a non-linear behaviour over time (Serreze and Stroeve, 2015), with a rapid decrease from the mid-1990s to 2010 (Stroeve et al., 2012), followed by a recent slowdown (Francis and Wu, 2020). However, projections suggest that summer Arctic sea ice could disappear in the near future, potentially before 2050 (Notz and SIMIP Community, 2020). Furthermore, rapid sea ice loss events are projected to increase in frequency and magnitude (Holland et al., 2006; Kay et al., 2011), and these events could affect the climate even to mid-latitudes through changes in the atmospheric circulation

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(e.g. Cohen et al., 2014; Vihma, 2014).

An in-depth understanding of the atmospheric circulation response to Arctic sea ice loss remains elusive to date, as indicated by the contrasting conclusions from the recent scientific literature (e.g. Barnes and Screen, 2015; Overland et al., 2015; Cohen et al., 2020). One possible reason for this lack of comprehensive understanding is the variety of approaches that have been used to study this scientific question. Studies based on observations or reanalyses have suggested robust associations between atmospheric circulation changes and sea ice variability (Cohen et al., 2020). In the historical record, low sea ice states are generally followed by a negative phase of the NAO that implies cold anomalies over eastern Eurasia (e.g. Honda et al., 2009; Outten and Esau, 2012; Mori et al., 2014; Hoshi et al., 2019; Cohen et al., 2020; Simon et al., 2020). However, observational or reanalysis-based studies present two main limitations. On the one hand, the length of the period of data availability is relatively short ($\sim$40 years), which increases the chances of observing random associations by chance (Smith et al., 2017, 2019). On the other hand, many other sources of variability than the sea ice act on the atmosphere, which renders the extraction of causal relationships a delicate endeavour.

To work around these issues, studies based on climate models have been used in complement to observational studies. There are two immediate advantages with the modelling approach. First, the sample size can be increased to improve the detection of possible relationships between sea ice and the atmosphere. Second, dedicated sensitivity experiments can be conducted to isolate the sea ice from other drivers of the atmosphere. There are also drawbacks with the modelling approach. Recent studies have suggested that climate models severely underestimate the real-world response of the atmospheric circulation to Arctic sea ice loss (Smith et al., 2022). In all models, the eddy-momentum feedback appears to be underestimated, which causes the models to capture less predictable content than there is in reality (Smith et al., 2022). This behaviour implies that, in ensemble forecasting systems, individual members have more difficulty in reproducing other ensemble members than actual observations. This issue, knows as the "signal-to-noise paradox", remains one of the main obstacles to achieving skillful predictions of the main modes of Northern Hemisphere climate variability (Scaife and Smith, 2018). Another drawback to modelling approaches is the diversity in the simulated responses, with models predicting either positive NAO (e.g. Singarayer et al., 2006; Strey et al., 2010; Rinke et al., 2013; Cassano et al., 2014; Screen et al., 2014) or negative NAO (e.g. Seierstad and Bader, 2009; Mori et al., 2014; Deser et al., 2015; Mori et al., 2019; Smith et al., 2022) phases in response to negative sea ice extent anomalies.

The discrepancies between modelling studies can partly be explained by the differences in the geographic location of the prescribed sea ice loss (Sun et al., 2015; Screen, 2017a; McKenna et al., 2018; Kelleher and Screen, 2018; Screen et al., 2018; Levine et al., 2021). On the one hand, the decline of sea ice in the Barents and Kara Seas, regions that have recently experienced one of the most rapid sea ice cover declines (Cavalieri and Parkinson, 2012; Serreze and Stroeve, 2015; Onarheim and Årthun, 2017), may stimulate a vertical wave propagation, resulting in a weakening of the stratospheric polar vortex (SPV) in winter (McKenna et al., 2018). This weakening is associated with a subsequent negative NAO index approximately 1-2 months

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later (García-Serrano et al., 2015; Koenigk et al., 2016; Screen, 2017b). On the other hand, the decline of sea ice in the Pacific sector, such as in the Chuckchi and Bering Seas or in the Sea of Okhotsk, could instead lead to a strengthening of the SPV (Sun et al., 2015; McKenna et al., 2018; Kelleher and Screen, 2018), resulting in a positive NAO index.

Additional factors contributing to the discrepancies in modelling studies include the difference in the background mean state of the climate models (Smith et al., 2017; Screen et al., 2018), the physics used in the models (Screen, 2014; Screen et al., 2018), or the presence of the atmosphere-ocean coupling (Deser et al., 2015, 2016). To mitigate these discrepancies as much as possible, coordinated experiments have been conducted by the Polar Amplification Model Intercomparison Project (PAMIP; Smith et al., 2019). Firstly, a large number of models performed these experiments to capture the range of model responses. Secondly, in all models the same pattern and magnitude of sea ice loss is prescribed. Lastly, each model has carried out a large ensemble of members, typically consisting of a minimum of 100 members, to account for internal climate variability. These experiments aim to enhance our understanding of the impact of the Arctic sea ice loss and to reconcile the divergent findings among studies.

This study examines the winter atmospheric circulation response to pan-Arctic (Arc) sea ice anomalies and two specific regional sea ice anomalies, namely one in the Barents-Kara (BK) Seas and one in the Sea of Okhotsk (Okhotsk), which have previously been associated with contrasting atmospheric circulation responses (Sun et al., 2015; Screen, 2017a). To achieve this, we use seven climate models and employ two distinct approaches. The first one involves sensitivity experiments performed within the PAMIP, while the second one entails a composite analysis from long (>500 yr) pre-industrial control simulations conducted within the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016). The PAMIP experiments isolate the atmospheric responses solely from sea ice loss, whereas the CMIP6 approach considers the change of other factors (such as sea surface temperature or snow cover) associated with sea ice loss, which may also influence the atmospheric circulation response. This study is the first to carry out a multi-model analysis of the atmospheric responses to regional and Arc sea ice losses using two distinct approaches. The primary goal is to assess and compare the atmospheric response to specific regions of sea ice loss between the two approaches employed. Furthermore, this study investigates the role of the atmosphere-ocean coupling in the atmospheric circulation response to sea ice loss.

2 Models and methods

We use 7 different climate models that have performed at least three sets of simulations, namely the pre-industrial control (piControl) simulation (requested by CMIP6), the pdSST-pdSIC simulation (requested by PAMIP) and the pdSST-futArcSIC simulation (requested by PAMIP). These models are the AWI-CM-1-1-MR, CNRM-CM6-1, CanESM5, CESM2, IPSL-CM6A-LR, MIROC6, and the HadGEM-GC31-MM (Table 1). For each model, we collected data for three atmospheric variables: the sea level pressure ("psl"), the zonal wind ("ua"), and the meridional wind ("va"), across all three sets of experiments. Ad-

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ditionally, we included four other sets of the PAMIP experiments, although not all the seven models have performed these experiments: the pdSST-futBKSeasSIC, the pdSST-futOkhotskSIC, the paSST-pdSIC and the paSST-futArcSIC. The description and the purpose of all the different experiments are detailed in Sect. 2.1 and Sect 2.2.

Table 1. List of the models used in this study, the resolution (lon × lat grid) of their atmospheric component, the top level of their atmosphere component, the number of vertical levels of their atmosphere component, the PAMIP experiments number, the number of members in the PAMIP experiments, and the length of the piControl simulation.

Models	Atm. resolution (lat x lon)	Top level	Vertical levels	PAMIP experiments No.	Number of members	Length of piControl simulation
1.AWI-CM-1-1-MR	192x384	80 km (0.01 hPa)	95	1.1, 1.6, 3.1, 3.2	100	500 yr
2.CanESM5	64x128	1hPa	49	1.1, 1.6, 3.1, 3.2	300	1000 yr
3.CESM2	192x288	2.25 hPa	32	1.1, 1.6	200	1200 yr
4.CNRM-CM6-1	128x256	78.4 km (0.01 hPa)	91	1.1, 1.6, 3.1, 3.2	100	500 yr
5.HadGEM3-GC31-MM	324x432	85 km (0.005 hPa)	85	1.1, 1.6, 2.1, 2.3, 3.1, 3.2	300	500 yr
6.IPSL-CM6A-LR	143x144	40 km (3.3 hPa)	79	1.1, 1.6, 2.1, 2.3, 3.1, 3.2	200	2000 yr
7.MIROC6	128x256	0.004 hPa	81	1.1, 1.6, 3.1, 3.2	100	800 yr

2.1 PAMIP experiments

We use 6 different experiments carried out in the framework of PAMIP. Experiment 1.1 (pdSST-pdSIC) simulates the present-day climate with constraints on the present-day sea surface temperature (SST) and the present-day sea ice concentration (SIC) for the atmosphere-only models. The present-day fields (of SST and SIC) forcing the models are based on the monthly means 1979–2008 HadISST data (Smith et al., 2019). Experiment 1.6 (pdSST-futArcSIC) is similar to 1.1, but with the Arctic SIC prescribed to match expected values under a global warming scenario of 2.0°C above pre-industrial conditions. Experiments 2.1 (pa-pdSIC) and 2.3 (pa-futArcSIC) are similar to 1.1 and 1.6 respectively, but performed with coupled atmosphere-ocean models, with sea ice concentration nudged using a relaxation timescale of 1 day (Smith et al., 2019). Experiments 3.1 (pdSST-futOkhotskSIC) and 3.2 (pdSST-futBKSeasSIC) are similar to 1.6 but with the SIC constrained only over the Sea of Okhotsk (3.1), and only over the BK Seas (3.2). In the atmosphere-only experiments with future sea ice conditions (1.6, 3.1, and 3.2), future SSTs are used in newly sea ice-free regions, while elsewhere, the SSTs remain fixed compared to present-day sea ice conditions. Each experiment starts on 1st of April and lasts for 14 months, with each model conducting at least 100 members

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to account for internal climate variability.

The comparison between one future SIC experiment and the 1.1 experiment with atmosphere-only models provides the atmospheric response to sea ice loss and the associated local change in SST. Specifically, the difference between 1.6 and 1.1 experiments gives the response to future Arc sea ice loss (Table 2). The difference between 3.2 and 1.1 and between 3.1 and 1.1 gives the response to future BK sea ice loss alone and future sea ice loss in the Okhotsk Sea alone, respectively (Table 2). Lastly, the difference between 2.3 and 2.1 reflects the same response as between 1.6 and 1.1, but for atmosphere-ocean coupled models (Table 2). Further details on the protocol of the PAMIP experiments are available in Smith et al. (2019).

All the output files were re-gridded to the resolution of the model with the coarsest grid, namely the CanESM5 model (64x128 grid). Robust differences in atmospheric variables are visualized using maps, where dots represent regions where at least 80% of the models agree on the sign of the response. To further assess significance, an additional criterion is applied, namely that at least 50% of the models show a mean difference exceeding one standard deviation (σ) of the present-day sea ice conditions. If both conditions are met, a triangle is displayed; if only the last condition is met, a cross is shown.

Table 2. Characteristics of the PAMIP experiments used in this study.

Abbr.	**Future experiment**	**Reference experiment**	**Future minus reference shows the response due to**	**Models**
Arc	1.6. pdSST-futArcSIC	1.1. pdSST-pdSIC	Future change in pan-Arctic SIC	All
Arc$_{cpl}$	2.3. pa-futArcSIC	2.1. pa-pdSIC	Future change in pan-Arctic SIC in coupled models	IPSL-CM6A-LR and HadGEM3-GC31-MM
BK	3.2. pdSST-futBKSeasSIC	1.1. pdSST-pdSIC	Future change in Barents-Kara SIC	All except CESM2
Okhotsk	3.1. pdSST-futOkhotskSIC	1.1. pdSST-pdSIC	Future change in SIC in the Sea of Okhotsk	All except CESM2

2.2 CMIP6 piControl coupled experiments

We use pre-industrial control simulations from CMIP6 (hereafter referred to as CMIP6-piC), with at least 500 years to ensure robust relationships. A composite analysis, similar to Delhaye et al. (2023), was performed based on the sea ice extent of the same three target areas used in the PAMIP experiments (Table 2), namely the Arc, the BK Seas, and the Okhotsk Sea. A lowpass filter in the sea ice extent was applied to remove variability longer than 10 years for the three target sea ice areas, as we want to focus on the sea ice extent anomalies from year-to-year timescales. For each model and each target sea ice area, years of low sea ice extent were picked if the sea ice extent anomaly was lower than -1σ of the whole simulation. Similarly,

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years of high sea ice extent were selected if the sea ice extent anomaly was greater than $+1\sigma$.

Afterwards, we conducted a comparison between the sea ice extent change in the CMIP6-piC composite and the PAMIP atmosphere-only experiments for the three target sea ice areas. To ensure the closest alignment between the two approaches (PAMIP vs. CMIP6-piC), the seasonal sea ice extent change between the approaches must fit as closely as possible. For the Arc target area, the month selected to construct the composite in the CMIP6-piC approach must be September because the sea ice extent response is largest this month in the PAMIP experiments (Fig. 1c). For the BK and Okhotsk target areas, the month selected must be October and January, respectively. However, for the Okhotsk target area, December was selected to ensure a minimum of three winter months in the composite, as the atmospheric response to sea ice loss can only be assessed after this reference month, i.e. only in positive lags.

The average difference in surface air temperature, sea level pressure, and zonal wind between years of low and high sea ice extents were computed for each model. The differences were calculated for the winter season, i.e. from December to February for Arc and BK, and from January to March for Okhotsk. In the Okhostk target area, December was excluded from the analysis to focus solely on responses in positive lags. Therefore, we examine the atmospheric changes from Lag +3 to Lag +5 in Arc, from Lag +2 to +4 in BK, and from Lag +1 to +3 in Okhotsk. Robust changes in atmospheric variables across the models are shown by maps in the same way as for the PAMIP experiments.

2.3 Indices

The NAO index is defined here as the principal component of the first empirical orthogonal function (EOF) of the sea level pressure anomalies over the North Atlantic (90°W-40°E, 20-80°N) as defined in Hurrell et al. (2003). The present-day SIC experiments (1.1 and 2.1) are taken as the reference to compute the sea level pressure anomalies in the future sea ice conditions experiments (1.6, 3.1, 3.2 and 2.3) for the PAMIP experiments. For the CMIP6-piC composites, the reference period used to calculate the NAO index is the length of each simulation. The SPV strength is computed as the zonally averaged zonal wind speed at 10hPa averaged over 54–66°N as in Smith et al. (2022).

We determine the eddy momentum feedback parameter for each model using a method based on the one of Smith et al. (2022). First, we calculate the divergence of the northward Eliassen-Palm (EP) flux based on the quasi-geostrophic momentum equations as shown in Edmon et al. (1980) leading to:

$$\nabla_\varphi F_\varphi = \frac{1}{r_0 cos\varphi}\frac{\partial}{\partial\varphi}(F_\varphi cos\varphi) \tag{1}$$

where φ is the latitude, r_0 is the radius of the Earth and F_φ is the northward EP flux given by

$$F_\varphi = -r_0 cos\varphi\overline{u'v'} \tag{2}$$

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where u and v are zonal and meridional velocities, the overbar represents the zonal mean, and the prime denotes the departures from the zonal mean. We use the monthly mean data for the zonal and meridional wind speeds. The eddy feedback strength or parameter corresponds to the local squared correlation between the winter zonally averaged zonal wind speed ($\overline{u}$) and the winter divergence of the northward EP flux ($\nabla_\varphi F_\varphi$) averaged over the troposphere (600 to 200 hPa) and over the mid-latitudes (40-72°N), i.e. where the local correlations are strongest. In the PAMIP simulations, only the present-day climate simulations (1.1 and 2.1) are used to determine the eddy feedback parameter as in Smith et al. (2022). The correlation is computed along the members in these experiments and for all the years of the simulation in the CMIP6-piC.

Several discrepancies are identified in this study compared to the method applied by Smith et al. (2022) to compute the eddy feedback parameter. They have used the full primitive equation to calculate $\nabla_\varphi F_\varphi$ from daily or hourly data of the zonal and meridional wind speeds. Our method (the quasi-geostrophic equations using monthly data) leads to an underestimation of the correlation between the winter $\overline{u}$ and the $\nabla_\varphi F_\varphi$, especially in low latitudes. As will be shown in the following, averaging the squared correlation only over 40-72°N, and not over 25-72°N as in Smith et al. (2022), enables us to compensate for the underestimation of the eddy feedback parameter computed with our method.

3 Results and discussion

3.1 Pan-Arctic sea ice loss

The Arc sea ice loss is greater in the PAMIP experiments than in the CMIP6-piC composites (Fig. 1). Specifically, the magnitude of sea ice extent decrease in the PAMIP experiments is approximately 4 times larger compared to the CMIP6-piC composite (Fig. 1c). In September, a loss of sea ice takes place in the Central Arctic for the PAMIP experiments, while it occurs only in the peripheral Arctic seas for the CMIP6-piC composites (Fig. 1a-b). Furthermore, the seasonality is also different between the two set of experiments. In the PAMIP experiments, there is a second peak in sea ice loss during winter, which is absent in the CMIP6-piC composites (Fig. 1c). Among the CMIP6 models, MIROC6 exhibits a lower magnitude of change in sea ice extent than other models (Fig. 1c). It is worth mentioning that all PAMIP models have the same change in sea ice extent, as the sea ice concentration is prescribed in the PAMIP experiments.

In the PAMIP experiments, the sea ice loss in Hudson Bay leads to a significant decrease in sea level pressure there, which propagates towards the North Atlantic region (Fig. 2a). A positive anomaly is simulated north of this negative anomaly, resulting in a dipole resembling a negative winter NAO-like pattern (Fig. 2a). Similarly, the CMIP6-piC composites also exhibit the negative NAO-like pattern response (Fig. 2b). To further investigate this, we computed the NAO index change for each model and each experiment (Fig. 2c). Both approaches combined, all models experience a decrease in the NAO index due to an Arc sea loss, except in one model for the PAMIP experiments (Fig. 2c). Furthermore, the multi-model mean with the 95% confidence interval indicates a decrease in the NAO index. Note that the change in NAO is statistically significant in 3 out of

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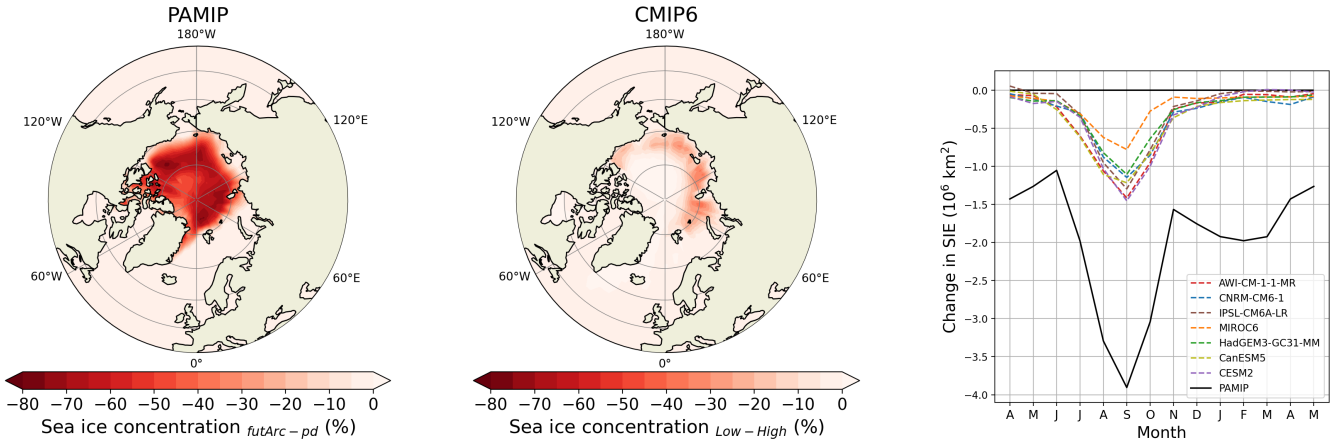

(a) (b) (c)

Figure 1. Multi-model mean difference in sea ice concentration between future and present-day Arc sea ice conditions in the PAMIP experiments (a) and between years of low sea ice extent and years of high sea ice extent in the CMIP6-piC runs (b). (c) displays the Arc sea ice extent changes (in $10^6 km^2$) in the PAMIP experiments (black line), and in the CMIP6-piC composites (colored dashed lines). Only one line is shown in PAMIP, as all the models are subjected to the same sea ice forcing.

the 7 models when considering both approaches (Fig. 2c).

Consistently with the decrease in the NAO index associated with an Arc sea ice loss, the zonal wind weakens in both the troposphere and the stratosphere at mid-latitudes (Fig. 2d-e). Moreover, this weakening is linked with an equatorward shift of the winter polar jet stream. The most pronounced weakening of zonal winds occurs within the stratospheric polar vortex (SPV) (Fig. 2d-e), and most models display a decrease in the SPV strength (Fig. 2f), consistent with the decrease in the NAO index. However, the statistical significance of the SPV weakening is limited to the IPSL-CM6A-LR model of the CMIP6-piC composites (Fig. 2f). These results show that the SPV response to Arc sea ice loss is weak compared to internal climate variability, even in sensitivity experiments with a large ensemble, such as in HadGEM3-GC31-MM (300 members), which shows no robust changes in SPV.

Despite the substantial discrepancy in the change of Arc sea ice extent, the atmosphere circulation response remains consistent across both approaches (Fig. 2). The negative NAO phase and the weakening in zonal winds in response to Arctic sea ice loss have been previously documented (e.g. Honda et al., 2009; Mori et al., 2014; Deser et al., 2015; Levine et al., 2021; Smith et al., 2022; Screen et al., 2022). These responses can be attributed to the following mechanism. According to the thermal wind theory, the Arctic warming due to sea ice loss decreases the temperature gradient between the Arctic and the equator (e.g. Cohen et al., 2014; Barnes and Screen, 2015; Cohen et al., 2020), consequently leading to the wind shear decrease on the poleward side of the jet stream (Smith et al., 2022). This generates a weakening of zonal winds at mid-latitudes (e.g. England

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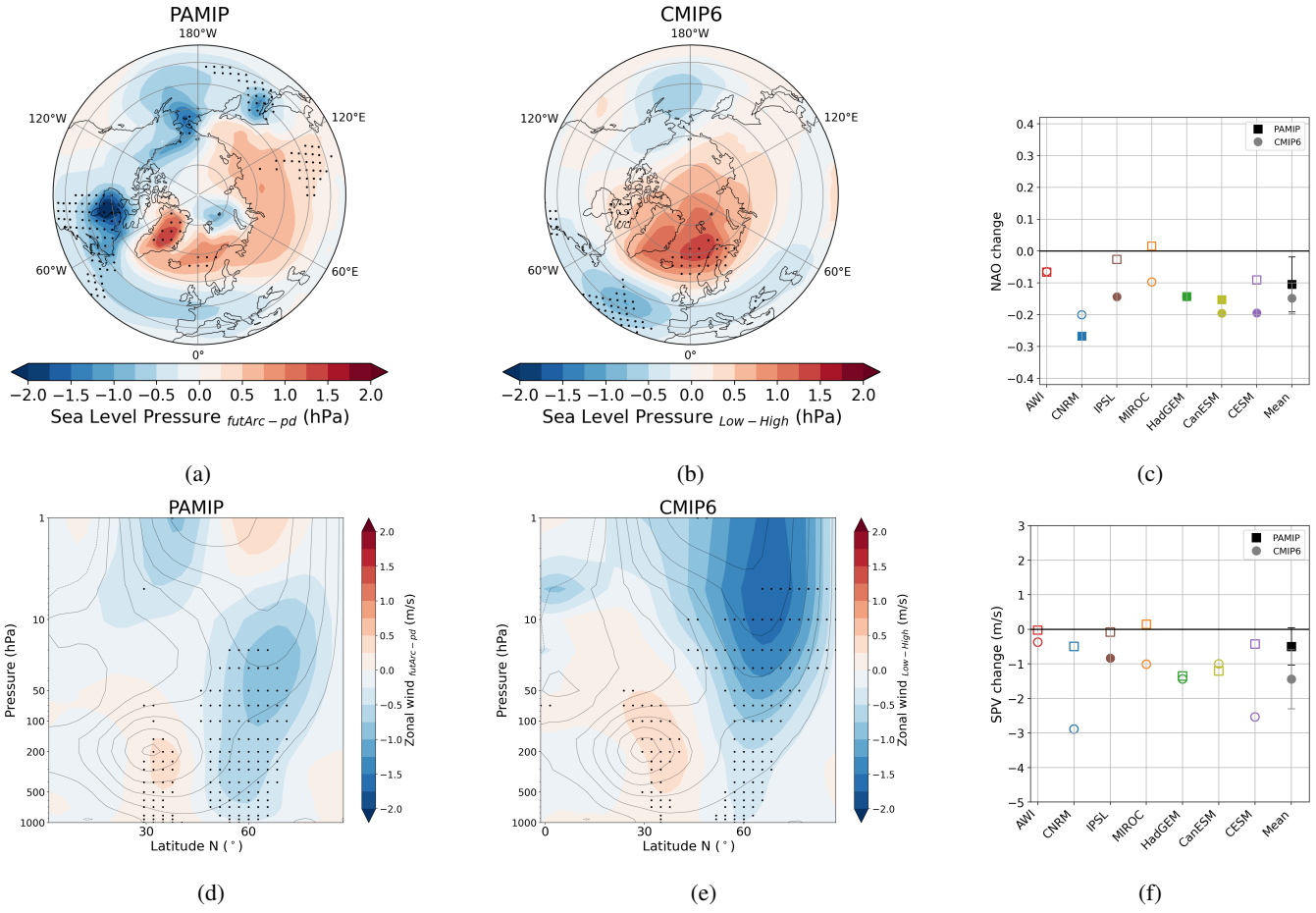

Figure 2. Multi-model mean difference in sea level pressure between future and present-day Arc sea ice conditions in the PAMIP experiments (a) and between years of low sea ice extent and years of high sea ice extent in CMIP6-piC runs (b) in winter (DJF). (c) displays the change in the NAO index between future and present-day sea ice conditions in the PAMIP experiments (squares) and between years of low sea ice extent and years of high sea ice extent in the CMIP6-piC runs (circles) for each model in winter (DJF). Filled circles and squares show a statistically significant response according to a 5% level Kolmogorov-Smirnov test for a given model in the corresponding set of experiments. The multi-model mean is shown by a black filled square (PAMIP) or a grey circle (CMIP6-piC), with the whiskers showing the 95% confidence intervals. (d) and (e) as (a) and (b) but for the zonally averaged zonal wind speed response. (f) as (c) but for the SPV change.

et al., 2018; Smith et al., 2022; Screen et al., 2022), which can be manifested by a decrease in the NAO index. However, it is important to acknowledge that a regional sea ice loss can yield diverse effects on the atmospheric circulation. Specifically, sea ice loss in the Atlantic sector may play a significant role in the weakening of zonal winds due to its larger impact on the weakening of the SPV. Conversely, a sea ice loss in the Pacific sector may result in an opposing response, i.e., a strengthening of zonal winds at mid-latitudes and of the SPV (Sun et al., 2015; Screen, 2017a; McKenna et al., 2018). Section 3.2 examines

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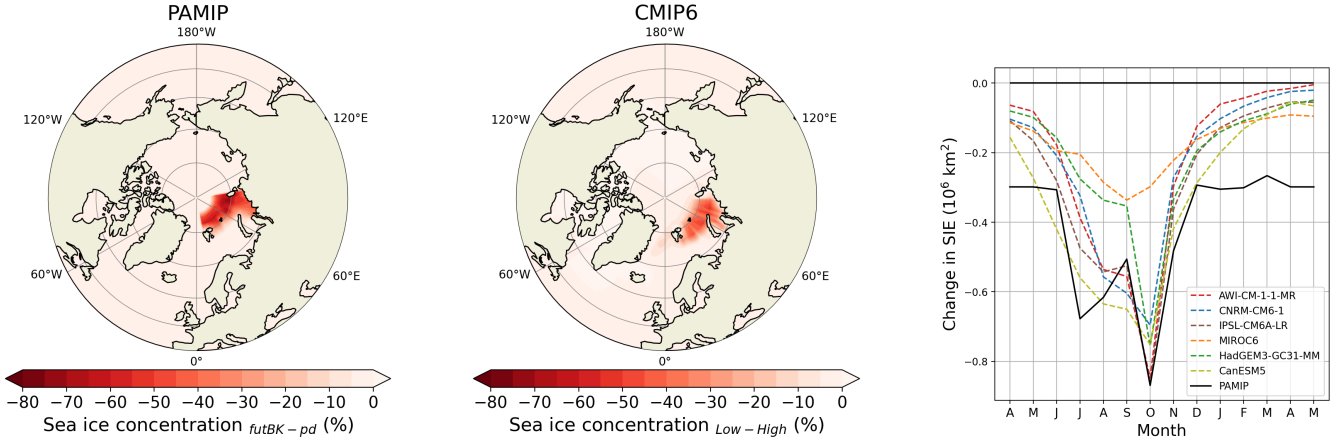
the atmospheric circulation responses to sea ice loss first in the BK Seas and then in the Sea of Okhotsk.

3.2 Regional sea ice loss

The reductions in BK sea ice extent are similar in the two approaches (Fig. 3), unlike the reductions in the Arc sea ice loss experiments (Fig. 1). Moreover, the changes in BK sea ice extent are generally consistent across all models in the CMIP6-piC composites, with the exception of MIROC6, which exhibits weaker changes (Fig. 3c). Note that for the composite approach, the sea ice changes between the low and high sea ice extent years are primarily attributed to natural variability. Consequently, it appears feasible to reproduce the projected BK sea ice loss at the end of the 21st century by solely examining the natural variability of sea ice in the CMIP6-piC simulation. In contrast, this is not possible for the projected Arc sea ice loss (Fig. 1).



(a) (b) (c)

Figure 3. Multi-model mean difference in sea ice concentration between future and present-day BK sea ice conditions in the PAMIP experiments (a) and between years of low sea ice extent and years of high sea ice extent in the CMIP6-piC runs (b). (c) displays the BK sea ice extent changes (in 10^6km^2) in the PAMIP experiments (black line), and in the CMIP6-piC composites (colored dashed lines). Only one line is shown in PAMIP, as all the models are subjected to the same sea ice forcing.

The atmospheric circulation response to BK sea ice loss shows less similarity between the two approaches compared to the Arc sea ice loss experiments (Fig. 4), despite a resemblance in the magnitude of sea ice loss in both approaches. In the PAMIP experiments, the negative NAO pattern is also simulated due to BK sea ice loss (Fig. 4a), albeit with less intensity compared to the Arc sea ice loss experiments (Fig. 2a). In contrast, in the CMIP6-piC composites, the negative NAO pattern due to BK sea ice loss is amplified relative to the Arc sea ice loss (Fig. 4b). The changes simulated in the NAO index align with these findings (Fig. 4c). Specifically, only the HadGEM3-GC31-MM model exhibits a statistically significant decrease in the NAO index for the PAMIP experiments, whereas 4 out of the 6 models show a statistically significant decrease in the CMIP6-piC composites

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(Fig. 4c). The multi-model mean NAO index for the PAMIP experiments exhibits a marginal negative value with a large model spread, while the model spread is weak in the CMIP6-piC composites (Fig. 4c).

The changes in zonal winds are consistent with the sea level pressure responses, i.e., weak changes in the PAMIP experiments and significant changes in the CMIP6-piC composites (Fig. 4d-f). Still, in the PAMIP experiments, most models simulate a weakening of zonal winds in the troposphere beyond 60°N (Fig. 4d). In contrast, the composite approach displays a larger zonal wind weakening, particularly in the stratosphere, starting around 45°N (Fig. 4e). Furthermore, the equatorward shift of zonal winds resulting from the Arc sea ice loss (Fig. 2d-e) is more intense in the CMIP6-piC composites for the BK sea ice loss (Fig. 4e). The changes in the SPV strength follow the change in the NAO index (Fig. 4f). Specifically, the PAMIP experiments exhibit weak changes, whereas the composites demonstrate a significant weakening of the SPV. However, the model spread is weaker in the PAMIP experiments compared to the CMIP6-piC composites.

Similarly to the BK experiments, the sea ice loss in the Okhotsk experiments displays closer agreement between the two approaches than in the Arc experiments (Fig. 5). Therefore, it also appears possible to replicate the future projected Okhotsk sea ice loss only by examining the natural variability of sea ice in the CMIP6-piC runs. However, model spread in the CMIP6-piC composites is larger than in the BK target areas (Fig. 5c), and the timing of the maximum sea ice loss typically occurs one month earlier in the CMIP6-piC composites compared to the PAMIP experiments. This lag can be attributed to the specific construction of the composite samples in this sea ice area (see Section 2.2).

In the PAMIP experiments, models only agree on a decrease in sea level pressure over the sea ice loss area, i.e., in the Sea of Okhotsk, and on a weak increase over eastern Eurasia (Fig. 6a). In the CMIP6-piC composites, the decrease in sea level pressure extends from the sea ice loss area to the North Pacific, resulting in a deepening of the Aleutian Low (Fig. 6b). Furthermore, an increase in sea level pressure occurs over eastern Europe (Fig. 6b). No clear response in the NAO index emerges due to Okhotsk sea ice loss, except a strong positive NAO in CanESM5 for the PAMIP experiments (Fig. 6c). The zonal wind response in high latitudes is similar in the two approaches, with a strengthening of zonal winds in the stratosphere (Fig. 6d-e). However, models disagree on this response, except locally in the PAMIP experiments (Fig. 6d). Notably, the SPV strengthening is statistically significant in only one model, and the model spread appears large in both approaches. (Fig. 6f).

The atmospheric circulation responses to regional sea ice loss show lower certainty than the responses to Arc sea ice loss. On the one hand, Arc sea ice loss produces a decrease in the NAO index and a weakening of the SPV in both approaches (Fig. 2). On the other hand, BK sea ice loss generates the same responses but with model agreement only in the CMIP6-piC composites (Fig. 4). Moreover, the response to Okhotsk sea ice loss exhibits a large model spread in the SPV/NAO changes, although the multi-model mean indicates a strengthening of the SPV in both approaches (Fig. 6). Hence, the circulation response to BK sea ice loss shows greater similarity to the response to Arc sea ice loss, albeit with increased uncertainty.

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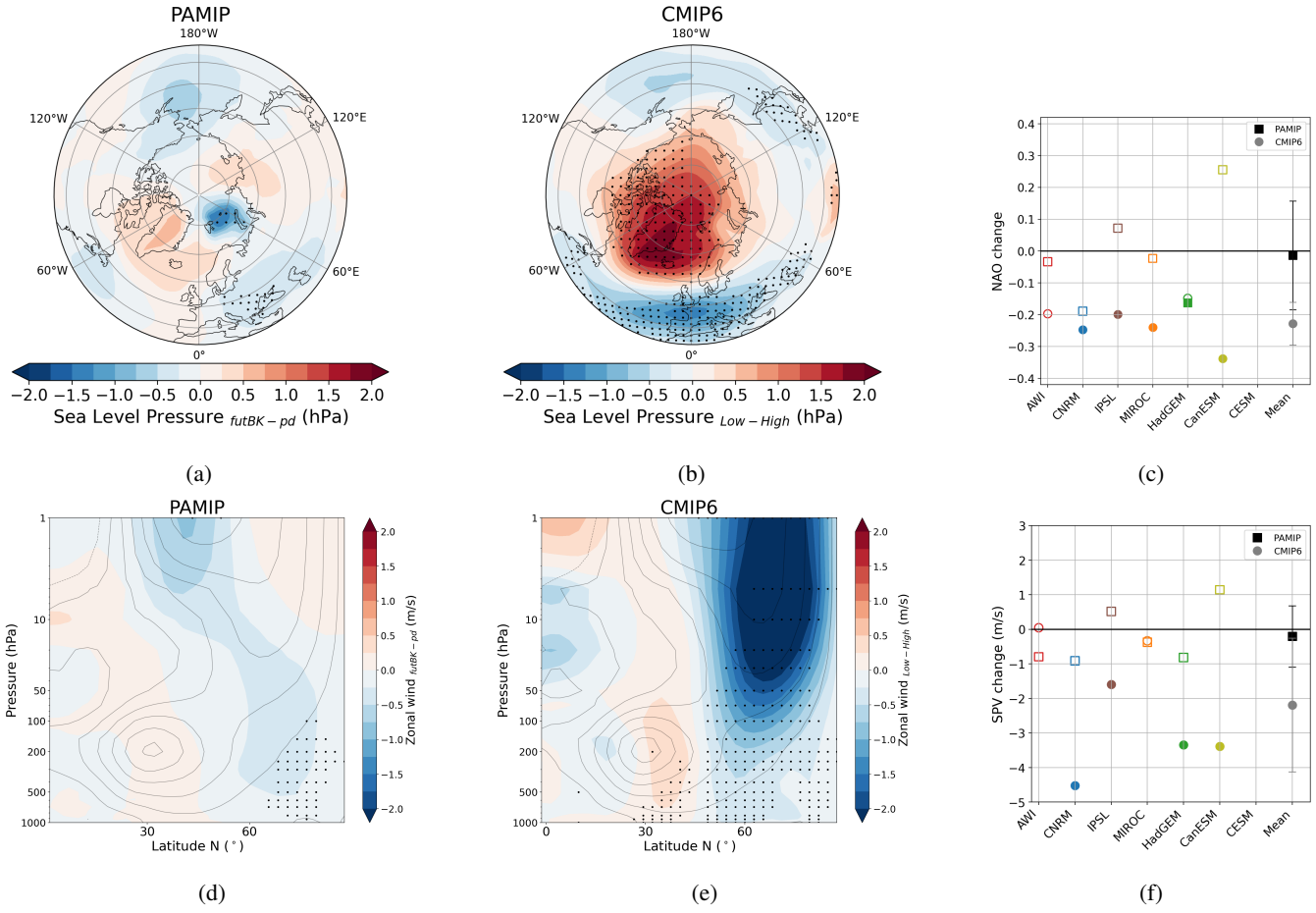

Figure 4. Multi-model mean difference in sea level pressure between future and present-day BK sea ice conditions in the PAMIP experiments (a) and between years of low sea ice extent and years of high sea ice extent in CMIP6-piC runs (b) in winter (DJF). (c) displays the change in NAO index between future and present-day sea ice condition in the PAMIP experiments (squares) and between years of low sea ice extent and years of high sea ice extent in the CMIP6-piC runs (circles) for each model in winter (DJF). Filled circles and squares show a statistically significant response according to a 5% level Kolmogorov-Smirnov test for a given model in the corresponding set of experiments. The multi-model mean is shown by a black filled square (PAMIP) or a grey circle (CMIP6-piC), with the whiskers showing the 95% confidence intervals. (d) and (e) as (a) and (b) but for response. (f) as (c) but for the zonally averaged zonal wind speed the SPV change.

The resemblance between Arc and BK sea ice losses in the CMIP6-piC composites can partly be attributed to the fact that the variability of the Arc sea ice extent in September is strongly dependent on the variability of the BK sea ice extent in October. Thus, similar years can be picked in the Arc and BK composites (not shown). However, in the PAMIP experiments, the Arc and BK experiments are independant, and one model can give constrasting atmospheric circulation reponses to sea ice loss in these areas, such as CanESM5 (Figs. 2c,f and 4c,f). Levine et al. (2021) have highlighted divergent zonal wind responses between future Arc and BK sea ice losses in a PAMIP model not included in our analysis. Nonetheless, our study shows that models

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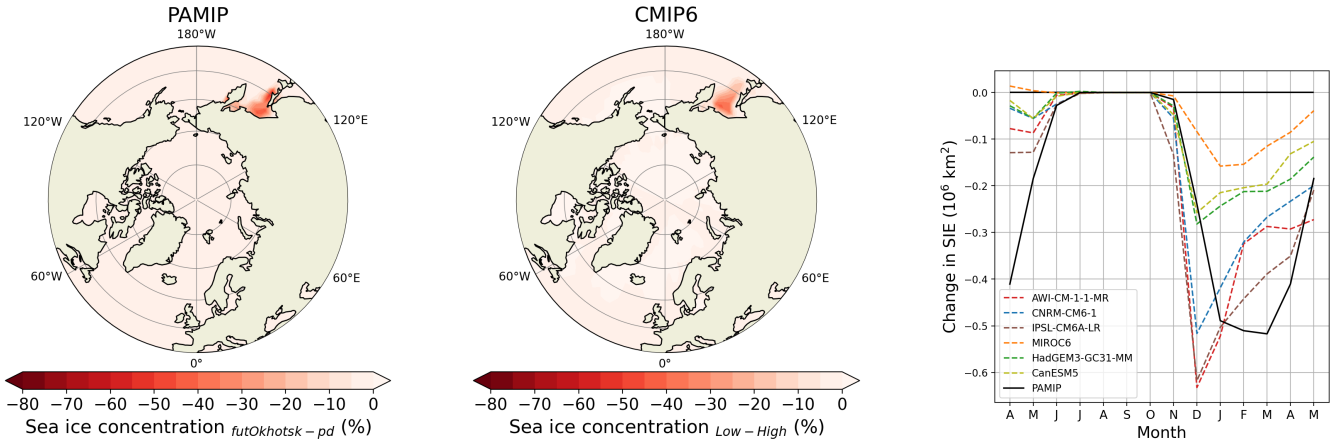

(a) (b) (c)

Figure 5. Multi-model mean difference in sea ice concentration between future and present-day Okhotsk sea ice conditions in the PAMIP experiments (a) and between years of low sea ice extent and years of high sea ice extent in the CMIP6-piC runs (b). (c) displays the Okhotsk sea ice extent changes (in $10^6 km^2$) in the PAMIP experiments (black line), and in the CMIP6-piC composites (colored dashed lines). Only one line is shown in PAMIP, as all the models are subjected to the same sea ice forcing.

usually generates consistent NAO/SPV responses to both Arc and BK sea ice losses, even in the PAMIP experiments (Figs. 2c,f and 4c,f). This emphasizes the usefulness of looking at the atmospheric responses to sea ice loss with several climate models.

In the regional sea ice loss experiments, there is a close agreement in the sea ice extent anomaly between the two approaches (Figs. 3 and 5). However, the atmospheric responses to regional sea ice losses exhibit larger discrepancies between the two approaches in comparison to the Arc sea ice loss experiments. Specifically, the decreases in NAO/SPV indices are larger in the CMIP6-piC composites compared to the PAMIP experiments, and these discrepancies are more pronounced in the BK sea ice loss experiments than in the Arc sea ice loss experiments. The divergent atmospheric circulation responses observed between the approaches used can be attributed to their inherent differences, and various factors can contribute to explaining the contrasting results. Next, we investigate the potential reasons for the amplified response in the CMIP6-piC composites compared to the PAMIP experiments in the Arc and BK target areas.

3.3 Why is the atmospheric circulation response larger in the CMIP6-piC composites?

The possible causes of difference between the PAMIP experiments and CMIP6-piC composites are 1) the coupling effect, 2) the differences in climatological background state such as the different sea ice conditions or the different atmospheric conditions, and 3) the differences in the methods used because confounding factors, such as the snow cover or the SSTs, are not

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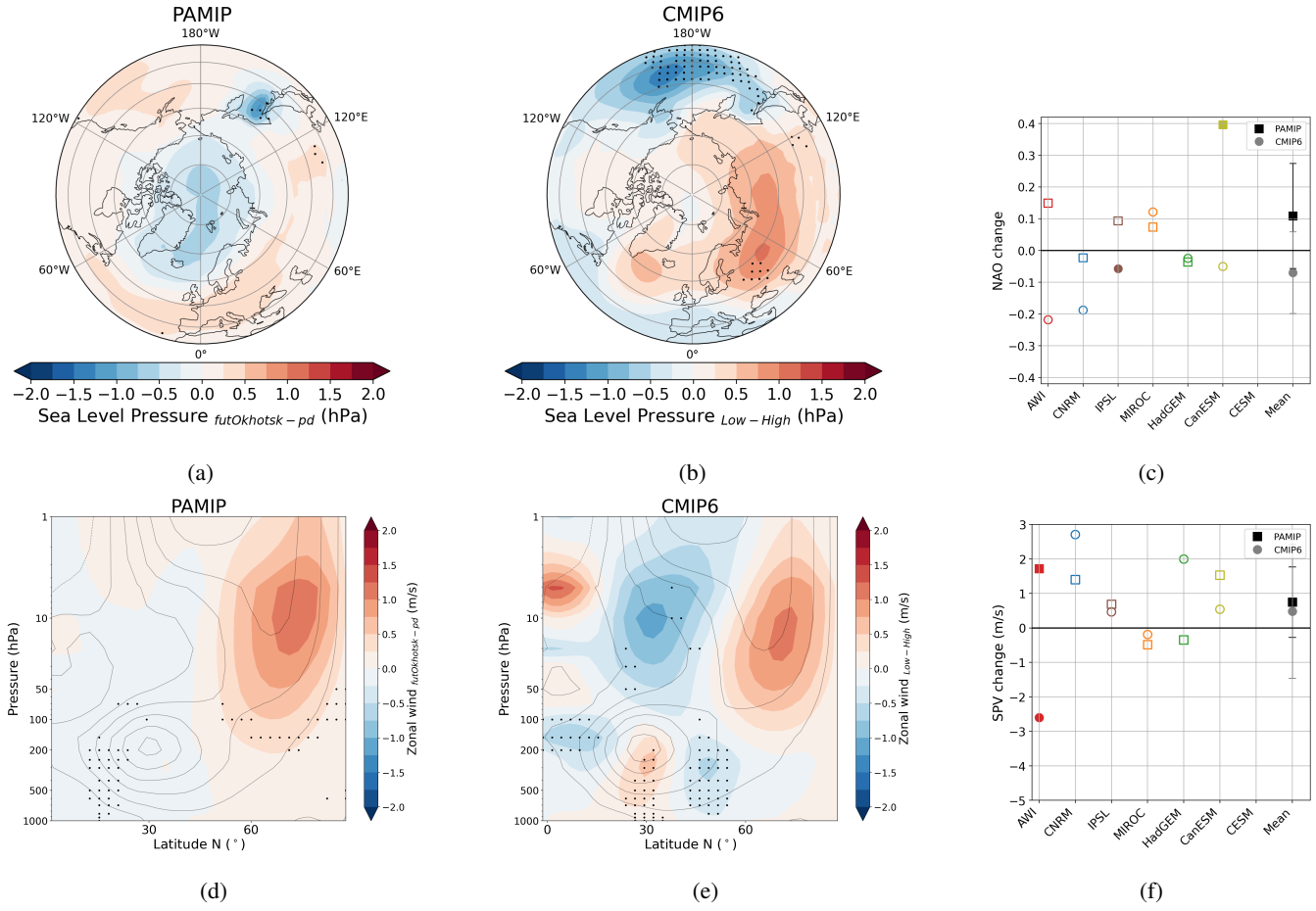

Figure 6. Multi-model mean difference in sea level pressure between future and present-day Okhotsk sea ice conditions in the PAMIP experiments (a) and between years of low sea ice extent and years of high sea ice extent in CMIP6-piC runs (b) in winter (DJF). (c) displays the change in NAO index between future and present-day sea ice conditions in the PAMIP experiments (squares) and between years of low sea ice extent and years of high sea ice extent in the CMIP6-piC runs (circles) for each model in winter (DJF). Filled circles and squares show a statistically significant response according to a 5% level Kolmogorov-Smirnov test for a given model in the corresponding set of experiments. The multi-model mean is shown by a black filled square (PAMIP) or a grey circle (CMIP6-piC), with the whiskers showing the 95% confidence intervals. (d) and (e) as (a) and (b) but for the zonally averaged zonal wind speed response. (f) as (c) but for the SPV change.

fixed for the CMIP6-piC runs and can affect the atmospheric responses.

The larger decrease in the NAO/SPV response in the CMIP6-piC composites compared to the PAMIP experiments may be attributed to the use of coupled models in the CMIP6-piC composites, whereas the PAMIP simulations (described in Section 3.1 and 3.2) use atmosphere-only models. Coupled models tend to amplify the extratropical atmospheric response to sea ice loss, such as the weakening of the westerly winds in the poleward flank of the jet stream (Deser et al., 2016; Smith et al., 2017).

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Thus, the coupling in the composite approach could explain the larger negative response in NAO/SPV than in the atmosphere-only PAMIP experiments.

To investigate the impact of atmosphere-ocean coupling, we can examine the PAMIP experiments conducted with coupled models. Specifically, IPSL-CM6A-LR and HadGEM3-GC31-MM have been run under future Arc sea ice loss conditions in coupled mode (Table 2). The impact of the coupling on the atmospheric circulation differs between the two models (Fig. 7). Nonetheless, neither of the models displays a more pronounced decrease in the NAO or in the zonal wind speed in the coupled models simulations. In fact, HadGEM3-GC31-MM simulates a weaker decrease in the NAO index with coupling (Fig. 7b-c), while IPSL-CM6A-LR shows a strengthening of the SPV with coupling (Fig. 7d,f). The largest impact of coupling on the zonal wind primarily occurs in the low latitudes (Fig. 7d-e).

Based on these results, we can conclude that the coupling itself does not lead to a larger response in PAMIP experiments and does not seem to be the main cause for the greater CMIP6-piC composite response compared to the PAMIP atmosphere-only response. This result diverges from the one of Simon et al. (2022), who identified a more significant weakening of zonal wind in IPSL-CM6A-LR with an atmosphere-ocean coupling. However, it is important to note that our comparison involved the future Arc sea ice loss relative to the present-day sea ice conditions, rather than comparing it to the pre-industrial one as conducted by Simon et al. (2022). Accounting for the atmosphere-ocean coupling might be more crucial in long simulations because the Atlantic Meridional Overturning Circulation (AMOC) can be slowed down after several decades (Sévellec et al., 2017). Furthermore, only two out of the seven models have conducted PAMIP coupled experiments, which prevents us from drawing a definitive conclusion regarding the role of atmosphere-ocean coupling on the atmospheric circulation response to sea ice loss.

To further investigate the possible role of coupling on the larger decrease in the NAO/SPV indices in the CMIP6-piC composites, the eddy feedback parameter has been computed for each model and each approach (Fig. 8). Recent studies have shown a robust relationship between the value of the this parameter and the simulated winter zonal wind response to sea ice loss (Smith et al., 2022; Screen et al., 2022). Models with larger eddy feedback parameter values, and thus closer to reanalyses, simulate a stronger weakening of mid-latitude westerlies in winter (and the SPV) in response to sea ice loss (Smith et al., 2022; Screen et al., 2022). In our study, the value of the eddy feedback parameter is also underestimated with a northward shift (not understood yet) compared to reanalyses (Fig. 8). Moreover, this parameter is slightly greater in the PAMIP experiments than in the CMIP6-piC runs (Fig. 8). Finally, the inter-model difference for this parameter is usually larger than the difference between the type of experiment used (PAMIP or CMIP6-piC). This highlights that the dependence of the eddy feedback is more closely related to the choice of model rather than the type of simulation or the presence of atmosphere-ocean coupling.

Similarly to the findings of Smith et al. (2022), we found a negative correlation between the eddy feedback parameter and the NAO/SPV change in response to an Arc sea ice loss (Fig. 9). However, this negative correlation is not statistically significant at a 5% level when the two approaches are combined. Nevertheless, if only the PAMIP experiments are considered, the

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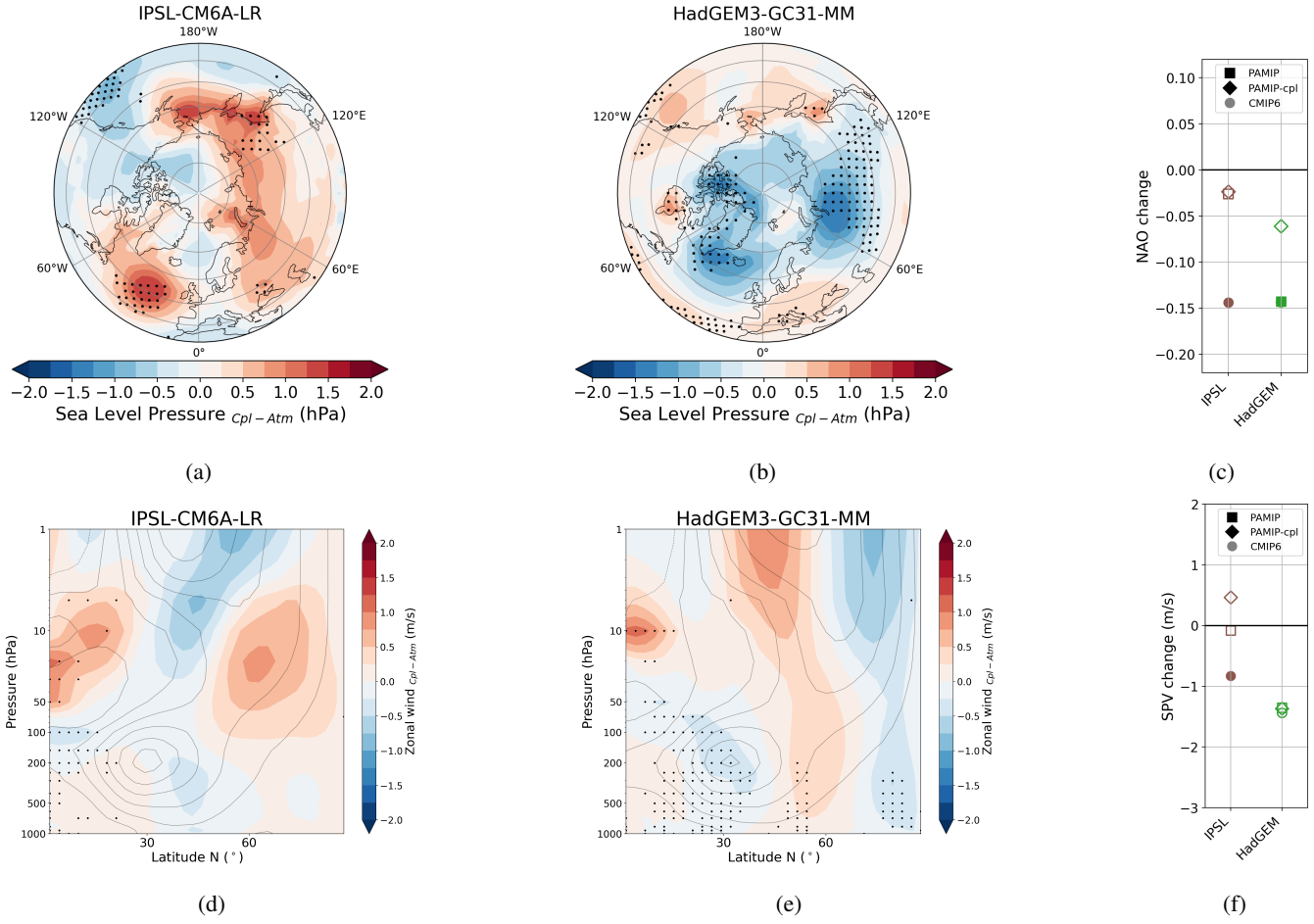

Figure 7. Difference in the winter sea level pressure response between the PAMIP coupled experiments and the PAMIP atmosphere-only experiments for the future Arc sea ice loss in IPSL-CM6A-LR (a) and in HadGEM3-GC31-MM (b). (c) displays the change in NAO index response in the atmosphere-only PAMIP experiments (squares), in the coupled PAMIP experiments (diamonds), and in the CMIP6-piC composites (circles) for both models in winter (DJF). Filled circles and squares show a statistically significant response according to a 5% level Kolmogorov-Smirnov test for a given model in the corresponding set of experiments. (d) and (e) as (a) and (b) but for the zonal mean zonal wind. (f) as (c) but for the SPV change. Dots on the maps indicate regions where the response between the coupled and the atmosphere-only PAMIP experiments exhibit statistically significant differences according to a 5% level Kolmogorov-Smirnov test.

correlation between the eddy feedback parameter and the SPV becomes statistically significant (Fig. 9), consistently with the results of Smith et al. (2022) and Screen et al. (2022). However, no clear relationship between the eddy feedback parameter and the NAO/SPV change emerges in response to a BK sea ice loss. This lack of relationship may be attributed to the limited number of available models because a correlation exists with the SPV change due to either an Arc or a BK sea ice anomaly of 28 models performing the CMIP6-piC (Fig. A1). This indicates that a larger ensemble of models allows for a robust correlation between these two variables. Nonetheless, no robust linear correlation exists with the NAO index response to BK sea ice loss

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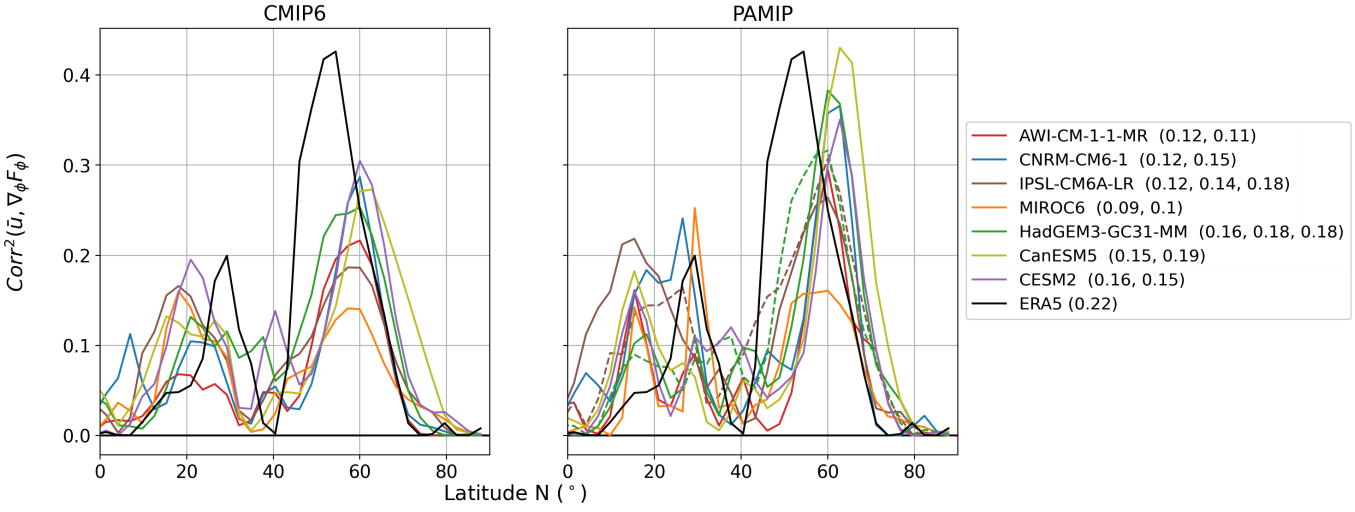

Figure 8. Squared correlation between winter $\nabla_\varphi F_\varphi$ and $\overline{u}$ averaged between 600 to 200 hPa from 0°N to 90°N in the CMIP6-piC runs (left) and in the PAMIP experiments (right). The dashed lines display the PAMIP coupled experiments and the black lines display the fifth generation of European ReAnalysis (ERA5 (1979-2021); Hersbach et al., 2020). The eddy feedback parameter (M) here is the squared correlation averaged over 40-72°N. In the legend, the first value stands for the CMIP6-piC runs, the second stands for the PAMIP atmosphere-only experiments and the third stands for the PAMIP coupled experiments when performed.

(Fig. A2).

Our study, along with the findings of Smith et al. (2022), demonstrates that the sensitivity of the winter NAO/SPV responses across models increases with higher values of the eddy feedback parameter. However, we found lower values of this parameter in the CMIP6-piC runs than in the PAMIP experiments (Fig. 8). Therefore, the difference in the eddy feedback parameter between the PAMIP experiments and CMIP6-piC runs cannot explain the larger decrease in the NAO/SPV indices in the CMIP6-piC composites. Moreover, the eddy feedback parameter in the PAMIP coupled experiments is larger than in the atmosphere-only experiments in only one of the two models available (Fig. 8). This suggests that coupling may not necessarily result in a more accurate representation of the eddy feedback in models, which could have led to a better detection of the short-term atmospheric circulation response. However, further research needs to be carried out with a larger ensemble of coupled models to assert this statement.

The discrepancies in background states among different experiments can lead to distinct atmospheric responses to a given forcing (Son, 2010; Sigmond and Scinocca, 2010; Garfinkel et al., 2013; Smith et al., 2017). In our analysis, for a given model, the climatological SPV strength is consistently lower in the CMIP6-piC simulations than in the PAMIP simulations (Fig. 10). Thus, the larger negative SPV response to Arc sea ice loss observed in 5 of the 7 models, and to BK sea ice loss observed in 4 of the 6 models, could be associated with the lower climatological winter SPV strength (Fig. 10). Smith et al. (2017) have obtained

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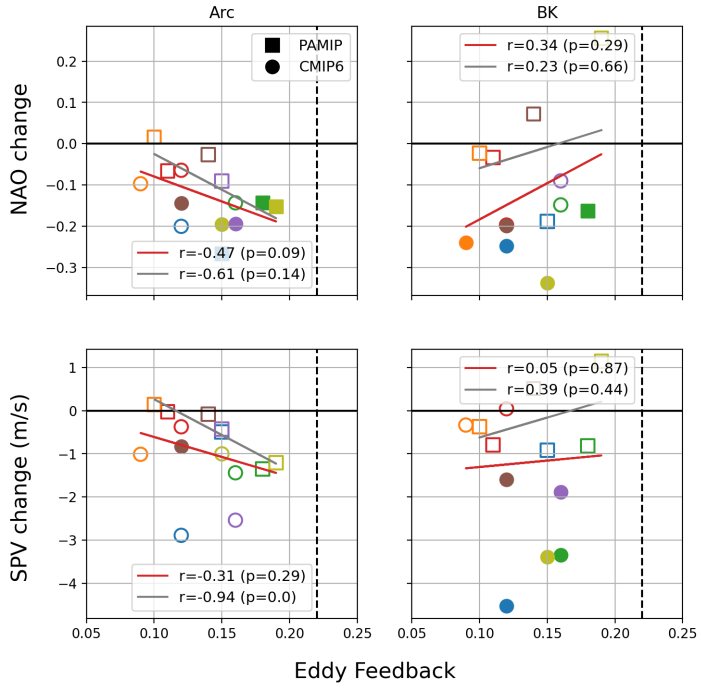

Figure 9. Change in NAO index (top) and in SPV (bottom) between future and present-day sea ice conditions in the PAMIP experiments (squares) and between years of low sea ice extent and years of high sea ice extent in CMIP6-piC runs (circles) according to the eddy feedback parameter. Filled circles and squares show a statistically significant response according to a 5% level Kolmogorov-Smirnov test for a given model in the corresponding set of experiments, for the Arc (left) and the BK (right). Red line and grey line show the linear regression with the correlation value R with its p-value for all models/approaches combined and for the PAMIP models only, respectively. The vertical black dashed line shows the Eddy feedback parameter for ERA5 (1979-2021).

similar results in a single-model study, but for the responses of the jet stream speed or latitude to sea ice loss. Nevertheless, the reasons behind the relationship between lower climatological SPV strength and larger negative SPV response have not been investigated in our study. Furthermore, the difference in initial sea ice extent between CMIP6-piC and PAMIP simulations is weak (Fig. A3), and thus could not explain the larger simulated responses in the CMIP6-piC composites. Consequently, the disparities in background state seems to play a role in the discrepancies between CMIP6-piC and PAMIP experiments, but only for the SPV background state.

The third possible cause of the discrepancies in the atmospheric circulation responses to sea ice loss between the CMIP6-piC and PAMIP experiments may arise from the use of different approaches for detecting the impact of Arctic sea ice loss. The PAMIP experiments specifically focus on isolating the direct effect of sea ice loss and the associated increase in SST in newly ice-free regions. In contrast, the composite analysis performed on the CMIP6-piC does not exclusively isolate the effect of sea ice loss, potentially leading to different results as other factors can play a role (Smith et al., 2017). It is important to

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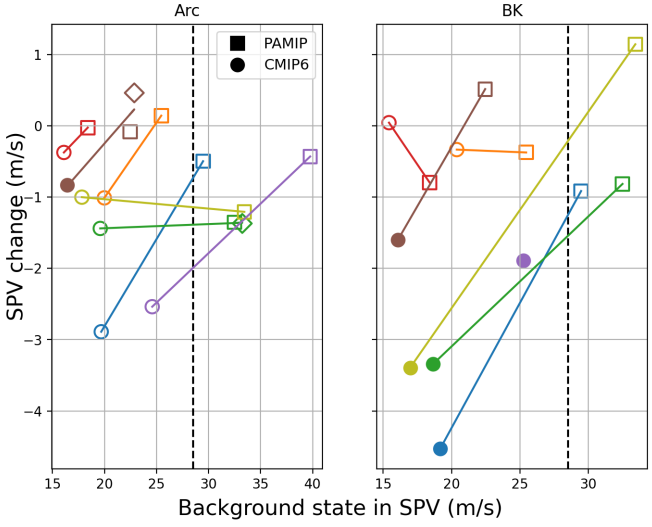

Figure 10. Difference in SPV strength between future and present sea ice conditions in the PAMIP experiments (squares) and between years of low sea ice extent and years of high sea ice extent in CMIP6-piC runs (circles) as a function of climatological SPV from the present-day simulation in the PAMIP experiments and of the years of high sea ice extent in the CMIP6-piC composites. Filled circles and squares show a statistically significant according to a 5% level Kolmogorov-Smirnov test for a given model in the corresponding set of experiments, for the Arc (left) and the BK (right). A line or a linear regression line is drawn between the different experiments of a same model. The vertical black dashed line shows the mean SPV strength for ERA5 (1979-2021).

acknowledge that certain factors contributing to sea ice loss cannot perfectly be separated from one another in the CMIP6-piC composites. These factors, such as confounding factors, could be the change in SST associated with the El Niño–Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO), the change in the snow cover, or the change in the Quasi-Biennial Oscillation (QBO). We examine these different factors below.

In the CMIP6-piC composites, a negative SST anomaly is simulated in the Pacific Ocean in the years with low BK sea ice extent compared to years with high BK sea ice extent (not shown). This anomaly is concurrent with a decrease in the ENSO index in almost all models (first row on the right in Fig. 11). El Niño events, which can be associated with warm PDO events, are linked to a weakening of the SPV (Manzini et al., 2006; Hurwitz et al., 2012; Domeisen et al., 2019) and to negative NAO conditions (Brönnimann, 2007). Furthermore, an El-Niño phase associated with low Arctic sea ice coverage also tends to produce a weakening of the SPV (Ma et al., 2022), although the atmospheric responses to sea ice loss and PDO do not appear to be additive (Simon et al., 2022). However, the more negative ENSO index during low BK sea ice extent years could not explain the dominant change in NAO/SPV simulated in the CMIP6-piC composites compared to the PAMIP simulations. Furthermore, the difference in ENSO index between years of low and high BK or Arc sea ice extents is not statistically significant for all

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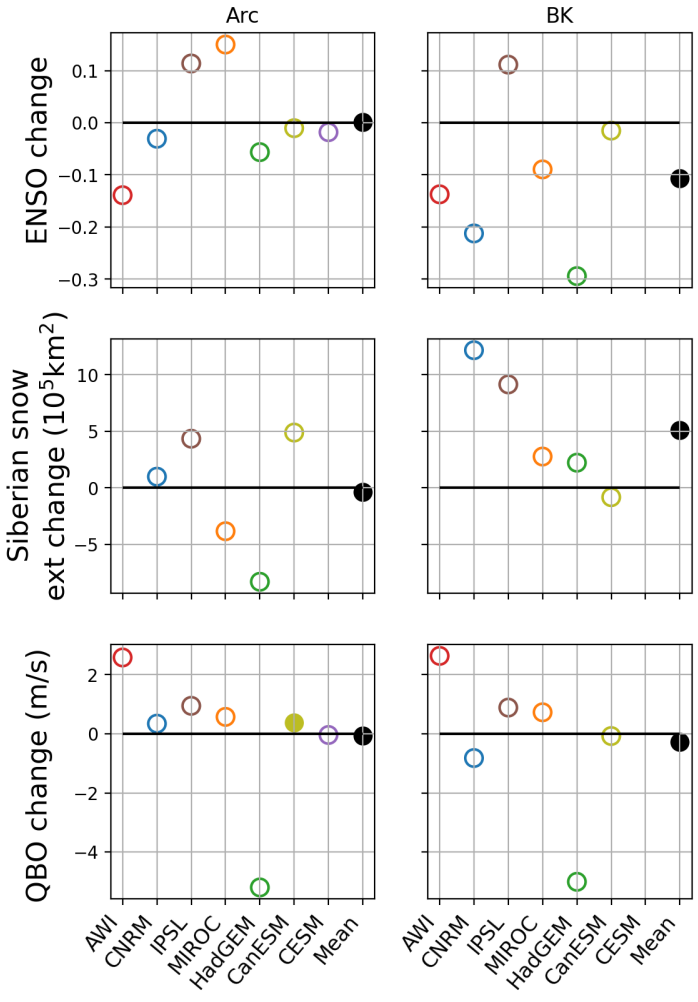

Figure 11. Three possible confounding factors in the CMIP6-piC composites in response to the Arc (left) and the BK sea ice loss (right). The first row displays the winter Nino 3.4 index change between years of low and high sea ice extents for the CMIP6-piC runs. The second row shows the November Siberian (43-56°N, 70-140°E according to Gastineau et al. (2017)) snow cover change between years of low and high sea ice extents for the CMIP6-piC runs. The third row displays the standardised winter QBO change between years of low and high sea ice extents for the CMIP6-piC runs. The QBO is defined here as the variation of the zonally averaged zonal wind speed at 10 hPa averaged between 5°S and 5°N. Filled circle shows a statistically significant according to a 5% level Kolmogorov-Smirnov test for a given model.

models (first row in Fig. 11).

The change in continental snow cover can also impact the winter atmospheric circulation (Brown et al., 2010; Cohen et al., 2007, 2012, 2014). For instance, an increase in autumn snow cover over Eurasia can trigger the weakening of the SPV in a similar manner to the loss of BK sea ice (Cohen et al., 2007, 2012, 2014; Gastineau et al., 2017; Simon et al., 2020). As the

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snow cover is not fixed in the CMIP6-piC runs, this could contribute to the larger decrease in the SPV strength observed in these simulations. An increase in Siberian autumn snow cover occurs in years of low BK sea ice extent in 4 out of the 5 available models (second row in Fig. 11). In CNRM-CM6-1 and IPSL-CM6A-LR, the snow cover increase appears to be considerable, which may partly explain the large gap between PAMIP experiments and CMIP6-piC composites in the NAO/SPV responses for these two models in the BK sea ice loss experiments (Fig. 4c,f). Nevertheless, it is important to note that the snow cover change between the low and high BK sea ice extent years is not statistically significant in all models (second row in Fig. 11).

The last confounding factor investigated in this study that may alter the atmospheric circulation associated with Arctic sea ice loss is the QBO. The SPV tends to strengthen in response to an Arctic sea ice loss during the westerly QBO phase and weaken during the easterly phase (Labe et al., 2019). However, no robust change is detected in the QBO index between years of low and high sea ice extent in the CMIP6-piC composites, except in CanESM5 after an Arc sea ice extent anomaly (third row in Fig. 11). Nonetheless, the QBO variability in this model is very weak (not shown) to potentially alter the atmospheric impact of Arctic sea ice loss. Similarly, in the PAMIP simulations, we found no robust change in the QBO between future and present sea ice conditions (not shown) that could have weakened the NAO/SPV responses.

In a large ensemble of models using the CMIP6-piC runs, the three possible confounding factors investigated in this study impact the model responses to SPV weakening after a BK sea ice loss (Delhaye et al., 2023). However, these factors do not provide a clear explanation for the larger SPV weakening in the CMIP6-piC composites compared to the PAMIP simulations. Moreover, all these factors, along with other unexplored factors, are interconnected and may produce a non-linear impact linked to the sea ice anomaly (Hall et al., 2015). This non-linearity between possible confounding factors and Arctic sea ice loss could hide the real reason of the disparity between CMIP6-piC composites and PAMIP experiments in the NAO/SPV responses. Moreover, the role of the background state should be considered, which introduces additional complexity to the interpretation of this discrepancy. The future Arc sea ice loss (or BK sea ice loss alone to a lesser extent) seems to play a role in the decrease in the winter NAO index or in the SPV strength, as observed in the PAMIP experiments in most models, but is generally not statistically significant. Furthermore, the sea ice loss in the real world is related to other climatic changes that could amplify the decreases in the SPV strength or in the NAO index, as in the CMIP6-piC composites. However, understanding the exact role of specific climate parameters in parallel to Arctic sea ice loss within fully coupled models remains a topic for future investigations.

4 Conclusions

The loss of Arctic sea ice is one of the main traits of polar climate change (Meredith et al., 2019), and large reductions in sea ice extent could impact the climate at mid-latitudes through atmospheric circulation changes (e.g. Chripko et al., 2021; Levine et al., 2021; Smith et al., 2022; Screen et al., 2022). However, the atmospheric impacts depend on the regional patterns of sea ice loss (e.g. Sun et al., 2015; Screen et al., 2015; McKenna et al., 2018; Levine et al., 2021). In this study, we have investigated

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the short-term atmospheric circulation changes in winter to Arc and to regional (BK and Okhotsk Seas) sea ice loss using two distinct approaches and seven climate models. The first approach consists of sensitivity experiments targeting the expected SIC at the end of this century, while the second one consists of a composite analysis in long CMIP6-piC runs based on the sea ice extent for the same three sea ice regions.

Our results show that the winter circulation response to Arc sea ice loss projects onto a negative NAO-like pattern in both approaches. Additionally, we found a weakening of the mid-latitude westerlies and SPV. The response to BK sea ice loss displays similarities with the response associated with Arc sea ice loss, whereas the response to Okhotsk sea ice loss differs but is uncertain. Moreover, the PAMIP experiments, which are designed to isolate the impact of sea ice loss, produce less pronounced and more uncertain NAO/SPV responses to BK sea ice loss than to Arc sea ice loss. Furthermore, our study highlights the importance of using a multi-model approach, as contrasting responses associated with Arc and BK sea ice losses can be found when relying on a single model. Thus, caution should be exercised when using a single model to understand the future effects of sea ice loss, as performed in some studies previously.

We showed that the larger decrease in the NAO/SPV indices in the CMIP6-piC composites compared to the PAMIP experiments does not result from the absence of atmosphere-ocean coupling in the PAMIP experiments. This conclusion is supported by the analysis of additional coupled PAMIP experiments, which does not reveal larger decreases in these two indices compared to PAMIP atmosphere-only experiments. Nonetheless, it is worth stressing that only two of the seven models have performed the PAMIP coupled experiments. Thus this conclusion needs further investigation with a larger ensemble of climate models. Furthermore, the eddy feedback parameter is not necessarily higher, i.e., closer to reanalyses, in coupled experiments (CMIP6-piC or PAMIP coupled) than in atmosphere-only experiments. However, models with greater feedback parameter result in a larger decrease in NAO/SPV indices to Arc sea ice loss, as shown by Smith et al. (2022). Consequently, our results indicate that atmosphere-ocean coupling does not systematically increase the eddy feedback parameter and does not lead to a larger decrease in NAO/SPV indices in winter in response to sea ice loss.

In conclusion, the use of composite analysis in control runs to examine the atmospheric circulation responses to Arc sea ice loss yields consistent results compared to sensitivity experiments, albeit with amplified responses. Specifically, future Arc sea ice loss alone leads to a decrease in the winter NAO index linked to a weakening of the mid-latitude westerlies and SPV. While a BK sea ice loss may lead to a similar response, this response exhibits less intensity and more uncertainty compared to Arc sea ice loss. Conversely, the response to the loss of sea ice in the Okhotsk Sea differs. These findings support the importance of the role played by the BK sea ice loss in the impacts of Arctic sea ice loss, even for projected future sea ice changes. However, it is important to acknowledge that tropical forcing, such as the ENSO, can also influence the winter atmospheric circulation. Therefore, the interplay between Arctic sea ice loss and tropical forcing should be considered when studying the future response in winter atmospheric circulation.

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Lastly, our study suggests that the atmosphere-ocean coupling may not be the primary driver for simulating amplified atmospheric circulation response to an Arctic sea ice loss, especially since the eddy feedback is not better simulated compared to atmosphere-only simulations. The larger decrease in NAO index and SPV strength in the CMIP6-piC composites compared to PAMIP experiments is probably due to disparities in the background state and in the presence of confounding factors in the CMIP6-piC composites. The understanding and quantification of the different climate factors that overestimate the winter NAO and SPV response linked to an Arc or a BK sea ice loss should be further investigated in fully coupled models.

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Appendix A

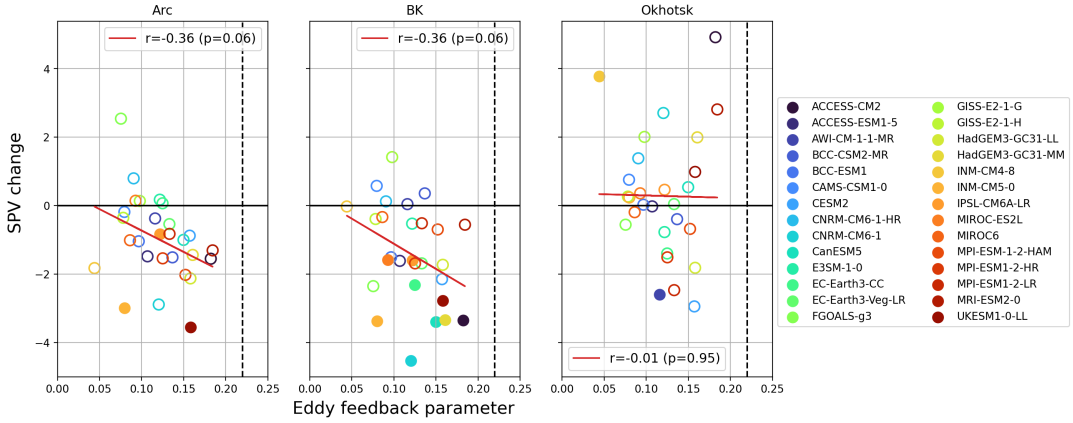

Figure A1. Change in SPV strength between years of low sea ice extent and years of high sea ice extent in the CMIP6-piC runs according to the eddy feedback parameter. Filled circles show a statistically significant according to a 5% level Kolmogorov-Smirnov test for a given model. Red line shows the linear regression with the correlation value R with its p-value. For the Arc (left), the BK (center) and the Okhotsk (right) target areas

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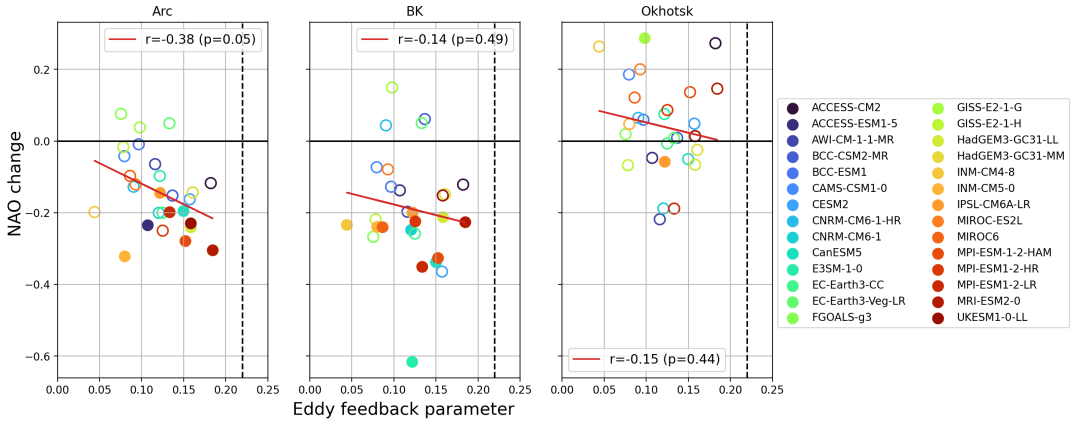

Figure A2. As Fig. A1 but for the NAO index.

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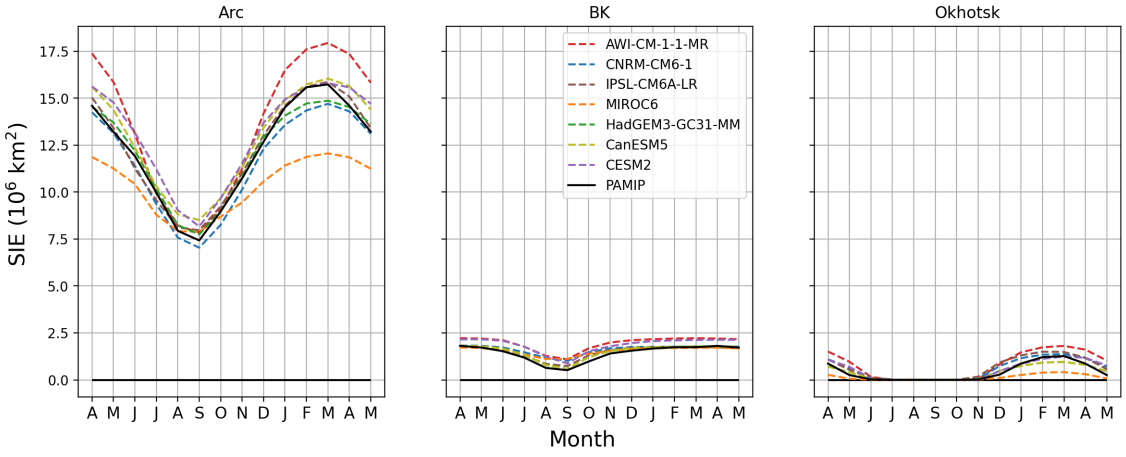

Figure A3. Sea ice extent in the present-day simulation for the PAMIP experiments (black solid line) and in the years of high sea ice extent for the CMIP6-piC runs (dashed lines), for the Arc (left), the BK (center), and the Okhotsk (right) target areas.

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Author contributions. SD, RM, FM and TF conceptualized the science plan. SD performed the analyses with the help of FM, TF, RM, LT. SD produced the figures and wrote the manuscript based on the insights from the co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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Data availability. The data from the all models are openly available and can be found at : https://esgf-node.llnl.gov/search/CMIP6/.

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