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Key Points:

- We assess the reversibility of Antarctic sea ice loss through Coupled Model Intercomparison Project Phase 6 experiments and quantify the inter-model differences
- Inter-model differences in sea ice loss reversibility mainly arise from variations in initial ocean stratification in the Antarctic Ocean
- Our observation-based assessment suggests that Antarctic sea ice loss may be largely reversible under today's ocean stratification conditions

Supporting Information:

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

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The Reversibility of Antarctic Sea Ice Loss Under CO₂ Removal Scenarios

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Abstract A pronounced decline in Antarctic sea ice has been observed since 2014, with major changes in the Earth system. This study investigates whether these impacts can be reversed by removing atmospheric greenhouse gases. Using carbon dioxide removal experiments from the Coupled Model Intercomparison Project Phase 6, we identify considerable inter-model diversity in projections of Antarctic sea ice recovery, partly driven by a positive feedback loop starting from different initial ocean stratification in the present climate. Specifically, during the CO₂ increasing period, models with stronger initial stratification tend to store heat in the upper layer but not in the deeper layer in the Antarctic Ocean, accelerating sea ice melting, which in turn strengthens ocean stratification and thus impedes sea ice recovery during the CO₂ decreasing period. Conversely, weaker stratification promotes sea ice recovery under carbon dioxide removal scenarios. This demonstrates that the initial ocean stratification intensity exerts a critical influence on the reversibility of Antarctic sea ice loss.

Plain Language Summary Antarctic sea ice plays a crucial role in global economic activities, human operations, and ocean-atmosphere dynamics. However, since 2014, a pronounced decline in Antarctic sea ice coverage has been observed. The climate system's hysteresis characteristics, particularly for the position of the intertropical convergence zone and sea level rise, have been well-documented under a decreasing CO₂ concentration scenario. Using the latest climate models, we find that Climate models exhibit significant divergence in projections of Antarctic sea ice recovery, primarily driven by their representation of initial ocean stratification. These results highlight the critical role of contemporary ocean thermal structure in determining post-emission-reduction sea ice loss reversibility.

1. Introduction

Changes in Antarctic sea ice influence surface albedo, oceanic circulation (Pellichero et al., 2018), the ecology (Watanabe et al., 2020), tropical climate (Geng et al., 2022), and the stability of ice shelves (Rye et al., 2014; Vaughan, 2005) with indirect effects on global sea levels (Kusahara et al., 2023; Massom et al., 2018). In response to global warming, the Arctic sea ice has displayed a rapid decline since 1979 (Maksym, 2019; Parkinson & Cavalieri, 2008; Simmonds, 2017), while Antarctic sea ice has shown a modest increasing trend from 1979 to 2014 (Comiso et al., 2017; Eayrs et al., 2021; Parkinson, 2019; Parkinson & Cavalieri, 2012; Simmonds, 2017). Several physical processes underpin this increasing trend: Southern Ocean upwelling brings up deep water last in contact with the atmosphere 100 s years earlier, moderating the rise in sea surface temperature (Armour et al., 2016). Reduced convection near the Antarctic continent limits the upward transport of warm subsurface water (Goosse & Zunz, 2014; J. Zhang, 2007), favoring sea ice growth. Internal climate variability, such as the Interdecadal Pacific Oscillation (Meehl et al., 2016) and Atlantic Multidecadal Oscillation (Li et al., 2014), also affects Antarctic sea ice growth. Liu (2025a) identify that natural sea ice variability contributes significantly to the simulated Antarctic sea ice expansion trends. Previous studies have also demonstrated that the natural variability associated with Southern Ocean convection may serve as a key mechanism driving recent sea ice expansion (Zhang et al., 2019). However, most state-of-the-art models predict a decline in Antarctic sea ice extent under greenhouse gas (GHG) forcing, indicating a susceptibility to anthropogenic influences (Roach et al., 2020).

Indeed, observed Antarctic sea ice has shown a marked decreasing trend since 2014 (Eayrs et al., 2021; Meehl et al., 2019; Parkinson, 2019; Wang et al., 2019), consistent with model projections.

To mitigate global warming, CO₂ removal (CDR) strategies will likely be necessary (Keller et al., 2018). Several studies have explored climate hysteresis and reversibility in CO₂ reduction experiments. Reversibility is often measured by whether the trajectory returned to its initial state as the CO₂ concentration recovered to the present-day level. These studies revealed that some variables, such as global mean surface air temperature (Frölicher & Joos, 2010; Wu et al., 2015), are largely reversible, while others, including sea level rise (Boucher et al., 2012; Bouttes et al., 2013), Antarctic ice sheet dynamics (Garbe et al., 2020), and the position of the intertropical convergence zone (Kug et al., 2021), exhibit irreversibility and hysteresis. Previous studies have demonstrated that the heat absorbed by the global ocean during the warming phase may attenuate the cooling effect under carbon dioxide removal scenarios (Oh et al., 2024). Regional differences in surface temperature response also emerge following a rapid decrease in CO₂ forcing; for example, the Arctic and East Asia show more immediate and reversible responses, whereas the Southern Ocean exhibits stronger signs of hysteresis (Kim et al., 2022). Long et al. (2025) also found that the surface mixed layer depth (MLD) of the tropical Indian Ocean generally exhibits a relatively rapid recovery toward pre-industrial conditions following CO₂ removal, while spatial patterns of MLD demonstrate irreversibility. However, due to contradicting results from different climate models (Ridley et al., 2012; Ridley & Hewitt, 2014), there is no consensus on the reversibility of Antarctic sea ice loss among these models.

Despite recent advancements in modeling, significant biases persist in simulating Antarctic sea ice, with substantial inter-model variability in the latest CMIP6 simulations (Roach et al., 2020). The lack of consensus on the reversibility of Antarctic sea ice loss among climate models may result from the model bias. Observation-constrained approaches have been employed to improve climate predictions (Community, 2020; Massonnet et al., 2012; Yu et al., 2022), particularly when strong correlations exist between model projection biases and errors in present climate. Therefore, identifying the specific model biases that play a crucial role in Antarctic sea ice loss reversibility is of key importance.

In this study, we aim to elucidate the primary factors that influence the reversibility of Antarctic sea ice loss. Section 2 details the CMIP6 model outputs and multi-source observational data sets employed, along with the corresponding data processing methodology framework. Section 3 systematically presents three core research findings: (a) quantitative analysis of inter-model variability in Antarctic sea ice response to CO₂ forcing based on multiple CMIP6 models, (b) the influence of initial stratification on Antarctic sea ice recoverability, and (c) evaluation of observed stratification parameters as predictors for sea ice recovery potential. The study concludes with an integrated discussion of the implications of these findings for Antarctic sea ice recoverability research.

2. Method

2.1. Data Set and Experiment

The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP) is launched within the CMIP6 framework to address the issue of CDR-induced climate change and its reversibility. Seven CMIP6 models participate in CDRMIP, including CESM2, ACCESS-ESM1-5, CNRM-ESM2-1, MIROC-ES2L, NorESM2-LM, CanESM5, and GFDL-ESM4. The CDR-reversibility experiments provide crucial opportunities to investigate the impacts of large-scale atmospheric CO₂ removal and establish a clear theoretical framework for understanding Earth system responses to CDR. The prerequisite simulations require the piControl and the 1pctCO₂ experiments. The 1pctCO₂ simulation prescribes the CO₂ concentration starting from the year 1850 levels (284.7 ppm) and then increasing by 1% per year from 1850 to 1989. Over 140 years, the atmospheric CO₂ concentration quadruples to 1138.8 ppm in 1989. In each model, the 1pctCO₂-cdr simulation begins from the end of the 140th year of 1pctCO₂, with a subsequent 1% annual removal of CO₂ until the concentration returns to preindustrial condition (284.7 ppm) over another 140 years from 1990 to 2129. After that, the simulation is stabilized at 284.7 ppm for at least 60 years from 2130 to 2189. In this study, Antarctic sea ice loss is considered reversible if sea ice area recovers to the preindustrial levels when atmospheric carbon dioxide (CO₂) concentrations return to preindustrial levels.

To investigate the response to different pathways of CO₂ emission, changes in climate variables are divided into three stages: the “ramp-up” period (CO₂ increases), the “ramp-down” period (CO₂ decreases), and the “restoring”

period (CO₂ stabilizes at preindustrial levels). We select the difference between the last 30 years of the ramp-down period (2100–2129) and the first 30 years of the ramp-up period (1850–1879) to show the divergence between these two periods. We then compare the divergence of Antarctic sea ice.

The observations in this study are primarily sourced from the objective analysis results of IAP (Li et al., 2020), Ishii (Ishii & Kimoto, 2009), and EN4 (Good et al., 2013) for the period 2007–2022. We further validated our findings using BOA-Argo (BOA) data sets, a gridded Argo product, with temperature and salinity profiles sourced from the China Argo Real-time Data Center (Li et al., 2017). The IAP results directly provide the N^2 index, while the results from Ishii, BOA, and EN4 have been converted into conservative temperature and absolute salinity variables. These variables are then used to calculate potential density and the squared buoyancy frequency according to the TEOS-10 standard (IOC et al., 2010).

2.2. Sea Ice Area and Ocean Heat Content Calculated

The sea ice area is calculated by multiplying the individual grid-cell with its sea ice concentration (SIC) and summing all grids together. The method for calculating ocean heat content (OHC) change is shown as follows (Lique & Steele, 2013):

$$\text{OHC} = \iint_z \rho_0 C_p (T - T_{\text{ref}}) dA dz$$

Since the OHC of the entire Antarctic region is being calculated, differentiation is performed concerning area and depth. Here, ρ_0 , C_p , and T represent seawater density, the ocean specific heat, and potential temperature, respectively. T_{ref} represents a reference temperature, which in this paper is the potential temperature under the piControl experiment.

2.3. Stratification Calculation

We calculate in situ density for each CMIP6 model's potential temperature and practical salinity (after conversion to conservative temperature and absolute salinity) using TEOS-10 standards (McDougall & Barker, 2011). The results are presented in the native (model-dependent) grids. Stratification is computed as the square of the buoyancy frequency (Li et al., 2020):

$$N^2 = gE = g \left[- \left(\frac{1}{\rho} \right) \left(\frac{\partial \sigma_n}{\partial z} \right) \right]$$

The ρ , σ_n and g represent the seawater density, the potential density and the gravity acceleration, respectively. The more stratified the ocean, the greater the buoyancy frequency. We further divide N^2 using the TEOS-10 formula, as shown in the following equation:

$$N^2 = g(\alpha^\Theta \Theta_z - \beta^\Theta S_{A_z})$$

Where α^Θ and β^Θ represent the thermal expansion and saline contraction coefficients, respectively. The subscript Z indicates the vertical gradient.

2.4. Observation-Constrained Method

The observation-constrained method is a statistical and computational technique used to improve model predictions by incorporating observational data. In this study, we found that the evolution of Antarctic sea ice loss heavily depends on the initial N^2 of the Antarctic Ocean (60°–90°S). Therefore, in the CDR experiment, we first calculate the regression of the change in Antarctic sea ice area onto initial N^2 for a given CO₂ concentration among the climate models. Then, we average the Ishii, IAP, BOA, and EN4 data sets in the 0–150 m layer from 2007 to 2022, calculate the observed initial N^2 at the present climate, and substitute the observed initial N^2 in the regression relationship to obtain the sea ice change under the observed constraint under this CO₂ concentration.

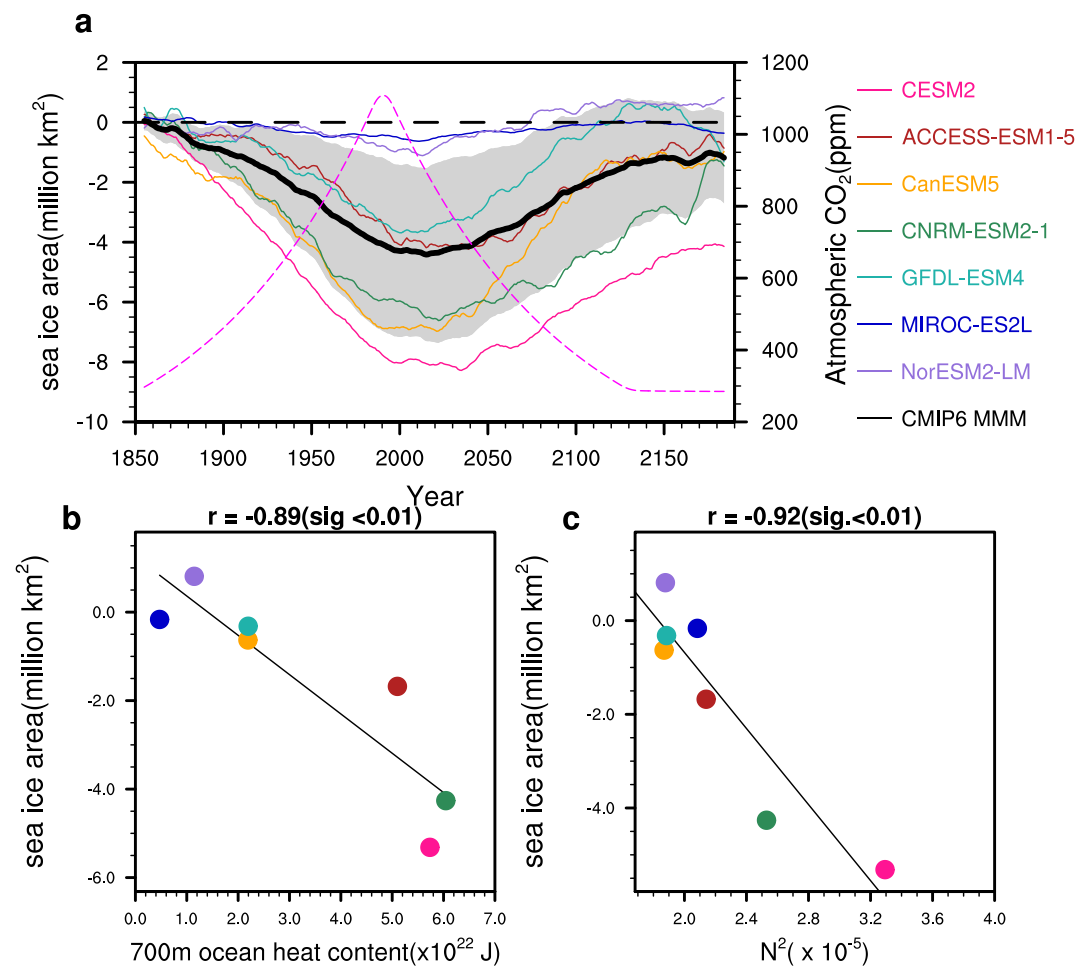


Figure 1. Evaluation of the annual mean Antarctic sea ice area anomaly in the CDR experiment and the main factors influencing the sea ice area recoverability. (a) Time evolution of the Antarctic sea ice area anomaly in the CMIP6 models. (b) Inter-model relationship between the change in Antarctic sea ice area and the change in 700 m ocean heat content of the Antarctic Ocean (60°–90°S). (c) Inter-model relationship between the change in Antarctic sea ice area and 0–150 m squared buoyancy frequency (N^2) in the Antarctic ocean (60°–90°S) at the initial period. The change is expressed as the difference between the last 30 years of the ramp-down period (2100–2129) and the first 30 years of the ramp-up period (1850–1879), and the initial period refers to 1850–1879. The black line in Panel (a) indicates the CMIP6 multi-model mean result, and the gray shadow shows the standard deviation across 7 model members. The magenta dashed line in Panel (a) indicates the time series of CO_2 concentration in the CDR-reversibility experiment. All temporal evolutions in Panel (a) are based on the annual mean and relative to the PiControl simulation and smoothed by an 11-year running mean.

3. Results

3.1. Inter-Model Spread in Antarctic Sea Ice Area Response to CO_2 Forcing

In the climate and carbon cycle reversibility experiment, as shown in Figure 1a, the CMIP6 multi-model mean (MMM) Antarctic sea ice area annual anomalies decrease by approximately 4 million km^2 (47.2%) during the ramp-up phase compared to the preindustrial control simulation. The annual mean sea ice area continues to decline in the first 30 years of the ramp-down phase and recovers thereafter. By 2129, despite the restoration of CO_2 concentrations to preindustrial levels, the sea ice area remains 1.4 million km^2 below its preindustrial state. During the subsequent period with restored constant CO_2 level, the annual mean anomaly continues to diminish, reaching 1.2 million km^2 by 2189. These results suggest that changes in Antarctic sea ice significantly lag CO_2 forcing. However, substantial inter-model variability exists, with a standard deviation of 2.9 million km^2 at the peak of GHG concentrations (1989) and 2.2 million km^2 when greenhouse gases return to preindustrial levels (2129), limiting the direct use of MMM projections for sea ice prediction.

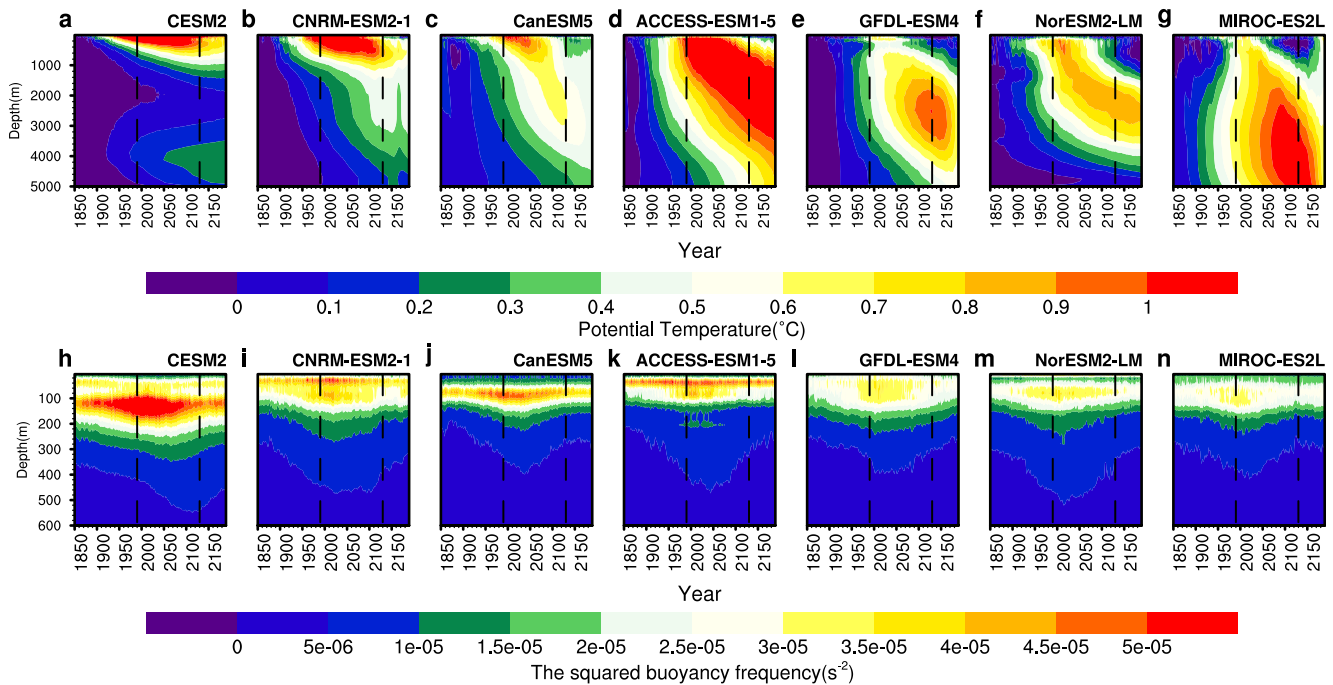


Figure 2. Annual mean vertical distribution of temperature anomaly and the squared buoyancy frequency in the Antarctic Ocean (60°–90°S). (a)–(g) represents the temporal variations of vertical temperature in the Antarctic Ocean. (h)–(n) The temporal variations of squared buoyancy frequency in the Antarctic Ocean. Temperature anomalies are relative to the PiControl simulation. The first black dashed line in Panel marks when the CO₂ concentration peaks. The second black dashed line in Panel marks when the CO₂ concentration returns to pre-industrial levels.

Antarctic sea ice variability is closely linked to the OHC of the upper ocean (Goosse & Zunz, 2014; Lecomte et al., 2017). Here, the upper ocean is defined as the top 700 m, while depths below 700 m are considered the deep ocean, following previous studies (Li et al., 2020; Oh et al., 2024). Figure 1b shows a strong negative correlation ($-0.89, p < 0.01$) between annual mean Antarctic sea ice anomalies and upper OHC anomalies, calculated as the difference between the 2100–2129 and 1850–1879 annual means. Upper OHC changes are significantly influenced by ocean convection, which is in turn related to ocean stratification (Ridley & Hewitt, 2014; J. Zhang, 2007). Figure 1c illustrates the correlation between the initial 150-m annual mean squared buoyancy frequency (N^2 index) from 1850 to 1879 in the Antarctic Ocean (60°–90°S) and changes in sea ice area. The N^2 index, representing the Brunt–Väisälä frequency (Section 2), characterizes ocean stratification, with higher values indicating stronger stratification. The analysis reveals a strong negative correlation ($-0.92, p < 0.01$) between sea ice changes and the N^2 index, demonstrating that the reversibility of sea ice loss depends on the initial ocean stratification.

3.2. Sensitivity of Antarctic Sea Ice Change to Initial Ocean Stratification

The models are divided into two groups based on whether Antarctic sea ice recovers during the ramp-down phase. In the first group, including CanESM5, CNRM-ESM2-1, and CESM2, Antarctic sea ice does not fully recover to pre-industrial levels. The second group, including GFDL-ESM4, MIROC-ES2L, and NorESM2-LM, shows reversibility. The model ACCESS-ESM1-5 is in the middle state. In the first group, maximum warming during the ramp-up period concentrates in the upper ocean layers (Figures 2a–2c), which hinders sea ice recovery. Conversely, in the second group (Figures 2e–2g), primary warming occurs in the deep ocean, peaking at depths around 3 km. During the ramp-down period, heat transports continuously to deeper layers, leaving the upper ocean relatively cooler, which facilitates sea ice recovery.

Figures 2h–2n illustrate the vertical distribution of the annual mean N^2 index in the Antarctic Ocean across different models, revealing that most changes in stratification occurred above 300 m. Ocean stratification strengthens as sea ice melts and weakens as sea ice grows. Throughout the transition from the ramp-up to the ramp-down phase, upper ocean stratification is lower in the second group of models compared to the first, with

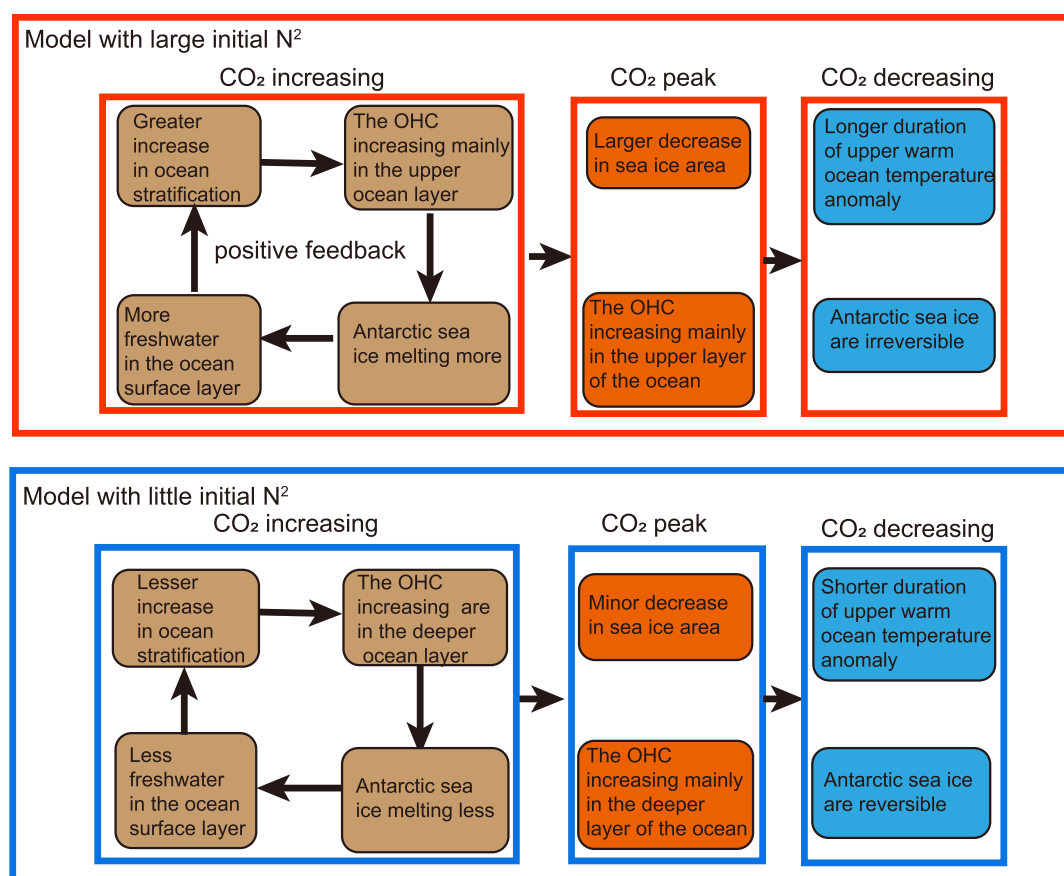


Figure 3. The schematic diagram for the diversity of Antarctic sea-ice reversibility among models in the CDR experiment. Enhanced upper ocean stratification traps heat, accelerating sea ice melt, which in turn reinforces ocean stratification. Consequently, the initial state of ocean stratification critically determines the reversibility of Antarctic sea ice loss in climate models: models with stronger stratification exhibit more rapid melting during CO₂ ramp-up and reduced recoverability during ramp-down, whereas those with weaker stratification demonstrate greater recoverability.

differences evident from the initial period. The maximal initial N^2 index above 150 m exceeds $4 \times 10^{-5} \text{ s}^{-2}$ in the first group, while it is less than $3 \times 10^{-5} \text{ s}^{-2}$ in the second group. These findings indicate that the recoverability of Antarctic sea ice in CDR-reversibility experiments is sensitive to initial ocean stratification.

Changes in stratification are primarily driven by salinity (Figure S1 in Supporting Information S1), in line with previous studies (Li et al., 2020; J. Zhang, 2007). When initial ocean stratification is strong, heat during the ramp-up period is primarily stored in upper layers, favoring sea ice melt. Sea ice melt reduces brine rejection, increasing surface freshwater and enhancing ocean stratification. This strengthened stratification traps heat in the upper layers, further accelerating sea ice melt, thus establishing a positive feedback loop. During the ramp-down phase, as the Antarctic Ocean continues to absorb GHG-induced heat for a long time (Figure S2 in Supporting Information S1) and store it in the upper layer, the upper-layer warm anomaly persists, prolonging the period of elevated temperatures and slowing sea ice recovery, rendering it irreversible.

In contrast, when initial ocean stratification is weak, heat during the ramp-up period is primarily stored in deeper layers, resulting in less sea ice melting and smaller changes in brine rejection. This limits the increase in surface freshwater, maintaining weaker stratification compared to the first group. As a result, during the ramp-down phase, the warm anomaly in the upper layer dissipates more quickly, allowing sea ice to recover more rapidly. Figure 3 illustrates the positive feedback process between ocean stratification and sea ice melting, highlighting the sensitivity of Antarctic sea ice changes to initial ocean stratification. The result is also consistent with Zhang et al. (2022).

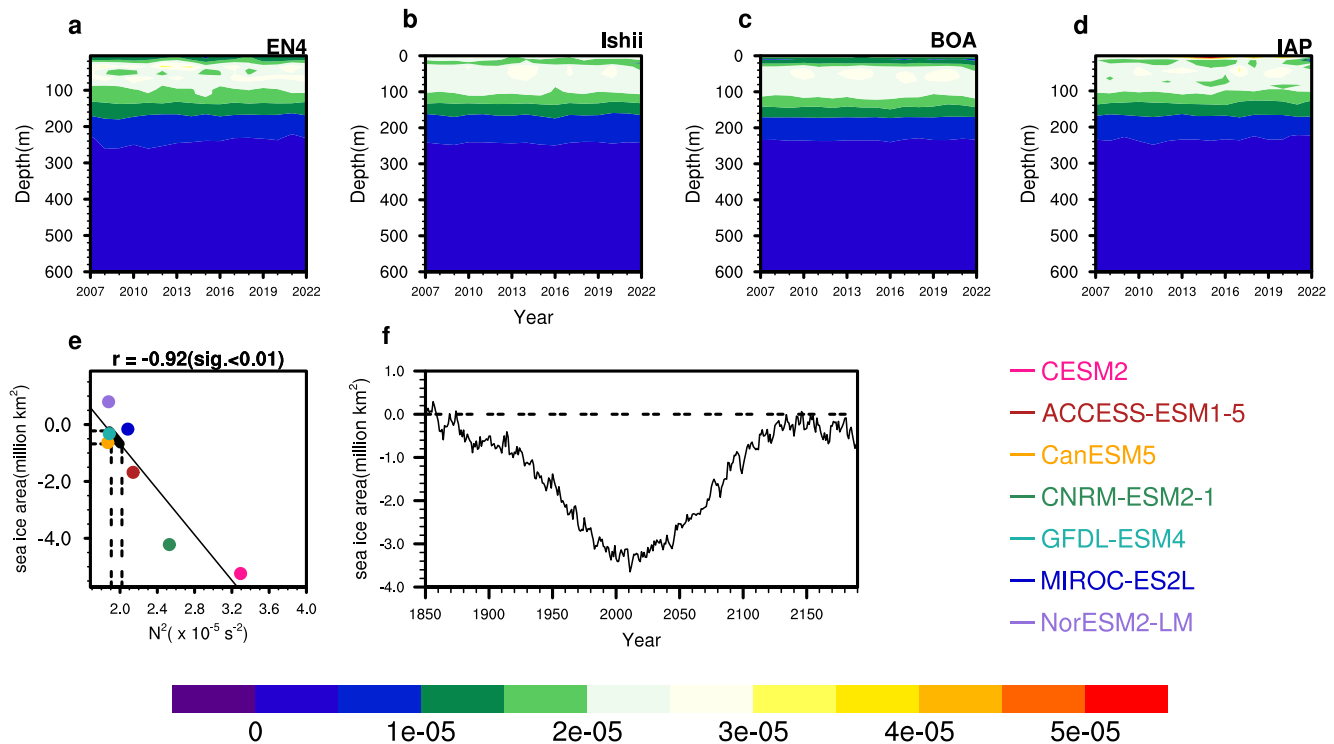


Figure 4. Observed annual mean squared buoyancy frequency in 2007–2022 and the projected sea ice changes based on an observation-constrained method (see Section 2). (a) observations from EN4, (b) from Ishii, (c) from BOA-Argo (BOA), and (d) from IAP. (e) Inter-model relationship between the change in Antarctic sea ice area and 0–150 m squared buoyancy frequency (N^2) in the Antarctic ocean ($60^\circ\text{--}90^\circ\text{S}$) at the initial period, which is the same as Figure 1c but adds the range of observed N^2 (thick black line). (f) The projected sea ice changes are based on an observation-constrained method (see Section 2).

The above positive feedback loop does not consider the sea ice transport. During the Antarctic sea ice expansion period, the Southern Ocean shows increased freshwater transport, reducing ice-ocean fluxes near Antarctica but increasing them in the open ocean northward, matching observations, whereas the opposite occurs during the reduction cases (Liu, 2025b). The sea ice transport may change the spatial distribution of regional stratification. How the deep water below the shallow halocline warms is also an important question. Comparative analysis reveals that CESM2 (classified as the first group of models) maintains stable stratification and sustained isopycnal slopes under a pronounced surface warming response in the abrupt- $4 \times \text{CO}_2$ experiment, whereas NorESM2-LM (classified as the second group of models) exhibits weaker stratification whose deep convection collapses under warming, deepening isopycnals south of 60°S and amplifying subsurface eddy heat transport (Gjermundsen et al., 2021).

3.3. Observed Antarctic Stratification to Predict Ice Recoverability

The initial stratification of the Antarctic Ocean plays a critical role in determining the reversibility of Antarctic sea ice loss. According to the study by Zhang et al. (2022), the initial oceanic conditions in the Southern Ocean also play a significant role in Antarctic sea ice predictability (Zhang et al., 2022). We analyze historical stratification using ocean objective analysis data sets IAP (Li et al., 2020), EN4 (Good et al., 2013), BOA (Li et al., 2017), and Ishii (Ishii & Kimoto, 2009). As shown in Figures 4a–4d, the maximal annual mean stratification values above 150 m in these data sets reach approximately $3 \times 10^{-5} \text{ s}^{-2}$, significantly lower than the values in the first model group but close to the second model group, suggesting that sea ice recoverability should resemble the behavior seen in the second group of models. The observed annual average stratification in 0–150 m ranges between $1.9 \times 10^{-5} \text{ s}^{-2}$ and $2.0 \times 10^{-5} \text{ s}^{-2}$. Using the linear relationship between initial stratification and changes in sea ice area, the observed initial stratification predicts a sea ice area change of about -0.22 to -0.67 million km^2 (Figure 4e), suggesting that Antarctic sea ice loss may potentially recover toward its initial state. Based on the regression of sea ice changes on initial stratification, we predict a relatively reliable Antarctic sea ice anomaly during the experiment. Figure 4f shows the observation-constrained Antarctic sea ice change under CDR-

reversibility forcing, which may recover to its initial value around the year 2134. This indicates that the reversibility of Antarctic sea ice loss is largely influenced by the condition of initial stratification.

4. Summary and Discussion

Our study primarily focuses on the recoverability of Antarctic sea ice simulated by different models. The results show strong inter-model variability in sea ice recoverability, consistent with previous studies (Ridley et al., 2012; Ridley & Hewitt, 2014). Most of the time, from CO₂ ramping up to ramping down, the Antarctic Ocean absorbs heat induced by greenhouse gases. Whether the heat is distributed in the surface or deep layer is vital to Antarctic sea ice recoverability. We reveal a positive feedback loop involving upper ocean stratification, GHG-induced vertical heat distribution, and sea ice melt in the Southern Ocean. Specifically, enhanced upper ocean stratification traps heat, accelerating sea ice melt, which in turn reinforces ocean stratification. Consequently, the initial state of ocean stratification critically determines the reversibility of Antarctic sea ice loss in climate models. models with stronger stratification exhibit more rapid melting during CO₂ ramp-up and reduced recoverability during ramp-down, whereas those with weaker stratification demonstrate greater recoverability. Thus, there is a significant negative correlation between the reversibility of Antarctic sea ice loss and the initial stratification of the Southern Ocean under current climatic conditions. Leveraging historical ocean stratification data, we deduce that the observed changes in Antarctic sea ice may indeed be recoverable through CO₂ removal efforts. In addition, the models of Antarctic sea ice recovery show an increase in SIC in the Ross Sea, but a reduction in sea ice in sectors such as the Western Pacific Ocean, the Bellingshausen and Amundsen Seas (Figure S3 in Supporting Information S1), suggesting that even if the total sea ice area in the Antarctic Ocean recovers, the spatial distribution of sea ice may still change substantially.

Some conclusions of this study may initially appear inconsistent with existing research. Previous studies have shown that enhanced stratification suppresses convective mixing, reducing upward heat transport from deeper warm water and consequently promoting sea ice growth (Haumann et al., 2020). However, our investigation focuses on sea ice changes under GHG forcing scenarios during the ramp-up period, where radiative heating primarily warms the surface ocean in open-water regions. In this context, strong stratification inhibits downward heat penetration, leading to thermal accumulation in the upper ocean. These findings are not physically contradictory but rather represent distinct mechanisms operating on different timescales.

This study has several limitations. First, this study has a relatively small sample size due to the limited number of models participating in the CDR experiments. Nevertheless, key physical processes identified in our analysis—particularly the relationship between sea ice melt and ocean stratification, as well as the connection between upper OHC and sea ice variability—have been corroborated by independent studies (Gjermundsen et al., 2021; Haumann et al., 2020), lending credibility to our findings. Second, our study mainly focuses on initial stratification as a key factor modulating Antarctic sea ice recoverability. However, other drivers—such as global surface temperature anomalies and initial Antarctic sea ice area—may also play significant roles in global warming (Holmes et al., 2022). Ridley and Hewitt (2014) further suggest that continental shelf-break currents could influence Antarctic sea ice recoverability in certain regions by redistributing SIC. Previous studies have similarly demonstrated that Antarctic sea ice recoverability exhibits an approximately linear relationship with local surface temperature under simulation scenarios analogous to the CMIP6 CDR-reversibility experiment (Ridley et al., 2012). Another important point is that this study focuses exclusively on the thermodynamic processes of Antarctic sea ice, without addressing its dynamic processes. Previous studies have indicated that changes in surface meridional winds associated with atmospheric pressure systems are significantly correlated with multidecadal-scale variations in Antarctic sea ice extent (Haumann et al., 2014; Turner et al., 2016). Zhang et al. (2022) indicate that the extreme lows of Antarctic sea ice in 2016 were largely influenced by atmospheric factors, particularly changes in surface wind fields. This dynamic change in sea ice also significantly influences the sea surface salinity (Haumann et al., 2016). Liu (2025b) show that a simulated Antarctic sea ice expansion trend is associated with a decreasing trend of sea-ice–ocean freshwater fluxes around the Antarctic coast but an increasing trend of freshwater fluxes to the north in the open ocean, a pattern consistent with observed sea-ice-driven salinity changes (Haumann et al., 2016). However, since only a limited number of models output sea ice velocity data and Near-Surface Wind data, future studies may need to incorporate more simulations to investigate the impact of this Southern Ocean freshwater transport on ocean stratification. Several studies also indicate that ocean stratification is modulated by freshwater flux, which is concurrently regulated by both Antarctic sea ice and the Antarctic ice sheet (Haumann et al., 2020; Schmidt et al., 2023). Therefore, understanding the combined

effects of these multiple factors could help constrain projections of Antarctic sea ice recoverability. The results of this study highlight the critical importance of accurately simulating the initial stratification of the Southern Ocean, such as better representing its three-dimensional structure of the ocean, as a key factor for enhancing the fidelity of CMIP6 climate models. These improvements can significantly reduce inter-model discrepancies and enable more reliable assessments of the reversibility of Antarctic sea ice loss.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The CMIP6 data are available at <https://pcmdi.llnl.gov/CMIP6/>. IAP is available at <http://www.ocean.iap.ac.cn/pages/dataService/dataService.html?navAnchor=dataService>; EN4 are available at <https://www.metoffice.gov.uk/hadobs/en4/download-en4-2-1.html>; Ishii are available at <https://climate.mri-jma.go.jp/pub/ocean/ts/>. BOA-Argo is available at <https://www.argo.org.cn/index.php?m=content&c=index&a=lists&catid=101>. The Gibbs-SeaWater (GSW) Oceanographic Toolbox has been used to calculate in situ density for each CMIP6 model's potential temperature and practical salinity (after conversion to conservative temperature and absolute salinity) (<https://github.com/TEOS-10/GSW-Python>). The data in this study is mainly analyzed with NCAR Command Language (NCL; v6.6.2, <https://www.ncl.ucar.edu/>) and Python, which are public access software.

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