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**Key Points:**

- A strengthened Antarctic Circumpolar Current results in a colder Antarctic but a warmer Arctic
- The temperature responses at both poles are amplified by the air-sea-ice coupling during cold seasons
- The pole-to-pole linkage via atmospheric pathway acts to compensate for the changes driven by oceanic pathways

**Supporting Information:**

Supporting Information may be found in the online version of this article.

**Correspondence to:**

X. Hu and S. Yang,
huxm6@mail.sysu.edu.cn;
yangsong3@mail.sysu.edu.cn

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**Author Contributions:**

**Conceptualization:** Xiaoming Hu, Song Yang
**Data curation:** Peixi Wang, Yuhui Han
**Formal analysis:** Peixi Wang, Xiaoming Hu
**Funding acquisition:** Song Yang
**Investigation:** Peixi Wang, Yuhui Han
**Methodology:** Xiaoming Hu
**Resources:** Zhenning Li, Yingfei Fang
**Software:** Zhenning Li
**Validation:** Xichen Li, Yingfei Fang, Jun Ying
**Visualization:** Peixi Wang, Yuhui Han
**Writing – original draft:** Peixi Wang
**Writing – review & editing:** Xiaoming Hu, Song Yang



# Impacts of Strengthened Antarctic Circumpolar Current on the Seasonality of Arctic Climate

**Peixi Wang[1], Yuhui Han[1], Xiaoming Hu[1], Zhenning Li[2], Xichen Li[3], Yingfei Fang[1], Jun Ying[4], and Song Yang[1]**

[1]School of Atmospheric Sciences, Sun Yat-sen University and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China, [2]Division of Environment and Sustainability, Hong Kong University of Science and Technology, Hong Kong, China, [3]Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, [4]State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou, China

**Abstract** To understand the role of the Antarctic Circumpolar Current (ACC) in the polar seasonality and its remote effect on the Arctic climate, we use the Community Earth System Model to perform Drake Passage (DP) open and closed experiments. Model results illustrate that in the opened DP, the ACC and Atlantic Meridional Overturning Circulation (AMOC) strengthen, leading to a colder Antarctic and a warmer Arctic. Notably, the temperature changes in both the Antarctic and the Arctic show significant seasonal differences, with the largest polar response during the cold seasons. Around the Antarctic, both the ACC and overturning circulation exhibit stronger acceleration in winter than in summer, causing more pronounced cooling in winter. Furthermore, negative seasonal energy transfer mechanism amplifies this cooling. In contrast, around the Arctic, the AMOC and ocean heat transport show relatively insignificant seasonal variation. Instead, it is the downward latent and sensible fluxes that induce amplified winter warming.

**Plain Language Summary** The Antarctic Circumpolar Current (ACC), as the most important ocean current in the Southern Ocean, has crucial influences on global ocean circulations and climate changes. To better comprehend the regional and remote roles of ACC in the current climate system, we close the Southern Ocean gateway, the Drake Passage (DP) in the fully coupled climate model to cut off the ACC and slow down this ocean circulation. Defining the climate response as the changes from closed DP to opened DP experiments, we find that the ACC strengthens as the DP is open. Our findings highlight a significant impact of the ACC on the current climate system, particularly on driving seasonal variations. The results also have further implications for the remote influence of the ACC on the Arctic climate through global oceanic circulation connections and local sea-ice-atmosphere interactions.

## 1. Introduction

In the current climate system, the climatological average temperature in the Arctic is higher than that in the Antarctic. As the greenhouse gases increase, the Arctic has experienced faster warming and a significant sea ice loss (Bekryaev et al., 2010; Eayrs et al., 2021; Hu et al., 2022; Rantanen et al., 2022; Stouffer et al., 1989). The asymmetry and the rapid warming have drawn considerable attention due to their potential impacts on global climate and human environments (Manabe et al., 1992; Park et al., 2018). Particularly, understanding the relationship between Arctic and Antarctic climate has become an important yet a challenging topic.

Previous studies have shown a strong and negative correlation between Arctic and Antarctic temperatures, a phenomenon known as the bipolar seesaw (Barbante et al., 2006; Blunier & Brook, 2001; Chylek et al., 2010). This pole-to-pole linkage has often been attributed to the influence of the Atlantic Ocean. Deser et al. (2015), using the Community Climate System Model, pointed out that the projected Arctic sea ice loss would lead to low-troposphere warming in both the Arctic and the Antarctic. W. Liu and Fedorov (2019) further demonstrated that Arctic sea ice decline, coupled with increased freshwater input into the source region of North Atlantic deep water, weakened the Atlantic Meridional Overturning Circulation (AMOC) on multidecadal and longer time-scales, leading to warming in the Southern Hemisphere. In addition to the sea ice loss, a warming in the Arctic could also induce Antarctic warming (Shin & Kang, 2021). Orihuela-Pinto et al. (2022) also demonstrated by model experiments that a collapsed AMOC would enhance tropical convection and deepen the Amundsen Sea Low near Antarctica. However, the impact of climate changes in the high latitudes of the Southern Hemisphere on the Northern Hemisphere, particularly on the Arctic, has received less attention. Projected Antarctic sea ice loss is expected to trigger robust Arctic warming, primarily through the response of the tropical sea surface temperatures to the changes in the Antarctic (England et al., 2020; Kim et al., 2022). Conversely, Antarctic Ice Sheet and associated sea ice expansion can induce Northern high-latitude cooling, whilst the Antarctic sea ice expansion is due mainly to natural variability of sea ice (An et al., 2024; W. Liu, 2025). W. Liu (2025) also showed that Antarctic sea ice expansion during 1979–2014 can trigger a northward ITCZ shift and SST cooling over the tropical south Pacific and south Atlantic. Moreover, surface temperature or heat content changes in the Southern Ocean, such as increased heat uptake or surface cooling, can shift the Hadley Circulation northward and lead to warming in the North Pacific and the Atlantic (Hwang et al., 2017; Kang et al., 2023). Over longer timescales, delayed Southern Ocean SST warming and reduced ocean heat uptake can cause a southward ITCZ shift (Liu et al., 2024).

Under global warming, the Antarctic Circumpolar Current (ACC), the largest current in the Southern Ocean, has intensified in either mean flow or eddy activity due to the accelerated and southward shifted westerlies (Beech et al., 2022; Hu et al., 2020; Li et al., 2022; Shi et al., 2021). To investigate the role of the ACC in the current climate system, several studies have conducted model experiments with opened/closed Southern Ocean gateway, the Drake Passage (DP). These experiments are performed by ocean-only models, ocean models coupled with simplified atmospheric models, and fully coupled models (England et al., 2017; Sijp & England, 2004; Toggweiler & Bjornsson, 2000; Toggweiler & Samuels, 1995; Yang et al., 2014). Comparing the climatology of opened DP with that of closed DP, models consistently show that in opened DP a complete ACC enhances the northward Ekman transport and upwelling in the Southern Ocean, which in turn strengthens the AMOC (Kuhlbrodt et al., 2007; Li et al., 2023). The changes in ocean circulation result in an anomalous northward energy transport, leading to cooling in the Antarctic and warming in the Arctic (England et al., 2017; Lee & Liu, 2023; Liu et al., 2020). Previous studies have been primarily focused on the climate impact of the ACC from the perspective of the oceanic dynamic and annual mean state changes. However, seasonal variation is a crucial component in polar climate variability, driven by the distinct seasonal changes in solar radiation and associated air-sea-ice interactions. Specifically, the sea ice albedo feedback and ocean heat uptake play important roles in the polar climate variations, and these two factors are inextricably linked to each other on seasonal timescales (Hu et al., 2022; Liu et al., 2023; Zhang et al., 2023). Given the key roles of air-sea coupling and the pronounced seasonality in polar climates, it is essential to explore the impacts of a strengthened ACC on the Arctic climate, particularly with an emphasis on seasonal variations.

## 2. Model Design and Methods

In this study, we discuss the impact of a strengthened ACC on the seasonality of Arctic climate using idealized model simulations, which is in line with a previous study of annual mean climate (Wang et al., 2024). Two fully coupled experiments were conducted: the control run with an opened DP (DPO) case and a sensitive run with a closed DP (DPC) case. In the DPC case, a land bridge of 500-km width and 10-m height connects the Antarctic Peninsula with the Cape Horn in South America. The current study employs the fully coupled Community Earth System Model (CESM) v1.2.2, a widely applied global climate model (Hurrell et al., 2013). The atmospheric component, the Community Atmospheric Model v4, has a horizontal resolution of 1.9° latitude × 2.5° longitude, with 26 vertical layers in a σ-P hybrid coordinate system and a top model height at 35 km. The ocean and sea ice models use 1° horizontal resolution, with the model ocean divided into 60 vertical layers, covering a depth up to 5,500 m.

Both the DPO and DPC cases are initialized with the $CO_2$ concentration set to the level of year 2000 (367 ppm). We define the model quasi-equilibrium state as the net radiation balance at the top of atmosphere (TOA). In the DPO case, the spin-up period is 249 years for the model to reach its quasi-equilibrium state. The DPC case requires a 900-year spin-up due to the longer adjustment timescale of ocean circulation. After reaching the quasi-equilibrium, each experiment is integrated for an additional 100 years. The climate impact of a strengthened ACC is assessed by comparing the climatological mean states between the DPO and DPC cases (DPO minus DPC), with the mean state defined as the average of years 310–349 for DPO and years 951–1,000 for DPC.

To evaluate the effect of air-sea coupling on surface temperature changes, we calculate the differences in surface energy budget, expressed as:

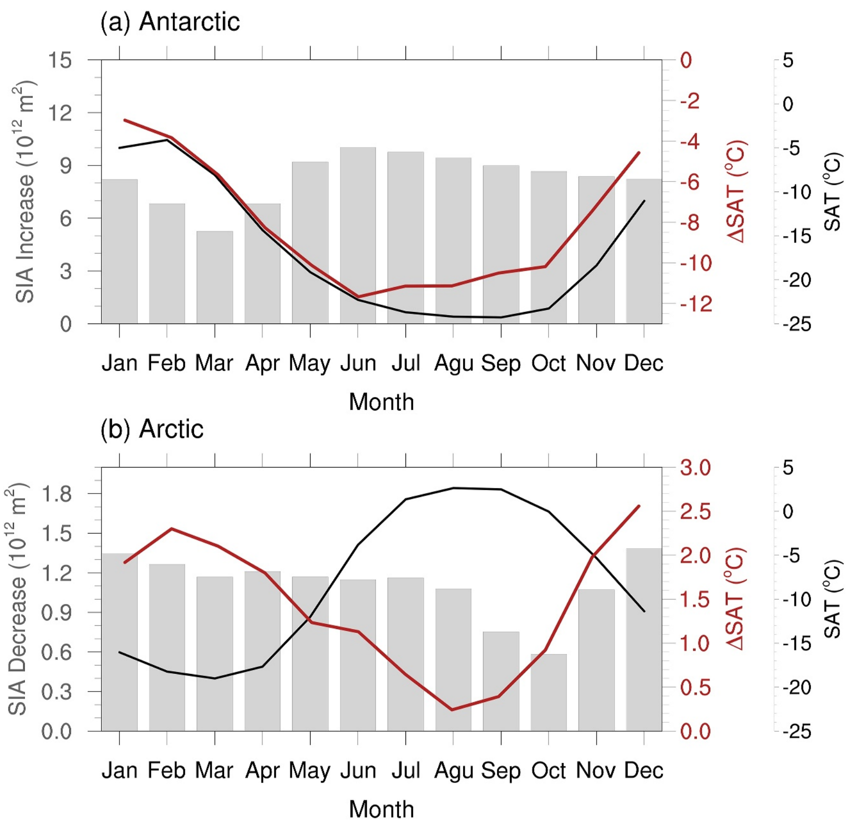


**Figure 1.** Seasonality of ΔSIA (gray bars), ΔSAT (red line) for the B2000 simulations, and the climatological mean SAT (black line) from the DPO case in (a) the Antarctic (60°S–90°S) and (b) the Arctic (60°N–90°N). Where "Δ" represents the DPO case minus the DPC case.

$$\Delta LW\_up = \Delta SW\_net + \Delta LW\_down + \Delta LH + \Delta SH + \Delta Dyn \quad (1)$$

where "Δ" represents the DPO case minus the DPC case. *SW_net*, *LW_up*, and *LW_down* denote surface net solar radiation and upward and downward longwave radiations, respectively. *LH* and *SH* are latent and sensible heat fluxes. *Dyn referring to the dynamic component primarily reflects oceanic heat uptake and heat transport*. (Serreze & Barry, 2005). For all terms positive values represent downward fluxes, except for *LW_up* and *Dyn*. For the *Dyn*, a negative value indicates net heat flux from the atmosphere into the upper ocean and a positive value signifies the opposite when the ocean heat transport can be neglected (Serreze et al., 2007).

## 3. Results

### 3.1. Seasonal Variations in the Differences in Climatological Mean States Between DPO and DPC Cases

As reported by previous studies (England et al., 2017; Sijp & England, 2004; Wang et al., 2024), an opened DP and thus a strengthened ACC lead to a stronger AMOC, resulting in a colder Antarctic and a warmer Arctic. Here, we focus on the seasonal variations of this climate response. The differences in monthly polar sea ice area (SIA; gray bars) and surface air temperature (SAT; red curves) between the DPO and DPC cases for the Arctic and the Antarctic are shown in Figures 1a and 1b, respectively. In the Antarctic, the warm seasons are December–January–February (DJF) and the cold seasons are June–July–August (JJA). In the Arctic, the seasons are the opposite.

As shown in Figure 1a, the Antarctic SAT anomalies peak with maximum cooling during the cold season (JJA) and minimum cooling in the warm season (DJF). Correspondingly, the SIA anomaly shows a growth from 5 to 10 million km$^2$, with the greatest sea ice expansion in winter. In the Arctic, the strongest warming and sea ice decline appear in boreal winter (DJF), where SAT increases from 0.3°C to 2.6°C and SIA decreases from 0.6 to 1.4

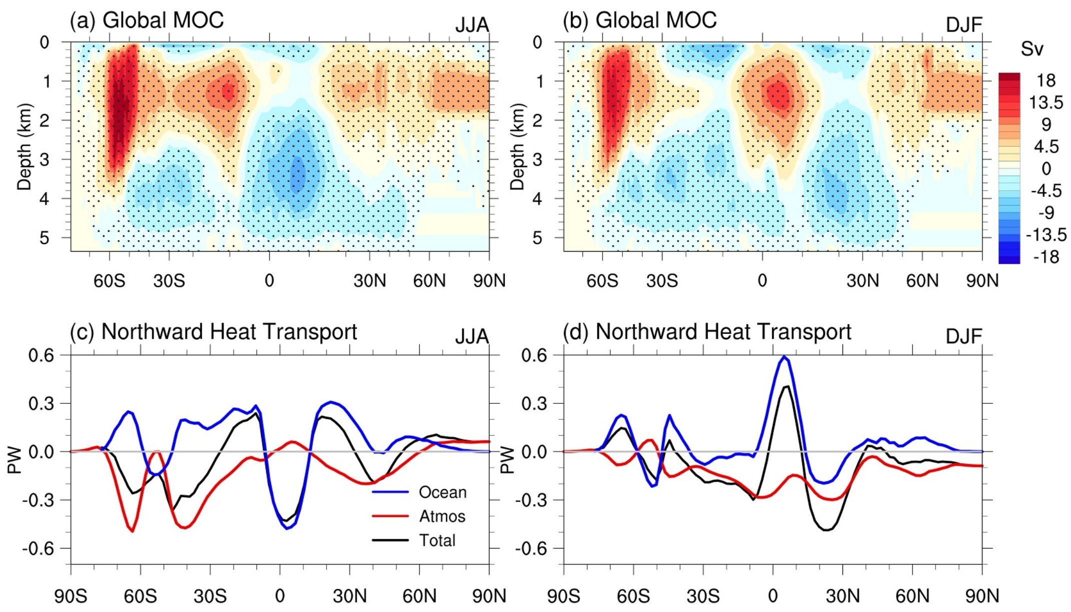


**Figure 2.** Seasonal differences between the DPO and DPC cases for (a, b) global meridional overturning circulation (in Sv, 1 Sv = $10^6$ $m^3$ $s^{-1}$), with positive value representing a clockwise circulation and negative value denoting a anticlockwise circulation. Shown also are (c, d) oceanic (blue line), atmospheric (red line), and total (black line) northward energy transport (PW, 1 PW = $10^{15}$ W), with positive value representing a northward transport and negative value signifying a southward transport. Stippling indicates the significant differences at the 95% confidence level based on the Student's *t*-test.

million $km^2$. This seasonal pattern is similar to the Arctic Amplification, where the largest warming appears in the cold season (Ding et al., 2017; Hu et al., 2022; Stouffer et al., 1989; Wu et al., 2019). In summary, the most notable feature is that the SAT and SIA anomalies reach their maximum absolute values during the cold seasons in both polar regions, a phenomenon referred to as "seasonal phase-locking." And the magnitude of Antarctic anomalies is approximately 4–8 times larger than that of Arctic anomalies. Specifically, the greatest climatological shifts in the Arctic are phase-locked in the austral summer, which differs from the maximum climate anomalies in Antarctica, occurring during the austral winter. This feature suggests that, while these climatological shifts originate from a strengthened ACC, other processes may contribute to the seasonal phase-locking phenomenon.

### 3.2. Role of Ocean Circulation in the Seasonal Phase-Locking

As aforementioned, the initial changes in the experiments originate from the ocean circulation. Therefore, we first investigate the role of ocean circulation in the seasonal phase-locking phenomenon. The differences in ocean circulation and the resultant anomalous northward energy transport during cold and warm seasons are shown in Figure 2. The seasonal atmospheric energy transport is calculated as the net top-of-atmosphere radiation minus the net surface heat flux and storage terms, following the methodology of Donohoe et al. (2020). Owing to the strengthened ACC, the Southern Ocean Meridional Overturning Circulation (MOC) intensifies by the Ekman pumping effect (Ekman, 1905; Figures 2a and 2b). This clockwise circulation anomaly would trigger a northward oceanic energy transport (Figures 2c and 2d) and cool Antarctica (Wen et al., 2018). Obviously, the MOC and northward oceanic heat transport anomalies are more pronounced in austral winter (JJA) compared to austral summer (DJF) in the Southern Ocean, which is relevant to stronger westerlies in austral winter. Consequently, Antarctic cooling and sea ice expansion are stronger in winter than in summer (Figure 1a).

In the Northern Hemisphere, the MOC (mainly in the Atlantic) also strengthens with an accelerated ACC, due primarily to the enhanced upwelling in the Southern Ocean (Kuhlbrodt et al., 2007; Figures 2a and 2b). As shown in Figures 2c and 2d, the stronger MOC leads to a northward oceanic energy transport anomaly around the 60°N, where the AMOC subsides. This northward energy transport contributes to warming in the Arctic (Lee et al., 2024). The northward oceanic energy transport exhibits a stronger change north of 60°N in DJF, which may contribute to the winter amplified warming in the Arctic. Notably, the northward energy transport by the

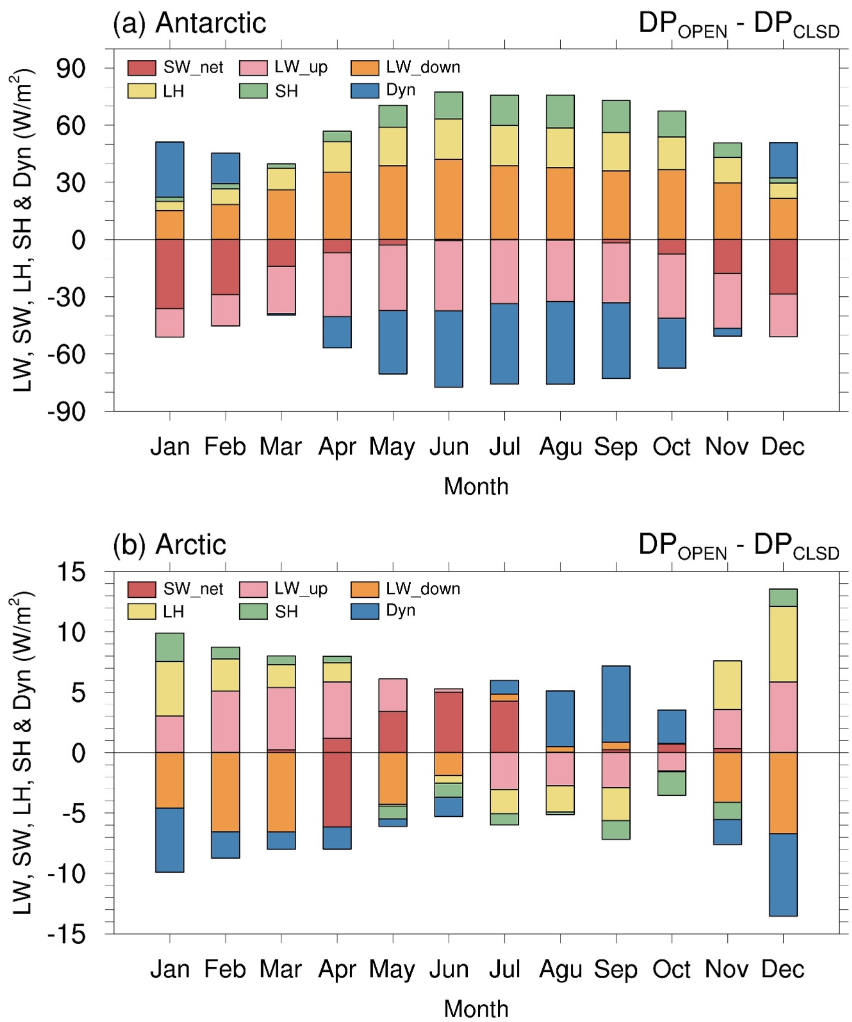


**Figure 3.** Seasonal differences in surface energy budget between the DPO and DPC cases in (a) the Antarctic and (b) the Arctic. The units for ΔSW_net (red), ΔLW_up (deep pink), ΔLW_down (light pink), ΔLH (brown), ΔSH (yellow), and ΔDyn (blue) are in W/m$^2$ (positive values standing for warming). The physical lengths of different bars are their values, with bars beyond the zero reference representing positive values while bars below the zero reference representing negative values.

atmosphere in the Arctic shows a seasonal variation, with anomalous northward transport in summer but southward transport in winter. Therefore, we next explore the role of air-sea coupling and related atmospheric processes in explaining the winter amplification in the Arctic.

### 3.3. Role of Air-Sea Coupling in the Seasonal Phase-Locking

A similar winter amplification has been observed in the Arctic warming under global warming (Rantanen et al., 2022; Stouffer et al., 1989; Taylor et al., 2022; Wu et al., 2019). Previous studies have revealed that local air-sea coupling plays an important role in this amplification, summarized as the seasonal energy transfer mechanism (SETM) (Hu et al., 2022; Liu et al., 2023; Zhang et al., 2023). The key processes in the SETM is that the abnormal solar radiation absorbed due to summer sea ice decline is stored in the Arctic Ocean and then released during winter, driving winter amplified warming in the absence of solar radiation. Given the crucial role of SETM in winter amplification, we next calculate the seasonality of differences in surface energy budget between the DPO and DPC cases to identify the primary contributor to the winter amplifications in the Antarctic and the Arctic driven by strengthened ACC. Based on Equation 1, the differences in surface energy budget between the DPO and DPC cases for both the Antarctic and the Arctic are shown in Figures 3a and 3b, with the corresponding spatial patterns in Figures 4 and 5. In the Antarctic, the reduced solar radiation dominates the total

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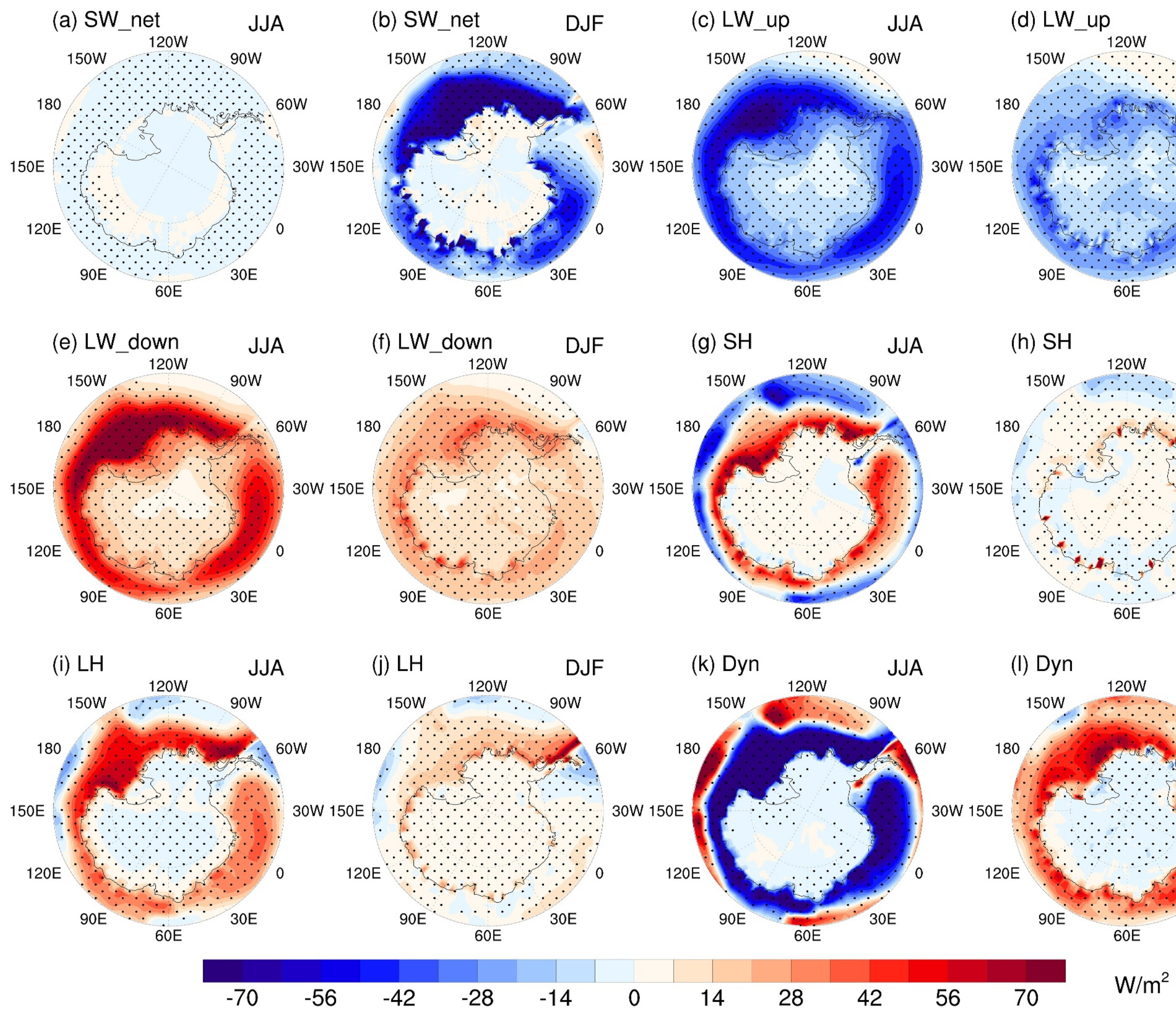


**Figure 4.** Antarctic seasonal differences between the DPO and DPC cases for (a, b) ΔSW_net, (c, d) ΔLW_up, (e, f) ΔLW_down, (g, h) ΔSH, (i, j) ΔLH, and (k, l) ΔDyn (in W/m$^2$, positive values for downward fluxes except for LW_up and Dyn). The first and third panels are for the average from June to August (boreal summer) and the second and fourth panels are from December to February (boreal winter). Stippling indicates the significant differences at the 95% confidence level based on the Student's *t*-test.

energy anomaly and cools the surface air in summer. While in winter, the dynamic component primarily contributes to the amplified cooling (Figure 3a). In the Arctic, the increased solar radiation and dynamic component are predominant in summer, while sensible and latent heat fluxes play a significant role in driving the winter amplified warming (Figure 3b). Because the seasonal ocean heat transport difference is smaller by 1–2 order of magnitude than the Dyn, we mainly consider the ocean content effect of the Dyn.

As aforementioned, the strengthened ACC in the DPO case leads to a colder Antarctic, resulting in sea ice expansion (Figure S1b in Supporting Information S1) and a corresponding decrease in net solar radiation in austral summer (Figure 4b). This reduced solar radiation decreases the energy stored in the ocean (Figure 4l; Figure S1j in Supporting Information S1), leading to less energy release from the ocean to the atmosphere in austral winter, thereby amplifying winter cooling in the DPO case (Figure 4k; Figure S1i in Supporting Information S1). This seasonal energy transfer process explains why the Antarctic shows stronger cooling in winter in spite of the anomalous southward energy transport by air (Figure 2c). However, this cooling effect related to the SETM is partially offset by surface sensible and latent heat fluxes, which are mainly determined by the differences in temperature, humidity, and wind speed between the surface and the overlying air (Myhre et al., 2018; Serreze & Barry, 2005). In the cold season, the positive atmosphere-surface temperature difference (Figure S1c in Supporting Information S1) and deceleration of near-surface zonal winds (Figure S1e in Supporting

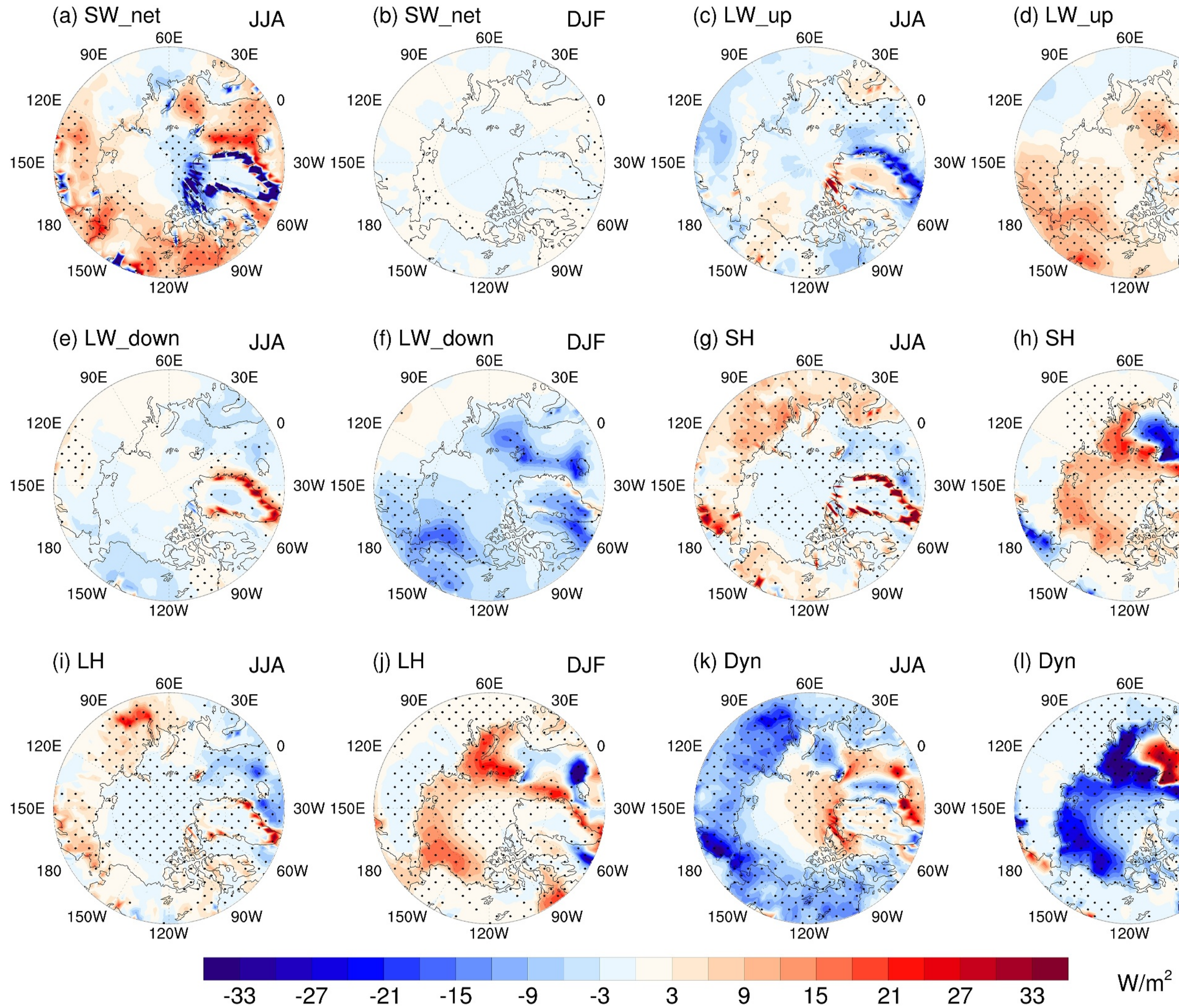


**Figure 5.** Same as Figure 4 but for the Arctic seasonal differences between the DPO and DPC cases. Stippling indicates the significant differences at the 95% confidence level based on the Student's *t*-test.

Information S1) lead to downward sensible and latent heat flux anomalies, which slightly warm the surface (Figures 4e and 4g; Figures S1c and S1e in Supporting Information S1). Overall, the coupling of reduced solar radiation supply in austral summer and the associated seasonal energy transfer mechanism dominate the winter cooling amplification in the Antarctic.

The processes responsible for winter amplification in the Arctic differ from those in the Antarctic. In the Arctic, the northward ocean heat transport by stronger AMOC leads to sea ice loss. Solar radiation supply increases due to the declined sea ice concentration in boreal summer (JJA), particularly around the sea ice edge (the significant decrease in solar radiation around Greenland may be a model error; Figure 5a; Figure S2a in Supporting Information S1). This increased solar radiation stores additional energy into the ocean. Conversely, the negative atmosphere-surface temperature difference and the acceleration of near-surface zonal winds lead to anomalous upward sensible and latent heat fluxes, causing energy to release from the upper ocean in summer and then cooling the atmosphere in subsequent winter (Figures 5g–5l; Figures S2c and S2e in Supporting Information S1). In boreal winter (DJF), a positive atmosphere-surface temperature difference, reduced near-surface zonal winds, and increased near-surface humidity result in anomalous downward sensible and latent heat fluxes, acting to warm the surface. This warming effect is more dominant and leads to the winter warming amplification in the Arctic.

## 4. Conclusions and Discussion

In this study, we investigate the impact of a strengthened ACC on the Arctic climate with an emphasis on its seasonal variations. We perform numerical experiments using the fully coupled CESM with the Drake Passage opened and closed (DPO and DPC). By discussing the differences between the DPO and DPC cases (DPO minus DPC), the climatological changes in both the Antarctic and the Arctic align with the findings from previous studies on annual mean responses (England et al., 2017; Sijp & England, 2004; Wang et al., 2024). In DPO, the ACC accelerates, leading to intensified upwelling in the Southern Ocean and a concurrent strengthening of the AMOC. The stronger ACC and AMOC lead to a northward oceanic energy transport anomaly, resulting in a colder Antarctic and a warmer Arctic.

For the seasonal variations of climatological changes, the most notable feature is that both the Arctic and the Antarctic exhibit their largest absolute climatological differences during the cold seasons, with their smallest differences during the warm seasons, a phenomenon referred to as "seasonal phase-locking." To understand this feature, we examine the roles of oceanic circulation and local atmosphere-sea-ice interaction in the winter amplification phenomenon. In the Antarctic, the ACC and Southern MOC show greater acceleration in winter than in summer. These changes in oceanic circulations intensify the northward oceanic heat transport, leading to more pronounced cooling during the Antarctic winter. While in the Arctic, the AMOC and oceanic heat transport changes exhibit fewer significant seasonal differences, indicating that the oceanic circulation alone cannot explain the winter amplification in the Arctic.

Furthermore, we calculate the surface energy budget to explore the role of local atmosphere-sea-ice interaction in the winter amplification. In the Antarctic, solar radiation decreases in austral summer as sea ice expands, reducing energy stored in the ocean. This reduced energy storage is then released during winter, cooling the surface. Consequently, the negative seasonal energy transfer mechanism contributes to the winter cooling amplification in the Antarctic. In contrast, in the Arctic, the winter warming amplification is driven by downward latent and sensible fluxes, which are attributed to the changes in near-surface zonal winds, atmosphere-surface temperature and humidity differences.

These model results highlight the crucial role of the ACC in the current climate system, particularly in driving its seasonal variations, and demonstrate the remote influence of the ACC on the Arctic climate via global oceanic circulation connections and local sea-ice-atmosphere interactions. The findings suggest broader implications for the potential climate impact of the change in the ACC driven by increased greenhouse gas concentration, although this requires further studies with much longer observational data.

## Data Availability Statement

The Community Earth System Model (Hurrell et al., 2013) is publicly available at https://www2.cesm.ucar.edu/models/cesm1.2/tags/index.html#CESM1_2_2.

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