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LETTER

# The role of the basic state in the climate response to future Arctic sea ice loss

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**Keywords:** climate, Arctic sea ice loss, model bias, stratospheric pathway

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## Abstract

There is great uncertainty in the atmospheric circulation response to future Arctic sea ice loss, with some models predicting a shift towards the negative phase of the North Atlantic Oscillation (NAO), while others predicting a more neutral NAO response. We investigate the potential role of systematic model biases in the spread of these responses by modifying the unperturbed (or 'control') climate (hereafter referred to as the 'basic state') of the Canadian Earth system model version 5 (CanESM5) in sea ice loss experiments based on the protocol of the Polar Amplification Model Intercomparison Project. We show that the presence or absence of the stratospheric pathway in response to sea ice loss depends on the basic state, and that only the CanESM5 version that shows a weakening of the stratospheric polar vortex features a strong negative NAO response. We propose a mechanism that explains this dependency, with a key role played by the vertical structure of the winds in the region between the subtropical jet and the stratospheric polar vortex ('the neck region winds'), which determines the extent to which anomalous planetary wave activity in response to sea ice loss propagates away from the polar vortex. Our results suggest that differences in the models' basic states could significantly contribute to model spread in the simulated atmospheric circulation response to sea ice loss, which may inform efforts to narrow the uncertainties regarding the impact of diminishing sea ice on mid-latitude climate.

## 1. Introduction

Over the past four decades, the extent of Arctic sea ice has been steadily declining, and climate models have projected that the Arctic Ocean will be seasonally ice-free by the middle of this century (e.g. Notz and Community 2020). While it is well established that Arctic sea ice loss leads to strong near-surface warming and is a key driver of Arctic amplification (Screen and Simmonds 2010), there remains substantial uncertainty regarding its remote impacts on mid-latitude climate (e.g. Screen *et al* 2018, Cohen *et al* 2020). This is mostly due to uncertainty in the consequences of sea ice loss for the mid-latitude circulation, which drives regional variations in climate change, particularly through the impact of the Northern Annular Mode (NAM) and North Atlantic Oscillation (NAO) on mid-latitude temperature and precipitation patterns (e.g. Blackport and Fyfe 2022, McKenna and Maycock 2022). Until recently, even the sign of the mid-latitude circulation response was unknown, with studies reporting negative, neutral and positive NAO responses to sea ice loss (see Screen *et al* (2018) and references therein). Some of this previous disagreement likely stemmed from the use of inconsistent lower boundary forcings (i.e. sea ice concentration (SIC) and sea surface temperature (SST) fields). In addition, the large impact of internal variability may have masked the forced response in studies for which sufficiently large ensembles were not available (e.g. Screen *et al* 2013).

In recent years, a consensus has emerged on the sign of the mid-latitude circulation response to sea ice loss. A key project that helped establish this consensus was the Polar Amplification Model Intercomparison

Project (PAMIP), which was part of the Sixth phase of the Coupled Modelling Intercomparison Project (CMIP6) (Smith *et al* 2019). Under PAMIP, more than a dozen modeling groups performed coordinated sea ice loss experiments using identical lower boundary forcings to facilitate like-for-like comparisons, and large ensembles to facilitate the identification of the forced response. Results of this exercise show that models robustly simulate a negative NAO response to sea ice loss (Smith *et al* 2022). However, it has also revealed that even under identical forcings there remains a large spread in the magnitude of this NAO response, with climate models simulating a wide range varying from a large negative NAO response to a more neutral NAO response (Screen *et al* 2022, Smith *et al* 2022). This implies a large spread, and hence large uncertainty, in the regional temperature and precipitation response to sea ice loss (Ye *et al* 2023).

Two 'pathways' have been proposed through which sea ice loss impacts the NAO: the tropospheric and stratospheric pathway. The tropospheric pathway includes a direct local baroclinic circulation response and an indirect large-scale barotropic pattern throughout the troposphere that resembles the NAM or NAO (Deser *et al* 2004). The stratospheric pathway involves sea ice loss in the Barents–Kara Seas in late autumn triggering increased upward heat flux, weakening the polar vortex in winter, followed by a negative phase of the NAO through downward coupling (Peings and Magnusdottir 2013, Kim *et al* 2014, Sun *et al* 2015, Nakamura *et al* 2016, Wu and Smith 2016, Zhang *et al* 2018, Xu *et al* 2021, 2023). The relative role of both mechanisms in the atmospheric response to Arctic sea ice loss under different forcings still needs further investigations (Peings and Magnusdottir 2013, De and Wu 2019, Zheng *et al* 2023). Under identical forcings employed in PAMIP simulations, even the sign of the stratospheric response is not robust (Smith *et al* 2022). Besides model uncertainty, recent studies have shown that part of the lack of robustness can be due to internal variability (Peings *et al* 2021, Streffing *et al* 2021), which can obscure the stratospheric and near-surface NAO response, even with 100 ensemble members (Sun *et al* 2022). These results suggest that for a robust identification of the stratospheric pathway and its impact on the NAO, the minimum of 100 ensemble members recommended by PAMIP may not be sufficient.

To gain insights into the spread of the simulated NAO response to sea ice loss it can be instructive to investigate the extent to which the response depends on the unperturbed (or 'control') climate, which is often referred to as 'the basic state'. While ideally the unperturbed climate is close to that in observations, models suffer from systematic model biases, and these biases can vary greatly between different models. Several previous studies suggest that these biases have a large impact on the climate response to sea ice loss (Sun *et al* 2015, Smith *et al* 2017, Cho *et al* 2022). However, these previous studies compared model versions that differed in more aspects than only the basic state, which complicated the identification of the exact role of the basic state. Sigmond and Scinocca (2010) found that with the exact same lower boundary forcings in the same model, the atmospheric circulation response to $CO_2$ doubling (in the absence of sea ice loss) is sensitive to the basic-state refractive properties for planetary wave propagation. In that study, the basic state was perturbed by changing internal parameters in orographic gravity wave drag (OGWD) scheme.

In this study we use the methodology of Sigmond and Scinocca (2010) to perturb the basic state, and investigate the impact of this perturbation on the response to sea ice loss in a single model. By using the same model, we can unambiguously attribute the difference in the responses to the differences in the basic state. By following the PAMIP protocol, using identical lower boundary forcings for the different basic states, our results can help identify the causes of the spread in simulated responses in the PAMIP models. We perturb the basic state such that it becomes very similar to that in the previous major version of our model, and show that this alteration leads to substantial changes in both the stratospheric and tropospheric response to future sea ice loss. Analysis of planetary waves and their changes under sea ice loss suggests that the zonal wind biases in the region between the subtropical jet and polar vortex play a key role, similar to what was found in Sigmond and Scinocca (2010) with regards to the response to $CO_2$ doubling. In section 2, we present the experimental design and methodology employed. Section 3 contains our findings and section 4 compares our results to previous studies, and discusses how our results could inform attempts to narrow the uncertainty in the climate response to sea ice loss.

## 2. Model, experiments and the perturbation of the basic state

### 2.1. Model

The model employed in this study is the Canadian Earth system model version 5 (CanESM5), a state-of-the-art Earth System Model developed at the Canadian Centre of Climate Modelling and Analysis (CCCma) (Swart *et al* 2019). The atmospheric component of CanESM5 is run at T63 spectral resolution (corresponding to an approximate resolution of 2.8° in both latitude and longitude), employs 49 vertical levels and has a model lid around 1 hPa. The stratospheric polar vortex has a small positive bias (figure 1(a)), which is consistent with a slight underestimation of the frequency of sudden stratospheric warmings (section

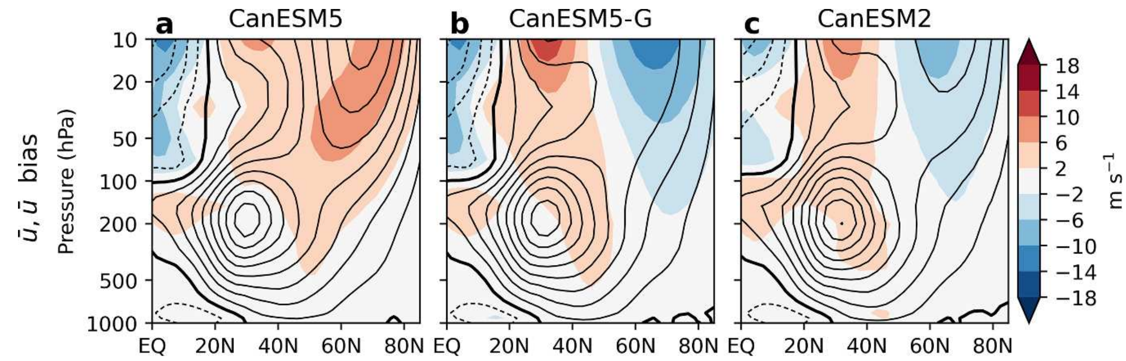


**Figure 1.** December–February (DJF) climatologies of zonal-mean zonal wind ($\bar{u}$, black contours, contour interval 5 m s$^{-1}$ with dashed contours denoting negative values and the thick solid line the 0 m s$^{-1}$ contour), and biases relative to the 1980–2009 ERA5 climatology (colors) in control (pdSST-pdSIC) simulations of (a) CanESM5, (b) CanESM5-G, and (c) 1980–2009 AMIP runs with CanESM2.

5.3.3 of Sigmond *et al* 2023). CanESM5 has been shown to be among the best CMIP6 models in terms of reproducing stratosphere-troposphere coupling (Ayarzagüena *et al* 2020, Butler *et al* 2023).

### 2.2. Experiments

To quantify the response to future sea ice loss, we follow the PAMIP protocol (Smith *et al* 2019) and compare atmosphere-only simulations prescribed with future sea ice loss to simulations that represent present-day conditions. The present-day simulation (*pdSST-pdSIC*) employs observed (1979-2008 averaged) SIC and SST fields, while in the future sea ice simulation (*pdSST-futArcSIC*) Arctic SIC and the SST in locations where sea ice is lost are replaced with projected values in a world that is 2 °C warmer than the pre-industrial average. All simulations are run with radiative forcings observed in the year 2000, start on 1 April, and run for 14 months. For further information on the PAMIP protocol including details on the construction of the lower boundary forcings, we refer the reader to Smith *et al* (2019). To extract the forced response from internal variability, PAMIP prescribes a minimum ensemble size of 100, but since previous studies have indicated that that may not be sufficient (see section 1), we run 300 ensemble members for each experiment. In CanESM5, the initial conditions for both *pdSST-pdSIC* and *pdSST-futArcSIC* runs were obtained from an ensemble of 10 atmosphere-only simulations with prescribed observed SIC and SST (commonly referred to as 'AMIP' runs) on 1 April of the year 2000, which are each perturbed 30 times by changing the seed in the random number generator for cloud physics in order to obtain initial conditions for 300 simulations.

### 2.3. Perturbing the basic state

We investigate the sensitivity of the response to sea ice loss by considering an alternative version of CanESM5, which was introduced by Sigmond *et al* (2023) and is referred to as 'CanESM5-G'. This version is identical to the regular CanESM5, except that the values of two free parameters in the Scinocca and McFarlane (2000) orographic gravity wave parameterization were changed to those in CanESM2, CCCma's previous major model version which was used for CMIP5. The resulting basic state (shown in figure 1(b)) is very similar to that of CanESM2 (see figure 1(c); from a four ensemble mean of AMIP simulations), with a stratospheric polar vortex that is much weaker than in CanESM5. CanESM5-G and CanESM2's stratospheric polar vortex strength are also weaker than in observations, which is consistent with a too high frequency of sudden stratospheric warmings (Kim *et al* 2017, Sigmond *et al* 2023). The modified orographic gravity wave settings in CanESM5-G resulted in a larger OGWD at the upper flank of the subtropical jet, as shown in figure 2. This increased OGWD resulted in a larger vertical curvature of the zonal mean zonal wind ($\bar{u}$, where the over bar denotes the zonal mean), contributing to a larger region where the quasi-geostrophic refractive index $R^2$ is negative (as indicated by the orange contours in figure 2), forming a larger barrier to equatorward planetary wave propagation. As a result, planetary waves that enter the stratosphere are prevented from propagating equatorward, deposit their momentum at high latitudes and slow down the stratospheric polar vortex (see supplementary material for more details). This mechanism is similar to that described in Sigmond and Scinocca (2010). In the rest of this Letter, the sensitivity of the sea ice loss-induced response to the basic state is investigated by comparing the response in the standard CanESM5 (with an 'unperturbed' basic state) to that in CanESM5-G (with a 'perturbed' basic state) (Sigmond 2023), using the exact same SIC and SST fields as prescribed by the PAMIP protocol.

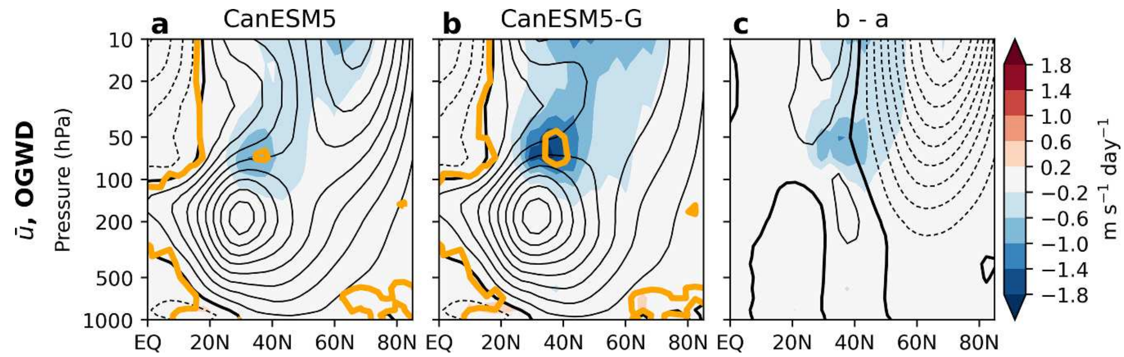


**Figure 2.** DJF climatologies of zonal mean zonal wind (black contours as in figure 1) and tendency of eastward wind due to orographic gravity waves (shading, OGWD)in (a) CanESM5, (b) CanESM5-G and (c) the difference. The orange contour denotes where the quasi-geostrophic refractive index squared $R^2$ is zero (with negative values around 38° N and 70 hPa).

## 3. Sensitivity to the basic state of the future Arctic sea ice loss-induced climate response

We first investigate the atmospheric circulation response to sea ice loss in the standard CanESM5 runs, which are part of our contribution to PAMIP. As shown in figures 3(a) and (d), this response consists of a pattern that projects strongly onto the negative phase of the NAM and the NAO, featuring a weakening of the polar vortex in the stratosphere, and weakening and equatorward shift of the Atlantic jet stream in the troposphere. Note that the Pacific jet strengthens, which has implications for the North American surface temperature patterns (Ronalds *et al* 2020). While the pattern of the tropospheric response is consistent with that in other PAMIP models, only one PAMIP model shows a stronger tropospheric $\bar{u}$ and jet shift response than CanESM5, as shown by, respectively, Smith *et al* (2022) and Screen *et al* (2022). CanESM5 is also the model with the third strongest deceleration of the stratospheric polar vortex (Smith *et al* 2022). Also consistent with other PAMIP models, the sea level pressure (SLP) lowers in regions where the prescribed sea ice loss is largest (figure 3(g)), which can be understood as a direct (thermodynamic heat low) response to surface warming (e.g. Deser *et al* 2004). Consistent with the PAMIP multi-model mean, a negative NAO response is simulated with an SLP increase in the North Atlantic and an SLP decrease south of that. Smith *et al* (2022) noted however that while this negative NAO response is found in the multi-model mean, less than 90% of the PAMIP models agree on the sign of the North Atlantic SLP response, implying uncertainty in regional climate responses as will be shown below.

How sensitive is this climate response to sea ice loss to the basic state? The second column of figure 3 shows the key result of this Letter that under the exact same sea ice loss perturbation, the CanESM5 version with the perturbed basic state (CanESM5-G) simulates a dramatically different response. The stratospheric polar vortex response in CanESM5-G is close to zero and the tropospheric $\bar{u}$ response and tropospheric jet stream responses are much weaker than in CanESM5 (figures 3(b) and (e)). The only circulation related response that does not change under the modified basic state is the thermal low responses in regions with large sea ice loss (figure 3(h)). The strong SLP dipole response associated with the negative NAO that was seen in CanESM5 is not present in CanESM5-G. This difference in NAO response has implications for regional surface temperature responses. The weakening of the Atlantic jet in CanESM5 amplifies the surface warming response to sea ice loss over Eastern Canada and Greenland and weakens the surface warming response over Northern Europe and parts of Asia, with no such modification of regional surface warming patterns in CanESM5-G (figures 3(j) and (k)). This explains the sensitivity of the surface temperature response to the basic state shown in figure 3(l). We also highlight the large role of internal variability in the simulated responses to sea ice loss (and its dependency on the basic state), with large variations between different 100 ensemble member averages (supplementary figure 4). This is consistent with previous studies (see section 1), and confirms that 100 member ensembles are not sufficient to filter out the forced response to projected sea ice loss under 2 °C global warming.

Why is the response to sea ice loss so sensitive to the basic state? The results of Smith *et al* (2022) and Screen *et al* (2022), who found that the strength of (tropospheric) eddy feedbacks correlates with the response to sea ice loss across PAMIP models, raise the question of whether the basic state perturbation altered the eddy feedbacks in such a way that they might explain the altered response to sea ice loss. To address this question, we calculated the eddy feedback parameter $m$ as defined in Smith *et al* (2022). We find that $m$ is not sensitive to the basic state ($m = 0.41$ for CanESM5 and $m = 0.40$ for CanESM5-G), implying that the different responses to sea ice loss between CanESM5 and CanESM5-G cannot be explained by their

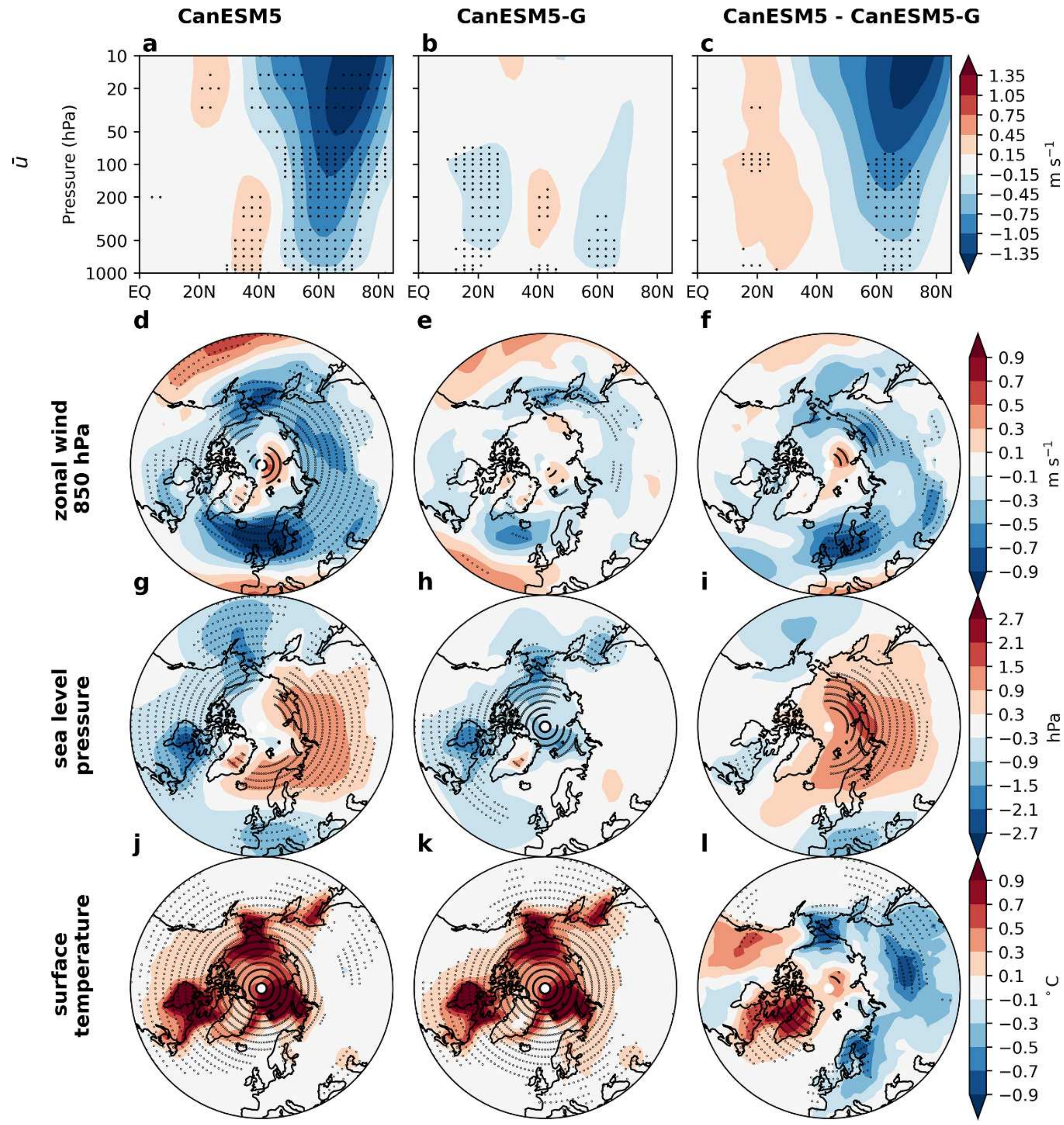


**Figure 3.** DJF mean response to future sea ice loss of (a)–(c) $\bar{u}$, (d)–(f) zonal wind at 850 hPa, (g)–(i) sea level pressure, and (j)–(l) surface temperature in (left) CanESM5, (middle) CanESM5-G, and (right) CanESM5 minus CanESM5-G. Note that for visual clarity, the shading interval of the surface temperature plots (j) and (k) is 5 times larger than that of the surface temperature difference plot (l), and that the color bar to the right corresponds to panel (l). Black dots denote statistical significant responses at a more than 95% confidence level according to a Student's *t* test.

differences in tropospheric eddy feedbacks (see also supplementary figure 5), and that we have to appeal to a different mechanism to explain this sensitivity.

Instead of tropospheric eddy feedbacks, our results point to a key role of the stratosphere. Previous studies have identified a stratospheric pathway in the response to sea ice loss, which acts to amplify the surface response (see section 1). The absence of a stratospheric $\bar{u}$ response in the December-February average (figure 3(b)) suggests that the modification of the basic state resulted in the elimination of the stratospheric pathway, which would be consistent with the weaker tropospheric response in CanESM5-G. Figure 4, which shows the $\bar{u}$ as a function of month confirms this. In November (figures 4(a) and (b)), both CanESM5 and CanESM5-G show a weaker tropospheric jet, which is consistent with the thermal wind response to the reduced meridional temperature response associated with Arctic amplification, and can be interpreted as the 'tropospheric pathway'. In CanESM5, a stratospheric signal appears in December, which then appears to propagate down to the troposphere and amplify the surface response in January and February (figures 4(c), (e) and (g)). This stratospheric pathway is not present in CanESM5-G. Hence, to understand why the response to sea ice loss is so sensitive to the basic state, we have to understand why the stratospheric pathway is present in CanESM5, but not in CanESM5-G.

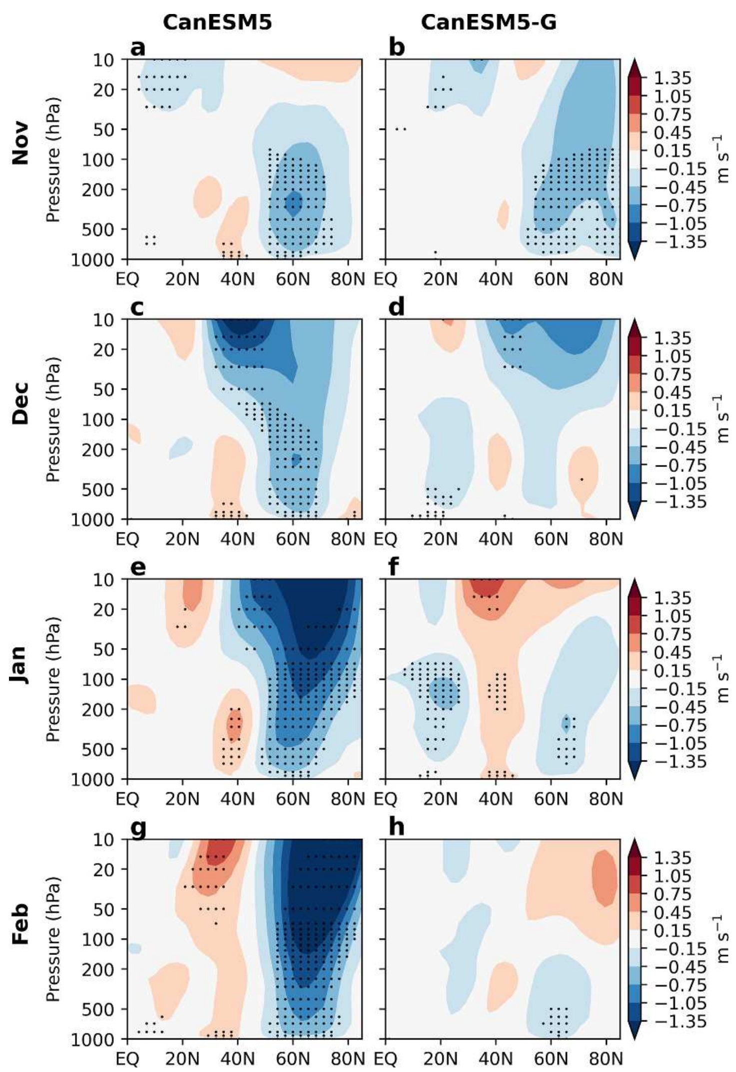


**Figure 4.** Zonal mean zonal wind response to future sea ice loss in (left) CanESM5, and (right) CanESM5-G for (a), (b) November, (c), (d) December, (e), (f) January and (g), (h) February. Black dots as in figure 3.

To this end, we investigate how resolved (planetary scale) waves respond to sea ice loss, and how this might be different between CanESM5 and CanESM5-G. Consistent with the mean response of the PAMIP models, we find that in response to sea ice loss, the generation of planetary waves in the troposphere reduces, which is consistent with reduced baroclinicity as a result of the reduced meridional temperature gradient associated with sea ice loss induced Arctic amplification (Smith *et al* 2022). This leads to reduced planetary wave activity entering the stratosphere, which is also consistent with the sea ice loss experiments of Smith *et al* (2017). As in Smith *et al* (2017), we next invert the signs and consider the response to sea ice increase, as the mechanism explaining the different responses is easiest to illustrate by considering the propagation away from an anomalous source. In figure 5 we attempt to explain why the stratospheric polar vortex strengthens in response to Arctic sea ice increase in CanESM5, but not in CanESM5-G (as illustrated by the black contours in figures 5(a) and (b).

We first consider the direct impacts of the enhanced Arctic cooling in response to sea ice increase. The enhanced Arctic cooling is associated with an enhanced meridional temperature gradient in the lower troposphere which through thermal wind balance acts to increase $\bar{u}$ in the upper troposphere and stratosphere. The divergence of the EPFD, which quantifies the $\bar{u}$ tendency as a result of the breaking of resolved waves and was saved as a part of the CMIP6 DynVarMIP project (Gerber and Manzini 2016), acts to further increase the $\bar{u}$ response in CanESM5 (as illustrated by the red colors in figures 5(a) and (c). By contrast, in CanESM5-G, there is EP-flux convergence (i.e. a negative EPFD) in response to sea ice increase (figures 5(b) and (d)), counteracting the thermal wind response and explaining the absence of a stratospheric $\bar{u}$ response in CanESM5-G.

To understand why EPFD increases in response to sea ice increase in CanESM5, but decreases in CanESM5-G, we follow Sigmond and Scinocca (2010) and present an EP flux budget over the stratospheric

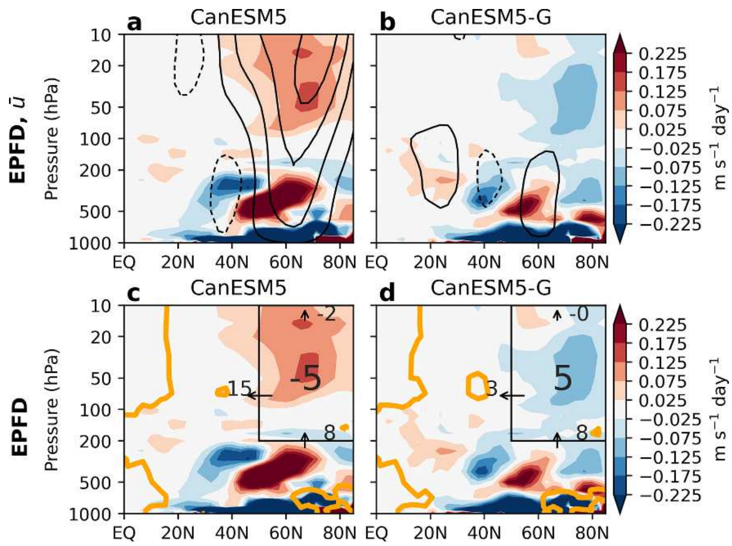


**Figure 5.** DJF mean response to sea ice *increase* of the tendency of $\bar{u}$ due to Eliassen–Palm flux divergence (EPFD, shading) in (a), (c) CanESM5 and (b), (d) CanESM5-G. Panels (a) and (b) also show the zonal-mean zonal wind response (contours at $\pm 0.15, 0.45, \ldots$ m s$^{-1}$), repeated (but inverted) from figures 3(a) and (b). In panels (c) and (d) the orange contours indicate the zero $R^2$ contour, repeated from figures 2(a) and (b). Panels (c) and (d) also shows a budget for resolved wave driving for the stratospheric box between 200 hPa and 10 hPa and north of 50° N. Numbers across the box represent EP fluxes integrated over the box boundaries, and the numbers in the box represent the resolved wave driving integrated over the box (units: $10^3$ kg m s$^{-4}$).

box north of 50° N and between 200 and 10 hPa. Figures 5(c) and (d) show that in response to sea ice increase, both CanESM5 and CanESM5-G simulate an increase of $8 \times 10^3$ kg m s$^{-4}$ of wave activity entering the stratospheric box from the troposphere, consistent with the decreased baroclinicity in response to sea ice loss described above. As these responses are almost identical in CanESM5 and CanESM5-G, vertical resolved wave propagation cannot explain the differences in the stratospheric EPFD responses. Instead, it appears that the difference in the EPFD responses is due to the difference in the equatorward propagation out of the stratospheric box. In CanESM5-G, the additional planetary waves in response to sea ice increase are 'stuck' in high latitudes, deposit their momentum and slow down the stratospheric $\bar{u}$, whereas in CanESM5 the additional planetary waves in response to sea ice loss propagate equatorward (i.e. out of the box), resulting in reduced planetary wave drag and hence an increase of $\bar{u}$. This different behavior in meridional wave propagation can be explained by the difference in the refractive properties of the basic state, with the $\bar{u}$ structure in CanESM5-G resulting in a large region of negative $R^2$, forming a barrier to equatorward planetary wave propagation, and a much smaller barrier in CanESM5 (as detailed in the supplementary material and indicated by the orange contours in figures 5(c) and (d)). In summary, our results show that in CanESM5, the refractive properties of the basic state allow for the stratospheric pathway in response to sea ice loss to occur, which amplifies the surface response, whereas the refractive properties of the modified basic state in CanESM5-G appears to suppress the stratospheric pathway, leading to a much reduced surface response. The aspect of the basic state that is key to the response to sea ice loss is the structure of zonal wind in the region between the subtropical jet and the stratospheric polar vortex, which determines the refractive properties of planetary waves, and whether anomalous planetary wave activity in response to sea ice loss propagates equatorward or remains at high latitudes.

## 4. Summary and discussion

In this Letter we have investigated the influence of the basic state on the climate response to future sea ice loss. The basic state in CanESM5 was perturbed in a controlled manner by changing free parameters in the orographic gravity wave parameterization, which resulted in a basic state that was very similar to that in our previous major model version, CanESM2. Under the exact same prescribed sea ice loss perturbation we find a dramatically different atmospheric circulation response, with the standard model simulating a strong negative NAO response associated with a weakening of the stratospheric polar vortex, and the model version with the perturbed basic state simulating a much weaker NAO response with no significant response in the stratosphere. These results suggest that for the climate response to sea ice loss the 'stratospheric pathway' is more important than the 'tropospheric pathway' and that the presence or absence of the stratospheric pathway depends on the basic state, at least in our model. Our results further suggest that the key aspect of the basic state is the zonal wind in the region between the subtropical jet and stratospheric polar vortex (hereafter referred to as the 'neck region winds'), which determines the reflective properties for planetary waves and where anomalous planetary wave activity in response to sea ice loss deposits its momentum.

Sun *et al* (2015) previously suggested that the climate response to sea ice loss may be sensitive to the basic state. They showed that the NAO response to sea ice loss was different in a high-top model compared to its low-top version, and suggested that the different responses could be related to differences in the stratospheric basic state, and in particular to the overly strong stratospheric polar vortex simulated by the low-top model. However, there were more differences between Sun *et al* (2015)'s high and low top models than just the strength of the stratospheric polar vortex, which complicates the identification of the exact reason for the differing responses. Sun *et al* (2015) suggested that the sensitivity could be related to differences in the upward propagation of planetary waves as a result of the difference in the strength of the stratospheric vortex, while here we show that the sensitivity in our model is related to differences in meridional wave propagation as a result of the difference in the vertical structure of the winds between the subtropical jet and the polar vortex.

Another previous study that highlighted the importance of the basic state for the response to sea ice loss is Smith *et al* (2017). They found different NAO responses in coupled and uncoupled sea ice experiments, and attributed these to biases in the modeled SSTs in the coupled runs, which through their impact on the atmospheric basic state controlled the sign of the NAO response to sea ice loss. Similar to our study, Smith *et al* (2017) suggested that differences in the responses can be explained by differences in the refractive properties of the basic state. However, the details of their mechanism are different since theirs focused on differences in the refractive index in the troposphere and its impact on tropospheric planetary wave propagation, whereas for the mechanism described here it is the difference in the basic state in the lower stratosphere and its impact on stratospheric planetary wave propagation that is crucial. Another fundamental difference is the fact that the source of the basic state differences in Smith *et al* (2017) is differences in the lower boundary forcing (i.e. the SST). As a result, the basic state sensitivity reported in Smith *et al* (2017) has no explanatory power regarding the spread in responses to sea ice loss in PAMIP model simulations, as the PAMIP models were prescribed with identical lower boundary forcings. This is in contrast to the results of the current study, as we have used identical lower boundary forcings in our basic state sensitivity experiments.

How might our results explain the large spread in PAMIP model responses to the same sea ice loss perturbation? Comparing our results with those of Smith *et al* (2022), it appears that the sensitivity to the basic state shown here reflects the spread in PAMIP model responses, with robust thermal low responses over regions with large sea ice loss, and a non-robust stratospheric vortex and tropospheric NAO response. A caveat of our results is that they are based on only one model, and we therefore encourage other investigators to repeat our basic state sensitivity experiments to assess the robustness of our results. Nevertheless, our results suggest that differences in the basic state between PAMIP models may be able to partly explain the difference in their responses to sea ice loss. Indeed, preliminary results, which will be reported in a future study, suggest that there is a statistical relationship across PAMIP models between the neck region winds (the key aspect of the basic state for shaping the response to sea ice loss identified in our study) in the control runs and the climate response to sea ice loss.

Our results underscore the importance of a realistic simulation of the neck region winds for accurate future climate projections. A practical recommendation for climate model developers is that they may want to increase efforts to reduce biases in the simulation of the neck region winds. A common problem in the climate model development is that the tuning of free parameters to improve a certain aspect of the simulation can often lead to the deterioration of an other bias. For example, Sigmond *et al* (2023) showed that tuning the free parameters in the OGWD scheme that achieved the most realistic polar vortex strength led to an increased bias in the strength of the neck-region winds. The results here suggest that for the most accurate simulated climate response to sea ice loss, model developers might want to prioritize reducing the biases in the winds in the neck region. This was also found by Sigmond and Scinocca (2010) with regards to the climate response to $CO_2$ doubling, which further highlights the importance of reducing biases in the neck region winds. A second avenue to reducing uncertainties in future climate projections could be to formulate an 'emergent constraint', where observations of the strength of the neck-region winds would constrain the real world response to sea ice loss. This would provide an alternative emergent constraint to that proposed in Smith *et al* (2022).

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://crd-data-donnees-rdc.ec.gc.ca/CCCMA/publications/2024_Sigmond_ERC_CanESM5-G-PAMIP.

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