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The influence of Antarctic Sea ice distribution on the Southern Ocean Overturning Circulation for the past 20,000 years.

Gagan Mandal [1,]*, Jia-Yuh Yu [2] and Shih-Yu Lee [1]

[1] Research Center for Environmental Changes, Academia Sinica, Taipei 11529, Taiwan; gagan.iitroorkee@gmail.com
[2] Department of Atmospheric Sciences, National Central University, Taoyuan 32001, Taiwan; jiayuh@atm.ncu.edu.tw
* Correspondence: gagan.iitroorkee@gmail.com (G.M.)
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Abstract: The changes in Southern Ocean physics are dynamically linked to westerly winds, ocean currents, and the distribution of Antarctic sea ice in the Southern Hemisphere. As a result, it is critical to comprehend the response of the Southern Ocean physics to the distribution of Antarctic sea ice on a basin scale. This modeling study employs a fully coupled Earth system model to investigate the effect of Antarctic Sea ice distribution on the Southern Ocean dynamics during the past twenty thousand years before the present. The findings show that the formation and melting of sea ice have an effect on the distribution of surface buoyancy flux over the Southern Ocean. The simulated sea ice edge (grid points in the ice model have a sea ice concentration above 5%) in the Southern Ocean almost demarcates the borderline between the lower and upper meridional overturning cells. The seemingly-permanent Antarctic sea ice edge (grid points in the ice model with a sea ice concentration greater than 80%) coincides with the shift of buoyancy flux from positive (buoyancy gain) to negative (buoyancy loss). Furthermore, the negative surface buoyancy flux zone has shifted polewards for the past twenty thousand years, with the exception of about 14.1 thousand years. Our findings show that the Antarctic sea ice feedback affects the surface buoyancy flux, which in turn affects the overturning circulation in the Southern Ocean.

Keywords: Southern Ocean; twenty thousand years before present; Buoyancy flux; Antarctic sea ice.

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1. Introduction

Studies have advocated that the Southern Ocean atmosphere, Antarctic sea ice, and ocean are dynamically interconnected (Ferrari et al., 2014; Morrison et al., 2015). For example, the ocean-sea ice feedback involves melting summertime sea ice, which brings liquid freshwater back to the ocean. Additionally, the formation of wintertime sea ice (brine rejection) brings salt content to the ocean surface. Thus, the Antarctic sea ice regulates freshwater flux by melting summertime sea ice and salt flux by wintertime brine rejection.

Numerous studies have found that the alteration in Southern Hemisphere westerly winds, Antarctic sea ice change, and accompanying surface buoyancy fluxes play a fundamental part in altering the atmospheric carbon dioxide concentrations on orbital timescales by modulating the Southern Ocean deep ocean stratification and overturning circulation (Ferrari et al., 2014; Jansen, 2017; Jansen & Nadeau, 2016; Marzocchi & Jansen, 2019; Morrison et al., 2011; Nadeau et al., 2019; Watson et al., 2015). The understanding of the Southern Ocean dynamics is currently developing. The paleoclimatology community recognizes that the Southern Ocean overturning circulation is primarily driven by wind (Anderson et al., 2009; Menviel et al., 2018). Several studies, however, have found that changes in buoyancy flux caused by freshwater discharge (Abernathey et al., 2016; Liu et al., 2021), ocean eddies (Lauderdale et al., 2017), topography (Liu et al., 2021), and Antarctic sea ice feedback (Ferrari et al., 2014; Jansen & Nadeau, 2016; Mandal et al., 2021; Mandal et al., 2022; Marzocchi & Jansen, 2017; Stein et al., 2020) contribute to the Southern Ocean dynamical changes during the most recent deglacial period. As a result, it is critical to comprehend the role of Antarctic sea ice in surface buoyancy flux, which influences the Southern Ocean overturning circulation.

Buoyancy flux is the density change across the air-sea interface initiated by heating/cooling and evaporation/precipitation. Positive buoyancy flux (buoyancy gain) indicates areas with lower surface ocean density. Furthermore, the area with higher surface ocean density is represented by negative buoyancy flux (buoyancy loss). Cold temperatures limit seawater thermal expansion at high latitudes in the Southern Ocean (Cerovečki et al., 2011). For that reason, freshwater changes dominate the Southern Ocean surface buoyancy forcing (Karstensen & Lorbacher, 2011) related to summertime sea ice melting (Abernathey et al., 2016; Fischer et al., 2010). Buoyancy gain from sea ice melt would help transform the deep returning flow into the Southern Ocean's intermediate and mode waters (Lund et al., 2021).

However, wintertime formation of the Southern Ocean sea ice and associated brine rejection contribute to buoyancy loss around Antarctica (Marshall & Speer, 2012; Talley, 2013). Buoyancy loss from Southern Ocean surface cooling and sea ice growth encourage bottom water formation into ocean basins. Recent research has shown that an alteration in the extent of Antarctic sea ice causes a change in surface buoyancy forcing, thus modulating the Southern Ocean overturning circulation (Chen & Wang, 2021; Ferrari et al., 2014; Lauderdale et al., 2017; Mandal et al., 2021; Watson et al., 2015).

Therefore, focusing on the Antarctic sea ice change is essential to understand the ocean's role in regulating atmospheric carbon dioxide concentrations on glacial-interglacial time scales. Previous studies have shown that the melting of Antarctic sea ice releases freshwater, which increases the buoyancy of Southern Ocean upwelled water (Iudicone et al., 2008) and strengthened the upper limb of the ocean meridional overturning circulation (Abernathey et al., 2016; Saenko et al., 2002). Furthermore, numerical simulations have confirmed the importance of freshwater fluxes in determining changes in Southern Ocean upwelling during the last deglacial period (Mandal et al., 2021; Mandal et al., 2022; Morrison et al., 2011).

The Southern Ocean sea ice coverage significantly boosts deep ocean carbon sequestration by reducing the exposure time of surface waters with the atmosphere and minimizing the vertical mixing of deep ocean waters, leading to deep ocean stratification (Ferrari et al., 2014; Stein et al., 2020). The presence of Antarctic sea ice decreases momentum exchange from air to the surface of the Southern Ocean while also reducing air-sea gas exchange, which increases deep ocean carbon sequestration (Stephens & Keeling, 2000). Furthermore, model-based and satellite data studies have also highlighted the critical role of Antarctic sea ice in future and present climate scenarios. Recent climate-induced variability in the extent of seasonal Antarctic sea ice has been shown in studies to have an influence on thermohaline circulation and marine primary production (Meredith et al., 2019). Therefore, focusing on and comprehending the significance of Antarctic sea ice distribution over the last 20K (K refers to thousand years before the present) will assist us in comprehending current and future changes in Southern Ocean dynamics.

2. Materials and Methods

This study uses a general circulation model that includes the ocean, atmosphere, ice, and land surfaces referred to as the TraCE-21ka experiment (Liu et al., 2009). A T31_gx3v5 resolution version of the Community Climate System Model (CCSM3) from the National Center for Atmospheric Research (NCAR) is included in the experiment. The modeling experiment uses the Community Atmosphere Model version 3 (CAM3), Community Sea Ice Model version 5 (CSIM5), Parallel Ocean Program version (POP), and Community Land Surface Model version 3 (CLM3). The boundary conditions for the climate model included transient variations in the meltwater fluxes in the Northern and Southern Hemispheres, incoming solar radiation, retreating continental ice sheet topography, which is indicated by the rise in eustatic sea level, and atmospheric greenhouse gas concentrations. The model output data are accessible to the public at https://www.earthsystemgrid.org/project/trace.html (most recent access was on 27 October 2022).

The atmospheric model for the experiment used the Community Atmospheric Model 3 (CAM3), which was run at a T31 resolution (about 3.75 degrees) and twenty-six hybrid vertical coordinate levels. The resolutions of the experiment output data from the Parallel Ocean Program (POP) and NCAR Community Sea Ice Model version 5 (CSIM5) are comparable (gx3v5). The ocean and ice output data contain 3.6 degrees of longitudinal resolution and varying degrees of latitudinal resolution, making them around 0.9 degrees close to the equator. As a result, the output data from the ocean and ice models were interpolated to a resolution of 3.75 degrees. The POP model contains a vertical z coordinate with twenty-five depth levels and ocean eddies parameterization (Gent & McWilliams, 1990). The CSIM5 model also includes a distribution of ice thickness on a subgrid scale.

This study examines the variation of the Antarctic sea ice coverage and surface buoyancy flux from the past twenty thousand years. The results are shown at 20K to 19K (Last Glacial Maximum), 17.3K to 16.3K (Heinrich 1 event), 12.5K to 11.5K (Younger Dryas event), 11K to 10K (onset of the Holocene), 6K to 5K and 2K to 1K periods to cover changes during the past twenty thousand years.

3. Results and Discussion

We analyzed the ocean and sea ice data to understand the Antarctic sea ice distribution feedback on the surface ocean properties for the past twenty thousand years.

This study defines the seemingly-permanent sea ice-ocean edge as the Southern Ocean surface area which is covered with sea ice most of the year. We calculated the seemingly-permanent sea ice-ocean edge as grid points in the ice model which have a sea ice concentration above eighty percent. Figure 1 highlights the near superimposition between the seemingly-permanent sea ice-ocean edge marked in blue and the borderline between positive to negative surface buoyancy fluxes shown in the solid black line from 20K-19K to 11K-10K period. This implies that the simulated Southern Ocean surface area covered by Antarctic sea ice for the majority of the year overlaps with the buoyancy loss zone (densification). Further analysis shows that in both the Indian and Pacific Ocean sectors, the latitudinal position of the buoyancy flux transition zone shifts poleward by about 11° from 20K-19K to 11K-10K period.

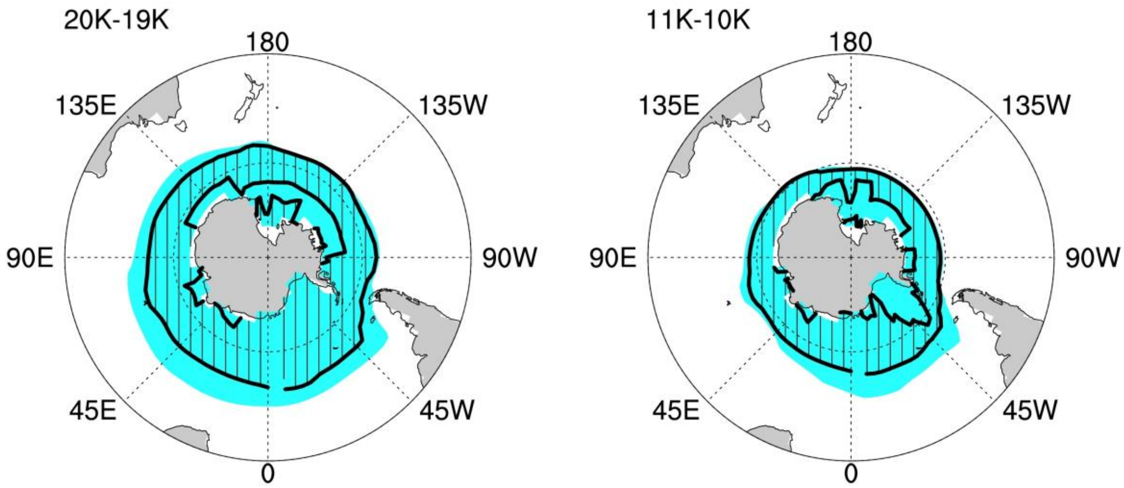

Figure 1. The Southern Hemisphere's seemingly-permanent sea ice coverage (blue color-shaded; fractional concentration) overlaps with the zone of surface buoyancy loss (black-shaded pattern) during 20K to 19K and 11K to 10K periods.

Specifically, the superimposition is better during the 11K to 10K in the Indian and Pacific Ocean sectors. On the other hand, the seemingly-permanent sea ice-ocean edge is equatorward displaced in the Atlantic Ocean sector. This is because of the equatorward transport of sea ice from the Weddell Sea gyre. Moreover, the demarcation between the positive and negative buoyancy fluxes also displaces equatorward in the Atlantic Ocean sector. However, the buoyancy flux transition zone does not overlap with the seemingly-permanent sea ice edge, unlike the Indian and Pacific Ocean sectors.

The 17.3K to 16.3K and 12.5K to 11.5K periods represent the Northern Hemisphere cooling and, therefore, Southern Hemisphere warming periods (bipolar seesaw) (Skinner et al., 2014). Figure 2 shows the overlapping between the seemingly-permanent sea ice-ocean edge and the borderline between the positive and negative buoyancy fluxes similar to the 11K to 10K periods. This shows the association of sea ice with surface buoyancy flux in the Southern Ocean during Southern Hemisphere warm events. Additionally, the inference stands true in the 6K-5K and 2K-1K periods highlighting the association of sea ice with surface buoyancy fluxes throughout the past 20 thousand years.

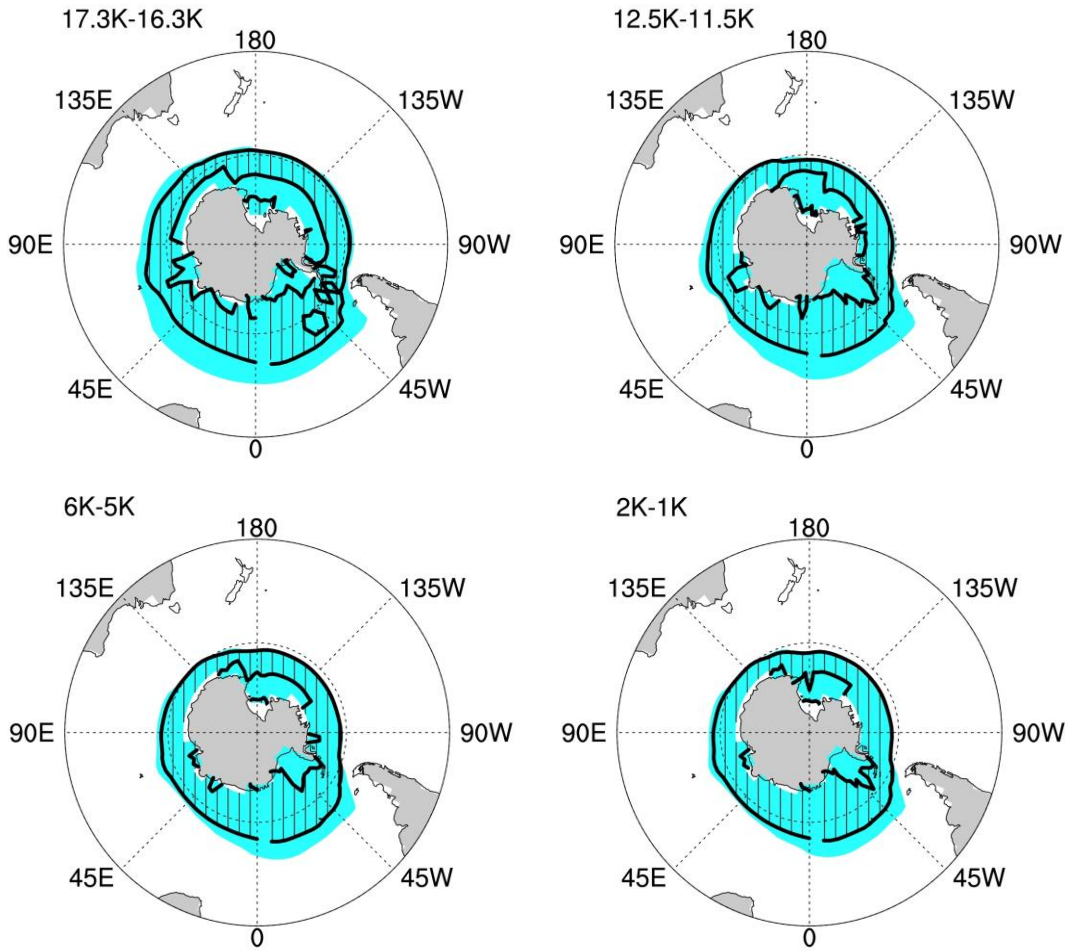

Figure 2. The Southern Hemisphere seemingly-permanent sea ice coverage (shaded in blue color; units are in a fraction) overlying the buoyancy loss zone (black shaded pattern) during 17.3K-16.3K, 12.5K-11.5K, 6K-5K, and 2K-1K periods.

Southern Ocean studies have shown that water draws from deeper ocean layers along inclined outcropping density surfaces poleward of the Antarctic polar front (Anderson et al., 2009). The rising of warmer deep water melts ice in the open ocean and on the shelf and, therefore, controls the northern extent of the Southern Ocean cryosphere. Studies have found that the 1027.6 $\mathrm{kg\,m^{-3}}$ isopycnals outcrop coincides with the winter ice edge. Therefore, the density surface of 1027.6 $\mathrm{kg\,m^{-3}}$ isopycnals roughly demarcate the division between the upper and lower meridional overturning cells (Marshall & Speer, 2012).

The grid points in the ice model with a sea ice concentration of more than five percent are considered to be the Antarctic sea ice-ocean border in this study. Figure 3 shows that the distribution of Southern Ocean surface waters varies during the deglacial period. The Southern Ocean's denser surface waters are equatorward expanded during 20K-19K than 11k-10K. Figure 3 highlights that the Antarctic sea-ocean edge reasonably overlaps with ocean surface density between 1027.5 to 1027.7 $\mathrm{kg\,m^{-3}}$ in the Indian and Pacific Ocean sectors. Therefore, the Antarctic sea ice edge coarsely demarcates the division between the upper and lower meridional overturning cells throughout the most recent deglacial period in the Pacific and Indian Ocean sectors. However, this association is not shown in the Atlantic Ocean sector.

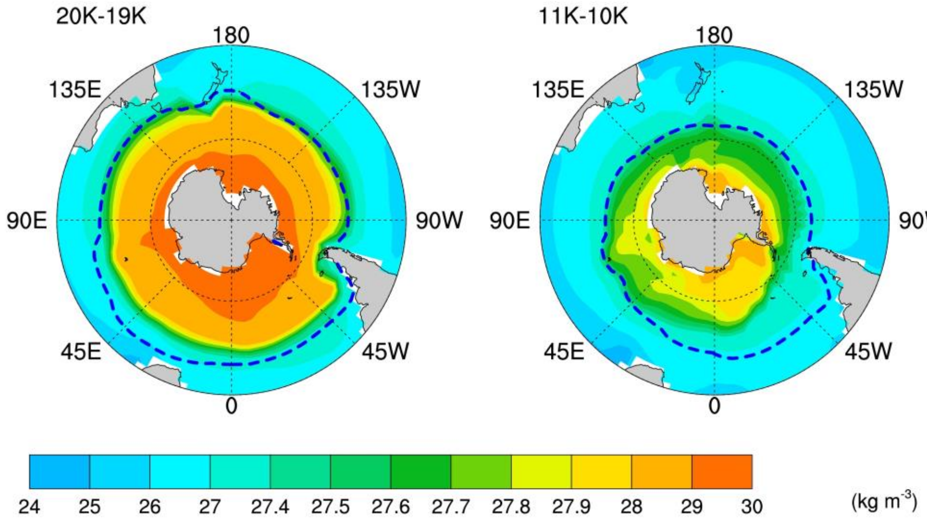

Figure 3. The density of the ocean's surface is shown in color-shaded in kilogram per cubic meters $\mathrm{kg\,m^{-3}}$ units. The ocean surface density data are deduced by 1000, resulting in an ocean surface density of 27.6 $\mathrm{kg\,m^{-3}}$ for a theoretical ocean surface density of 1027.6 $\mathrm{kg\,m^{-3}}$. The surface ocean density is overlaid on the annual mean sea ice-ocean edge (blue dashed line) during the 20K-19K and 11K-10K periods.

During the 17.3K-16.3K and 12.5K-11.5K Southern Hemisphere warming periods, figure 4 shows the overlapping between the seemingly-permanent sea ice-ocean edge and the borderline between the positive and negative buoyancy fluxes similar to 11K-10K period. This shows the association of sea ice with surface buoyancy flux in the Southern Ocean during Southern Hemisphere warm events. Additionally, the inference stands true in the 6K-5K and 2K-1K periods highlighting the association of sea ice with surface buoyancy fluxes throughout the past 20 thousand years.

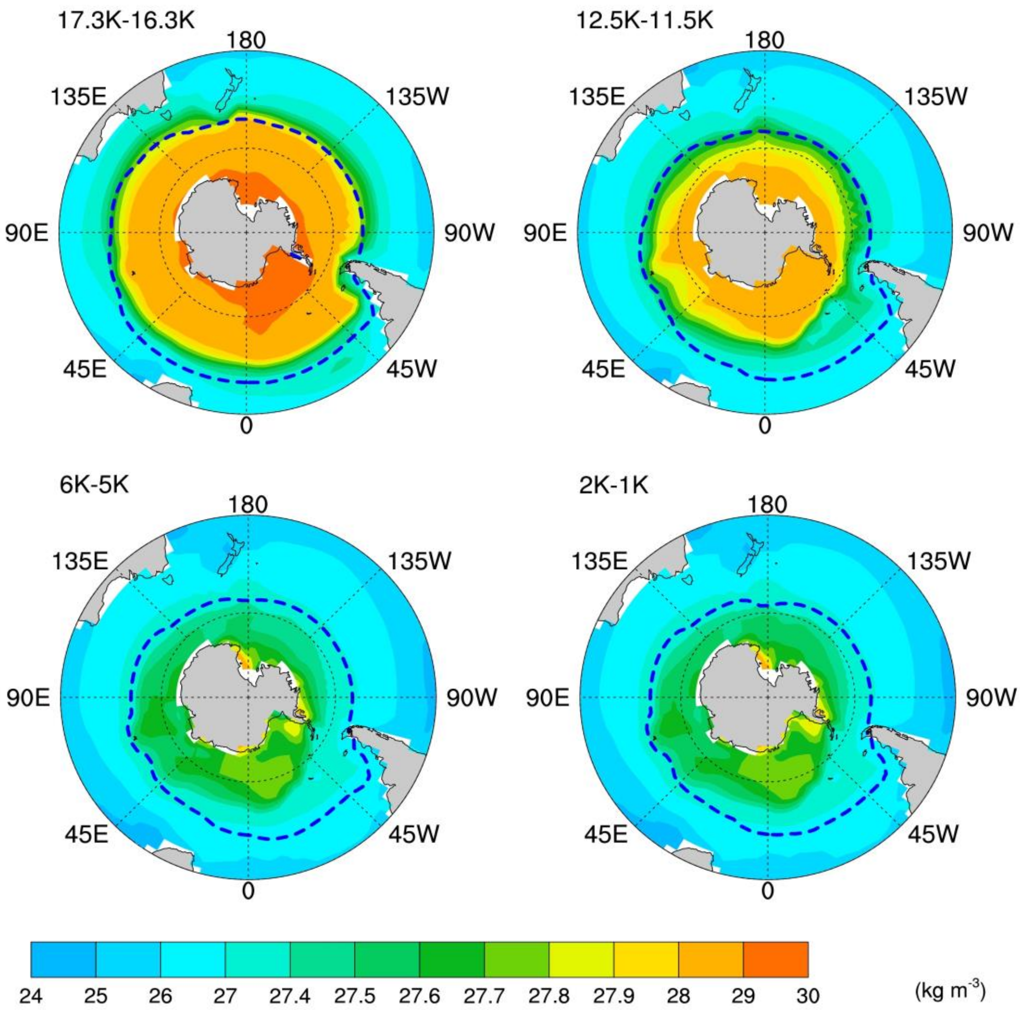

Figure 4. The density of the ocean's surface is shown in color-shaded in kilogram per cubic meters ($kg\,m^{-3}$) units. The surface ocean density is overlaid on the annual mean sea ice-ocean edge (blue dashed line) during the 17.3K-16.3K, 12.5K-11.5K, 6K-5K, and 2K-1K periods.

The Allerød warm phase (14K-12.9K) was brought on by the meltwater pulse 1A (mwp-1A) event, which the model experiment predicted occurred at around 14.1K (Liu et al., 2009). During the mwp-1A event, the model experiment implemented both the Southern (Antarctic) and Northern Hemisphere meltwater forcings. This meltwater forcing in the Southern is three times more than in the Northern Hemisphere and was included in the ocean model as a freshwater flux onto the surface ocean in the Weddell Sea (Atlantic Ocean) region, as indicated by surface freshening in figure 5. Therefore, the 14.1K event characterizes the response of freshwater freshening on the surface Southern Ocean in the Atlantic Ocean sector.

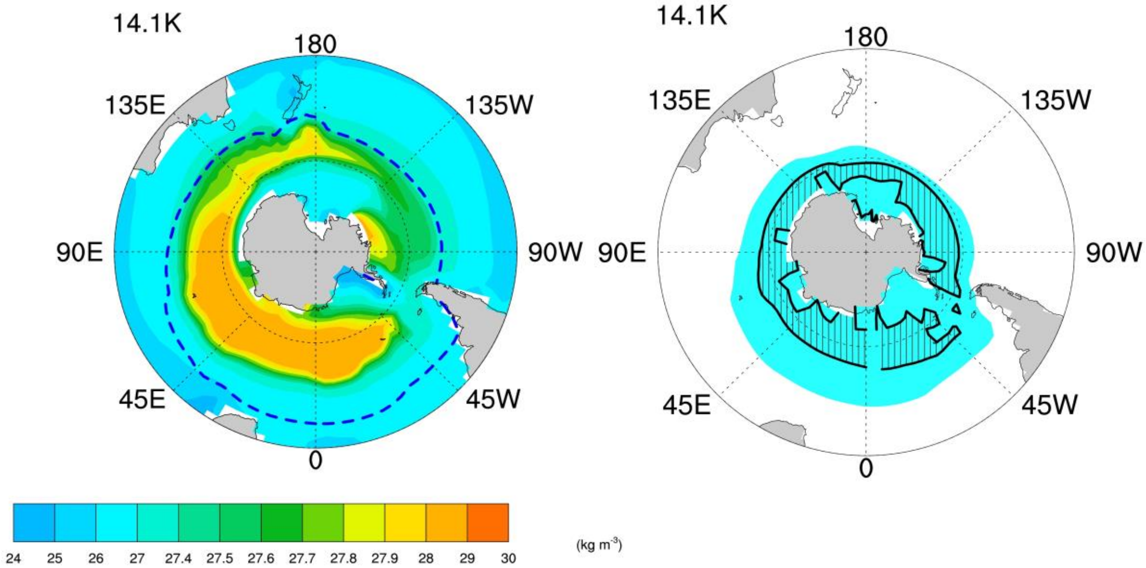

Figure 5. The Southern Hemisphere seemingly-permanent sea ice coverage (blue dashed line) overlays surface ocean density (color-shaded in kilogram per cubic meters $(\mathrm{kg\,m^{-3}})$). Also, the buoyancy loss zone (black shaded pattern) overlays the Antarctic seemingly-permanent sea ice coverage (shaded in blue color; units are in a fraction).

Figure 5 shows the near superimposition between the seemingly-permanent sea ice-ocean edge and the borderline between the negative and positive buoyancy fluxes in the Indian and Pacific Ocean sectors but does not follow in the Atlantic Ocean sector, which is similar throughout the last deglacial period. Additionally, the surface ocean is anomalously fresh near the Antarctic continent in the Atlantic Ocean (Weddell Sea) and Pacific Ocean sectors in response to surface freshwater forcing. The sea ice edge also overlaps with ocean surface density between 1027.5 to 1027.7 $\mathrm{kg\,m^{-3}}$ in the Indian and Pacific Ocean sectors, but does not follow in the Atlantic Ocean sectors.

4. Conclusions

This study investigates the association of the Antarctic sea ice distribution on the Southern Ocean surface density and associated buoyancy flux employing the TraCE-21ka model experiment. The seemingly-permanent sea ice coverage overlays with the buoyancy loss zone over the Southern Ocean during the past 22 thousand years. Consequently, an alteration in the Antarctic sea ice distribution would alter the surface buoyancy flux coverage. Moreover, the Southern Ocean surface area which is covered with sea ice most of the year regulates the Southern Ocean circulation by demarcating the borderline between the upper (Atlantic Meridional Ocean Circulation) and lower meridional overturning circulation.

This study emphasizes the importance of studying Antarctic sea ice distribution to understand the coupling of atmosphere-ocean-sea ice at high latitudes. It also highlights the association between Antarctic sea ice coverage, surface buoyancy forcing, and the Southern Ocean overturning circulation. This relationship is critical in future climate modeling studies in order to recognize the changes in the Southern Ocean overturning circulation and their climate implications. Therefore, this research may aid in understanding the natural global warming process and its impacts on the dynamics of the Southern Ocean.

Supplementary Materials: Not applicable.

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Data Availability Statement: The TraCE-21ka experiment model output data are available in the public domain (https://www.earthsystemgrid.org/project/trace.html). Last accessed on 27 October 2022.

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Conflicts of Interest: The authors declare no conflict of interest.

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