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To cite this article: F Feba *et al* 2026 *Environ. Res.: Climate* **5** 035012

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ENVIRONMENTAL RESEARCH CLIMATE



PAPER

OPEN ACCESS

RECEIVED

16 November 2025

REVISED

14 May 2026

ACCEPTED FOR PUBLICATION

1 June 2026

PUBLISHED

22 June 2026

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The oceanic response to winds in the Antarctic sea ice loss at the end of the 1970s

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Keywords: Antarctic sea ice, climate model, sea ice loss, polar climate variability, Southern Ocean, wind circulation, EC-Earth Model
Supplementary material for this article is available [online](#)

Abstract

The sea ice extent (SIE) in the Southern Ocean experienced a substantial decline in the late 1970s, although less pronounced than the one observed in 2016. Though several studies explain the decline since 2016, the 1970s drop is critical in understanding the long-term variability of SIE. To investigate the underlying mechanisms for this decline, we conducted wind stress-forced multi-ensemble experiments using the general circulation model EC-Earth3 with constant pre-industrial CO₂. Using this anomaly-perturbation technique, we reproduce the drop during the late 1970s, despite the control (no-perturbation) run showing no such trend. The loss in SIE expresses spatial heterogeneity across different sectors of the Southern Ocean, with the maximum absolute loss occurring the King Hakon sector, followed by the Weddell Sea and Indian Ocean sectors. The loss of SIE co-occurred with an increase in temperature and salinity at the surface. Our analysis shows that this loss of SIE can be attributed to a twofold wind-driven oceanic response. (1) During the late 1970s, the wind stress curl was anomalously negative, driving a stronger Ekman upwelling, bringing salt and warmer water from the subsurface to the surface. (2) The winds shifted to a stronger phase during the same period, influencing the vertical mixing, inducing a deeper mixed layer and the entrainment of warmer and saltier water at depth in the mixed layer. This study highlights the importance of winds in driving ocean processes and thereby influencing the interannual variability of SIE in the Southern Ocean. Our results finally indicate that the late 1970s rapid sea ice loss event shares several characteristics with the recent post-2016 retreat, including a significant surface salinification despite substantial sea ice loss, suggesting that common mechanisms might be at play between the two periods and thus providing an insightful analogy to understand the current decline.

1. Introduction

The Southern Ocean sea ice is a large-scale, dynamic entity that acts as a barrier between the oceanic layer underneath and the atmosphere above, modulating the thermal, moisture, momentum and gaseous fluxes (Goosse and Fichefet 1999, Rintoul 2018, Schroeter 2025). Over the past decade, the Southern Ocean sea ice extent (SIE) has received a surge in interest owing to its puzzling behaviour. For almost four decades, the SIE showed a slightly positive trend from 1979 to 2015 despite warming trends across nearly the entirety of the globe (Thomas *et al* 2015, Armour *et al* 2016, Hobbs *et al* 2016, Parkinson 2019). This period was followed by the alarming SIE drop in 2016 (Turner *et al* 2017, Meehl *et al* 2019) and subsequently in 2023 and 2024 (Roach and Meier 2025), marking a shift from the earlier observed upward trend to a pronounced low-extent regime (Fogt *et al* 2022, Purich and Doddridge 2023, Hobbs *et al* 2024, Abram *et al* 2025).

Several studies have proposed different mechanisms that, individually and collectively, with varying degrees, have possibly contributed to these drops in SIE, with atmospheric circulation clearly playing a dominant role. In particular, variations in the strength of the Amundsen Sea Low contributed to the SIE loss by modifying atmospheric heat transport and sea ice transport (Turner *et al* 2017, Jena *et al* 2024, Wang *et al* 2024). There were also some influences from the tropics, i.e. the extreme El Niño of 2015 (Stuecker *et al* 2017), with a weaker impact related to the 2023 ENSO conditions (Espinosa *et al* 2024), or a Rossby wave teleconnection from the tropical Indian Ocean (Purich and England 2019). Bonan *et al* (2024) also identified the relative roles of different flavours of ENSO and circulation features responsible for both the long-term expansion of Antarctic sea ice and its recent abrupt decline. The positive phase of the zonal wave number three is also reported to have influenced the early melting and the rapid decline in SIE in 2016 due to an anomalous atmospheric southward heat transport (Schlosser *et al* 2018).

Such wind circulation changes explain the majority of the interannual variability patterns and trends through both dynamic and thermodynamic effects across different regions of the Southern Ocean (Raphael 2007, Lefebvre and Goosse 2008, Massom *et al* 2008, Holland and Kwok 2012, Hosking *et al* 2013, Raphael and Hobbs 2014, Matear *et al* 2015). However, the role of the ocean is also important, providing a preconditioning that could amplify the response to the atmospheric perturbations and feedbacks that prolong the influence of this perturbation. A warmer ocean causes delayed ice growth, and so a thinner ice pack on average, which in turn can melt earlier and more easily during the next season. In this framework, the subsurface warming observed before 2016 has been considered as an important element explaining the post-2016 shift in SIE (Lecomte *et al* 2017, Meehl *et al* 2019, Zhang *et al* 2022, Purich and Doddridge 2023, Wilson *et al* 2023, 2026, Hobbs *et al* 2024, Spira *et al* 2026). The negative decadal trend of wind stress curl (WSC) associated with the positive phase of the Southern annular mode caused an Ekman suction that induced warming in the Southern Ocean and contributed to the 2016 low SIE (Meehl *et al* 2019, Zhang *et al* 2022). In addition to this impact on the upwelling of warm water, stronger westerlies can also transport colder Antarctic surface water northward or reduce the horizontal heat transport in some sectors, driving sea ice expansion. Modifying the stratification of the water column and the vertical exchanges affects the winter ice thickness and SIE (Lecomte *et al* 2017, Himmich *et al* 2024, Spira *et al* 2025). Based on an analysis of 110 000 hydrographic profiles, Spira *et al* (2026) identified a thinning of the winter water layer between 2005 and 2015, which forms below sea ice in winter and is sustained in summer below the mixed layer as a water layer at near-freezing temperatures. As this layer limits the exchanges between the warmer waters at depth and the surface, the consequent thinning reduces the strength of the barrier. Additionally, strong winds in 2015 were able to induce a large transport of heat from depth to the surface, contributing to the observed shift in SIE after 2015.

Many studies have been devoted to the shift in SIE after 2015, but the lack of long and homogeneous data records for SIE is a constraining factor in understanding the possibility of the occurrence of such sea ice loss events predating the satellite era from 1979. Nevertheless, several sea ice reconstructions based on various indirect climate records are available, although not without limitations (de la Mare 2009, Dalaiden *et al* 2021, Fogt *et al* 2022, Goosse *et al* 2024). These reconstructed longer datasets are essential in studying long-term trends or multidecadal variability in the sea ice, for example, the sector-wise variability of the sea ice edge in the Southern Ocean (Yang *et al* 2021) or the influences of tropical drivers (Dalaiden *et al* 2024). Recently, a multi-variate spatial reconstruction for the period 1958–2023 shows a loss of SIE of the order of 0.5 million km² in the Southern Ocean in the late 1970s (Goosse *et al* 2024). Using a Bayesian reconstruction, another study also notes the probability of exceptionally low SIE in the Southern Ocean during the late 1970s (Raphael *et al* 2025).

Though the reconstructions establish the presence of an earlier sea ice loss predating the satellite era, the mechanisms leading to this loss have not been explored in detail, necessitating a further detailed study. The analysis of the atmospheric circulation in the 1970s suggests a triggering role of the atmospheric circulation as observed during the post-2015 decrease (Goosse *et al* 2024), but the oceanic contribution is more uncertain. The ocean has likely integrated the atmospheric forcing, prolonging the effect of the atmospheric anomalies; however, it is unclear if the ocean has only this relatively passive role or a more active one in the event. In the present study, we thus look at the potential role of the response of the ocean to wind changes and whether it could be the inception of this loss of SIE in the Southern Ocean towards the end of the 1970s.

In order to understand this potential role of ocean dynamics, we use here an Earth system model (ESM) to simulate the sea ice loss at the end of the 1970s. Recent studies have shown that when the winds are nudged in the atmosphere towards observations in an ESM, the model is able to follow some of the key characteristics of the observed changes in SIE (Blanchard-Wrigglesworth *et al* 2021, Roach

et al 2023). This approach could have been applied here to try to reproduce the shift in SIE at the end of the 1970s. However, the wind nudging modifies atmospheric heat transport as well as the fluxes at the atmosphere-ocean-ice interface. It is thus impossible to disentangle the direct effect on sea ice of those imposed changes in the atmosphere from the response of the ocean. We have thus applied a different methodology in which we only perturb the wind stress at the surface based on observed winds. This modifies the oceanic circulation, which in turn influences the SIE and the atmosphere. With this experimental design, any change in the SIE must have its origin first in the ocean, allowing us to determine if modification of the oceanic state can explain a significant part of the SIE shift at the end of the 1970s. This approach also helps us to single out the role of dynamical factors, since the thermodynamical factors (large-scale atmospheric advection) are by design left unchanged.

2. Methods

2.1. Model description

In this study, we carried out simulations using the European Community ESM (EC-Earth; Döscher *et al* 2022). The EC-Earth is a fully coupled atmosphere-ocean-ice model. The atmospheric component of EC-Earth is the integrated forecast system (IFS) from the European Centre for Medium-Range Weather Forecasts (ECMWFs), cycle CY36R4. The atmospheric grid is the IFS standard resolution (T255L91), with approximately 80 km grid spacing and 91 vertical levels. The oceanic component is the Nucleus for European Modelling of the Ocean version 3.6 (NEMO; Madec and the NEMO team, 2015), with the Louvain-la-Neuve Sea Ice Model (version 3; Vancoppenolle *et al* 2012, Rousset *et al* 2015). The ocean-sea ice coupled NEMO3.6-LIM3 is used at 1° resolution on the standard ORCA1 configuration with 75 vertical levels. The atmosphere and ocean-sea ice are coupled using the Ocean Atmosphere Sea Ice Soil coupler version 3 with the Model Coupling Toolkit. Our version, EC-Earth 3.3.3.2 is thus very similar to the one used for Coupled Model Intercomparison Project phase 6 (CMIP6), EC-Earth 3.3 (Döscher *et al* 2022).

2.2. Experimental setup

Our study focuses on the low-frequency variability at interannual to multidecadal timescales, and forcing or nudging with monthly anomalies is a standard approach for studies at these timescales (e.g. Deser *et al* 2017, Polkova *et al* 2019, Garcia-Oliva *et al* 2024). Here, as a first attempt, we try a new approach by adding monthly perturbations to isolate the role of wind stress from other wind influences, including the impact of wind changes on atmospheric transport and turbulent heat fluxes. The perturbation modifies both the wind-driven Ekman velocities and the wind-induced vertical mixing. For instance, Spira *et al* (2026) also used monthly anomalies to analyse the role of wind on mixed layer depth in order to explain the recent changes in Antarctica (see their figure 5(c)). However, the effect of wind forcing is only partly accounted for by using monthly anomalies, as higher frequency variability can strongly influence mixed layer dynamics (e.g. du Plessis *et al* 2026). Nevertheless, we consider that adding daily perturbations to the wind stress simulated by EC-Earth could lead to non-physical perturbations, in which, for instance, sea ice moves at high speed or diverges strongly while the atmosphere above remains very calm. Alternatively, if a strong wind anomaly is added to a situation with already large winds simulated by EC-Earth, this would lead to unrealistically large winds that could perturb the model's dynamics.

Our experiment is designed to force the model with monthly wind stress anomalies from ECMWF Reanalysis version 5 (ERA5, Hersbach *et al* 2023). The goal is to introduce perturbation only on momentum transfer by using wind stress anomalies. All changes in temperature (and atmospheric circulation) arise from feedbacks computed by EC-Earth. These anomalies are estimated compared to the mean seasonal cycle computed over the period 1960–2022. We modify the surface boundary conditions in NEMO during the coupling stage by adding wind stress perturbations to the value transferred from IFS by the coupler, consistently perturbing the model at all time steps. Therefore, the atmosphere can only be perturbed through the effect of the ocean, removing the direct atmospheric influences from obfuscating any potential signal coming from the ocean.

To begin with, we carried out a control run (EC-CTL) with the standard configuration of the model, as a reference that will be compared to our perturbed experiments for assessing the impact of the wind forcing. All our simulations are run with prescribed CO₂, employing the constant pre-industrial conditions as defined for the CMIP6 (Eyring *et al* 2016), with greenhouse gases maintained at the constant levels as in the pre-industrial period. Such simulations without anthropogenically induced forcings help differentiate the natural internal variability of the model climate system and identify the direct effect of

the wind stress perturbation. We then carry out six ensemble members forced with identical wind stress anomalies.

Our initial reference run, EC-CTL, is a free run, allowing the model to evolve on its own. Each ensemble member (ECN1-ECN6) starts in 1960 and runs through 2022. The monthly wind-stress-anomaly forcing is equivalent across all members. The difference in members arises from the ocean state at initialisation. All ensemble members start in 1960 with initial conditions in EC-CTL selected at a consecutive interval of 10 years. This implies that the ocean state at initialisation for ECN1 is year 110 of the EC-CTL run. For the subsequent members, ECN2, ECN3, etc, the ocean state is initialised from years 120, 130, etc, of the EC-CTL run. This indicates an effective spin-up time of at least 110 years for each ensemble member, a sufficient time scale to reach a steady state in the upper ocean. The different initial states are integral to separating the role of internal variability, due to the differing phases of various climate modes, from the effect of the wind-stress perturbation. For our analysis, we calculate the ensemble mean (EnsMean) from the six ensemble members.

All the ensemble members and the control run have a robust and consistent seasonality for the Southern Ocean SIE, comparable to that of the CMIP6 simulations (Roach *et al* 2020). For each ensemble run, from 1960 to 2022, the mean seasonal cycle has a summer minimum of ~ 2 million km^2 in February and a winter maximum of ~ 19 million km^2 in September (supplementary figure 1). The monthly bias or the difference between monthly climatological SIE in EnsMean when compared with observational data from NSIDC (DiGirolamo *et al* 2022) shows an underestimate of the total SIE, with the least bias in February (-2.27 million km^2) and the maximum bias in April (-3.93 million km^2). The standard deviation across the ensemble members has been calculated for each year (supplementary figure 2), with a mean of 0.41 million km^2 over the total period, 1960–2022. The coefficient of variation (ratio of standard deviation to mean), which indicates the spread of the ensemble members, for the same period, is 4.28%.

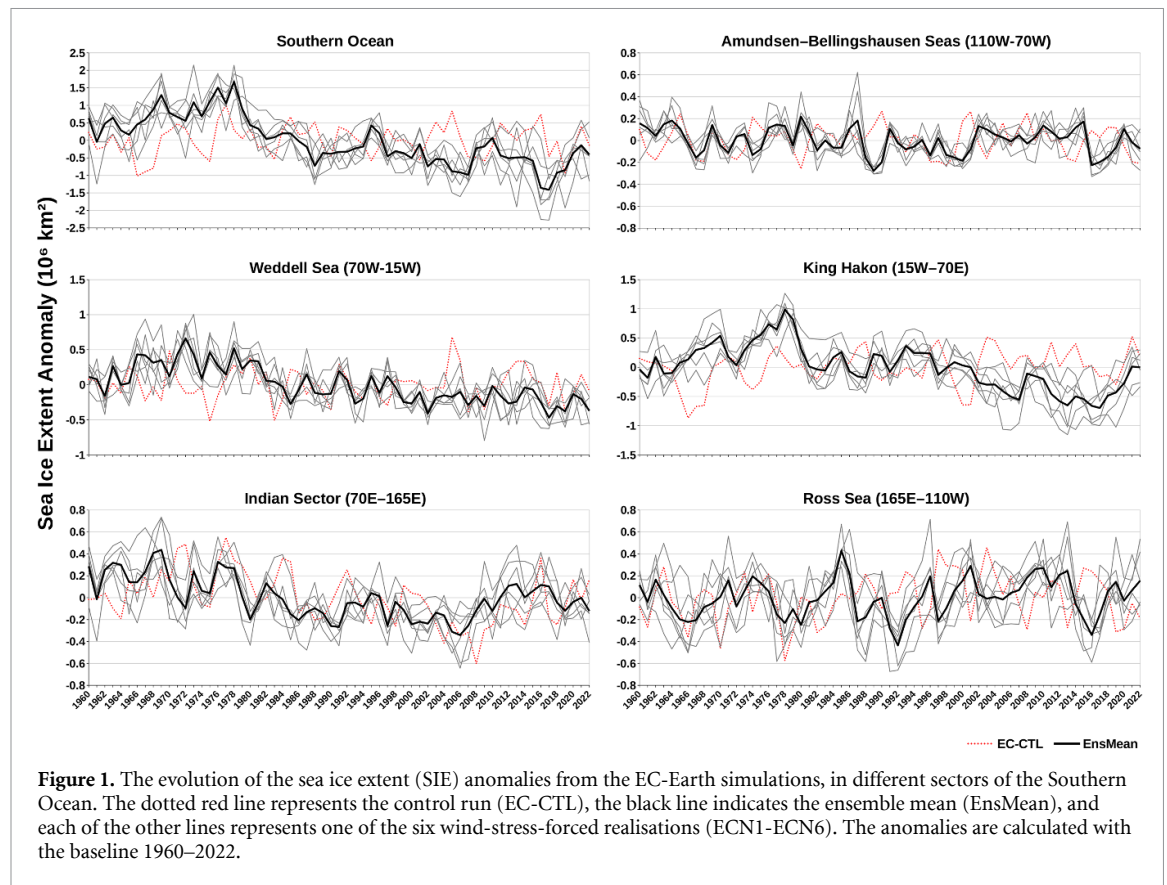
3. Results

3.1. Evolution of the southern ocean SIE

The evolution of the Southern Ocean SIE anomalies from our EC-Earth simulations is shown in figure 1. As expected, the interannual variability of the EC-CTL diverges from the individual ensemble members and the ensemble mean (EnsMean). However, all the wind stress forced simulations display similar multidecadal variability, and all the ensemble members are able to capture the observed drop (Goosse *et al* 2024) in SIE at the end of the 1970s. By contrast, the EC-CTL experiment displays no such trend, suggesting that it is driven by the wind stress anomalies imposed in the perturbed experiments. The total SIE from the EnsMean, in the Southern Ocean, shows a steady increase in annual mean of over 1 million km^2 from 1960 (10.4 million km^2) to the mid-1970s (11.3 million km^2 in 1976), followed by a loss of about 12% during the next decade (9.3 million km^2 in 1990). A similar pattern of an increase and a subsequent decline in the late 1970s is apparent in the King Hakon and Weddell Sea sectors. The Indian Ocean sector had a decreasing SIE trend during the same period, although no increase was evident before the loss. The Amundsen-Bellinghousen seas show a very low decline in SIE, whereas the Ross Sea sector has no discernible trend throughout the run duration. The wind stress forced simulations (EnsMean) also show a SIE minimum in 2016, but we will not investigate in more detail this smaller drop and will focus on the clearer and larger signal at the end of the 1970s.

3.2. The southern ocean before and after the sea ice loss

The period of maximum SIE extent in the EnsMean was in the late 1970s, and the subsequent minimum extent occurred during the early 1990s. We thus selected two periods, the period of maximum extent before the loss from 1976 to 1980 (pre-loss), and the subsequent minimum extent from 1990 to 1994 (post-loss), to compare and identify contrasting patterns (supplementary figure 3). From the EnsMean, the difference between the pre-loss (1976–1980) and post-loss (1990–1994) periods indicates a decrease of 1.28 million km^2 of SIE across the total Southern Ocean, with the ensemble members ranging from a minimum loss of 0.8 million km^2 to a maximum of 1.54 million km^2 . We have extended the periods of choice to a decade to assess the sensitivity of our results. We calculated the difference between an extended post-loss period (1990–1999) and an extended pre-loss period (1971–1980) from the EnsMean (supplementary figure 4). The region with sea ice loss is almost the same as our earlier choice of the



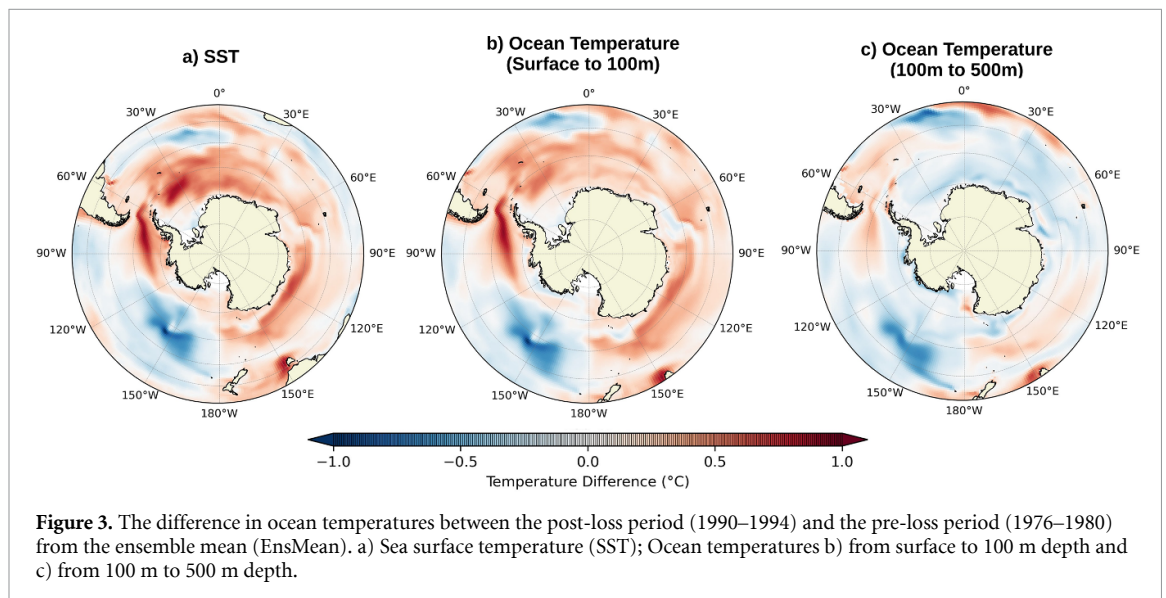
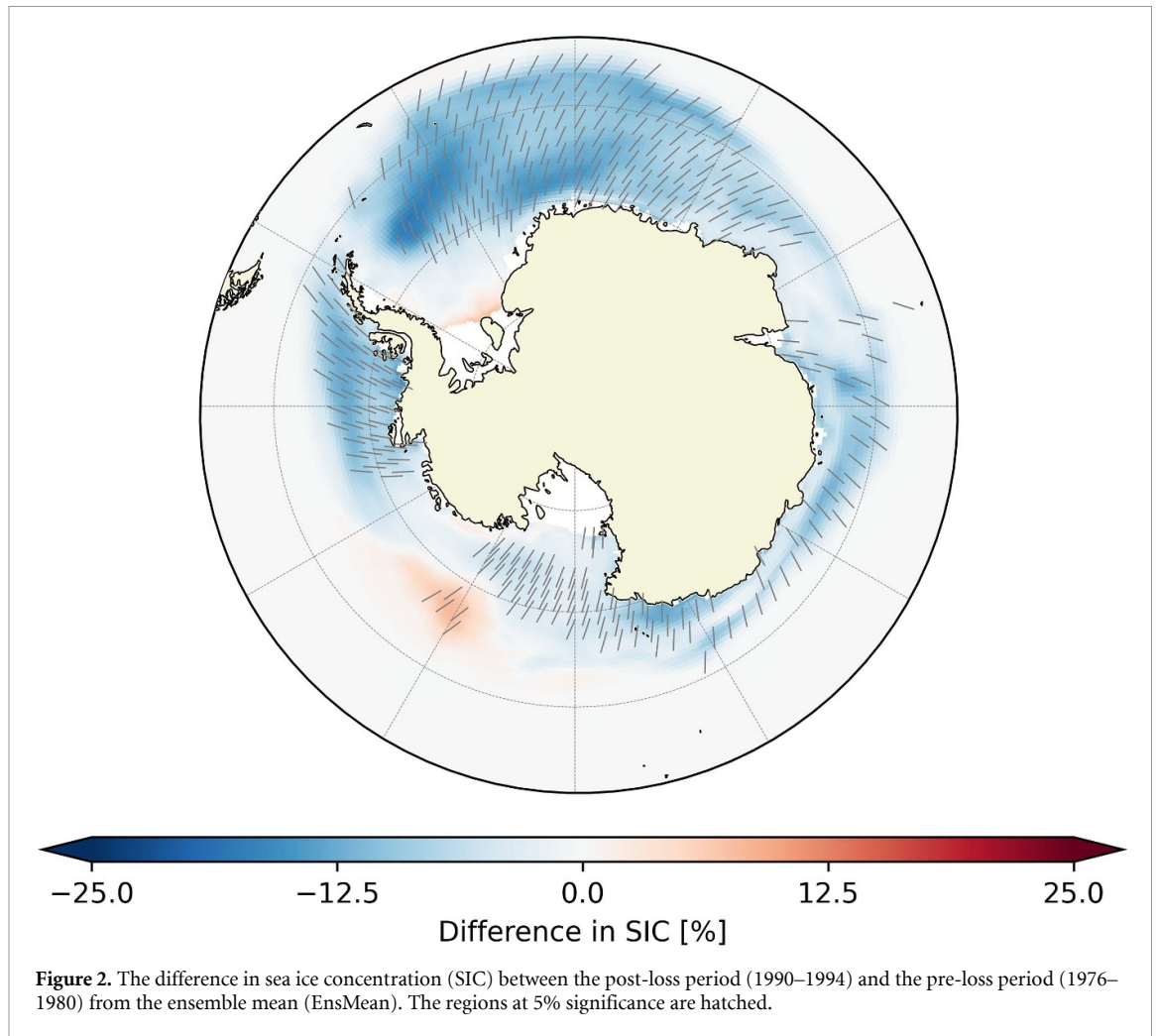
post-loss period (1990–1994) and the pre-loss period (1976–1980), although the magnitude of loss is lower.

The loss of mean SIE, is evident as negative anomalies in sea ice concentration almost everywhere except in the north of the Ross Sea (figure 2). Sector-wise in the EnsMean, the SIE loss is more pronounced in the King Hakon, Weddell Sea and Indian Ocean sectors. The Weddell Sea lost 0.36 million km² (Ensemble range: 0.18 million km² to 0.54 million km²), the King Hakon Sector lost 0.4 million km² (Ensemble range: 0.27 million km² to 0.66 million km²), and the Indian Ocean sector lost 0.23 million km² (Ensemble range: 0.07 million km² to 0.38 million km²) of SIE, which contributed to 28.2%, 38.6% and 18% respectively to the total loss of SIE in the Southern Ocean. These sectors also had a large contribution to the loss, as identified in the reconstruction of Goosse *et al* (2024).

All the ensemble members consistently show losses of varying magnitudes in all sectors in the Southern Ocean except for the Ross Sea, where the members differ and are non-conforming about an increase or decrease (supplementary figure 5).

However, the maximum loss of SIE is observed over the region from 55°S to 70°S and from 50°W to 30°E, the Eastern Weddell Sea (EWS) sector (figure 2). The EWS, in the EnsMean, lost 0.8 million km² of SIE in a decade compared to the pre-loss period. The SIE loss from the EWS sector contributed to about 63% of the total loss in SIE in the entire Southern Ocean during the same period. We then examine other oceanic parameters to understand the causes for this sea ice loss over the EWS region.

Unsurprisingly, the sea surface temperature (SST) difference fields reveal a warming over the EWS sector and more generally in all the sectors where SIE decreases (figure 3(a)). The ocean temperatures from the surface to 100 m depth have also shown a warming over the EWS sector during the same decade. Contrastingly, between the depths of 100 m and 500 m, the ocean temperatures show a relative cooling during this period (figure 3(c)). The surface-to-subsurface contrast in warming/cooling is prominent in the EWS sector, with the warming at the surface shifting to a cooling below 100 m depth. In some other regions, the cooling or warming tendency persists in the same phase from the surface to the deeper layers. In the larger Ross Sea Sector, between 180 and 120°W, the cooling from the SST extends to the deeper layers. This is also the region of increased SIE during the late 1970s (figure 2, supplementary figure 6). In the Amundsen-Bellingshausen Seas, the surface warming extends to the deeper layers.



During the same period, the mixed layer depth (MLD) also underwent several changes. The MLD deepened in the post-loss period relative to the pre-loss period over most of the Southern Ocean, though a shallowing of the MLD can be noticed in the western Weddell Sea, close to the Antarctic Peninsula (figure 4(a)). In the EWS sector, the MLD increase coincides with the loss of SIE (supplementary figure 7).

The increase in MLD co-occurred with a simultaneous rise in surface salinity. The differences in the vertical profiles of temperature and salinity over the EWS sector show an increase in both parameters at

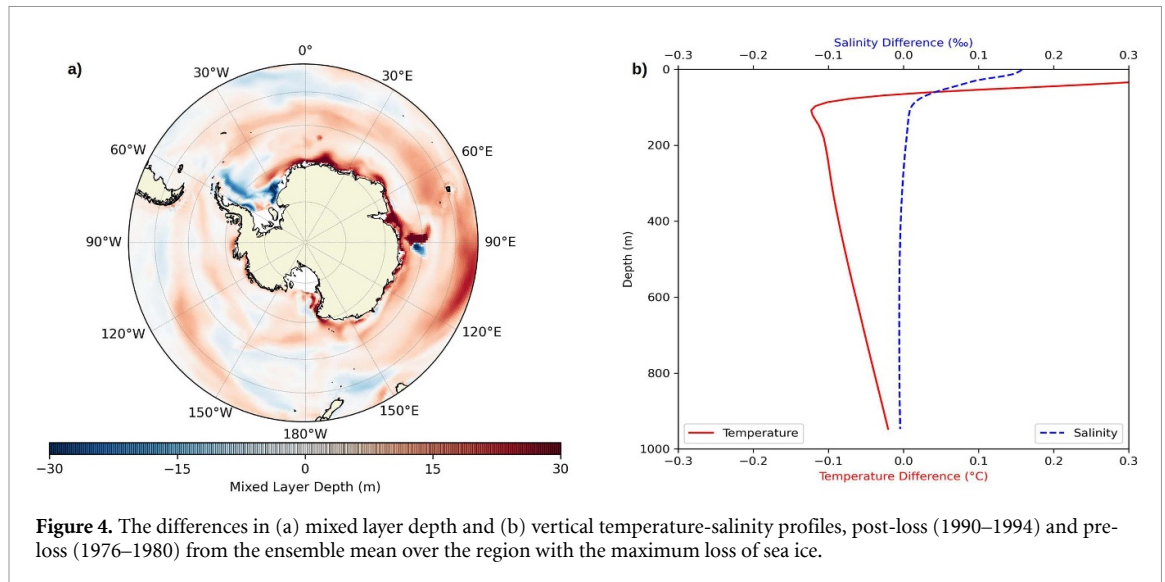


Figure 4. The differences in (a) mixed layer depth and (b) vertical temperature-salinity profiles, post-loss (1990–1994) and pre-loss (1976–1980) from the ensemble mean over the region with the maximum loss of sea ice.

the surface (figure 4(b)). The salinity showed a difference between the two periods that increased gradually upwards from above 100 m with a difference of 0.15 psu at the surface; however, there was no discernible difference in salinity below the 100 m depth. Meanwhile, the temperature difference showed a steep decreasing difference between the two periods with a difference of 0.45 °C at the surface to about 100 m depth where the temperature decreased by 0.13 °C. Below the depth of 100 m, the temperature difference decreases gradually with depth, showing a contrasting surface warming and subsurface cooling.

The increase in salinity in the Southern Ocean could be due to several factors. Freezing and melting of sea ice exert a strong control on oceanic surface salinity. However, during the late 1970s, the SIE decreases should have freshened the surface while our results are in contrast to this showing the salinity increasing simultaneously with decreasing SIE. Furthermore, there is very little difference in horizontal ocean current during the pre-loss or post-loss periods (supplementary figure 8). This rules out the hypothesis of horizontal advective supply of salts from other regions. Conclusively, the other remaining source of salinity is from below the surface. The increase in temperature along with salinity at the surface from the post-loss period compared to the pre-loss period also implies a supply from below as subsurface is warmer and saltier.

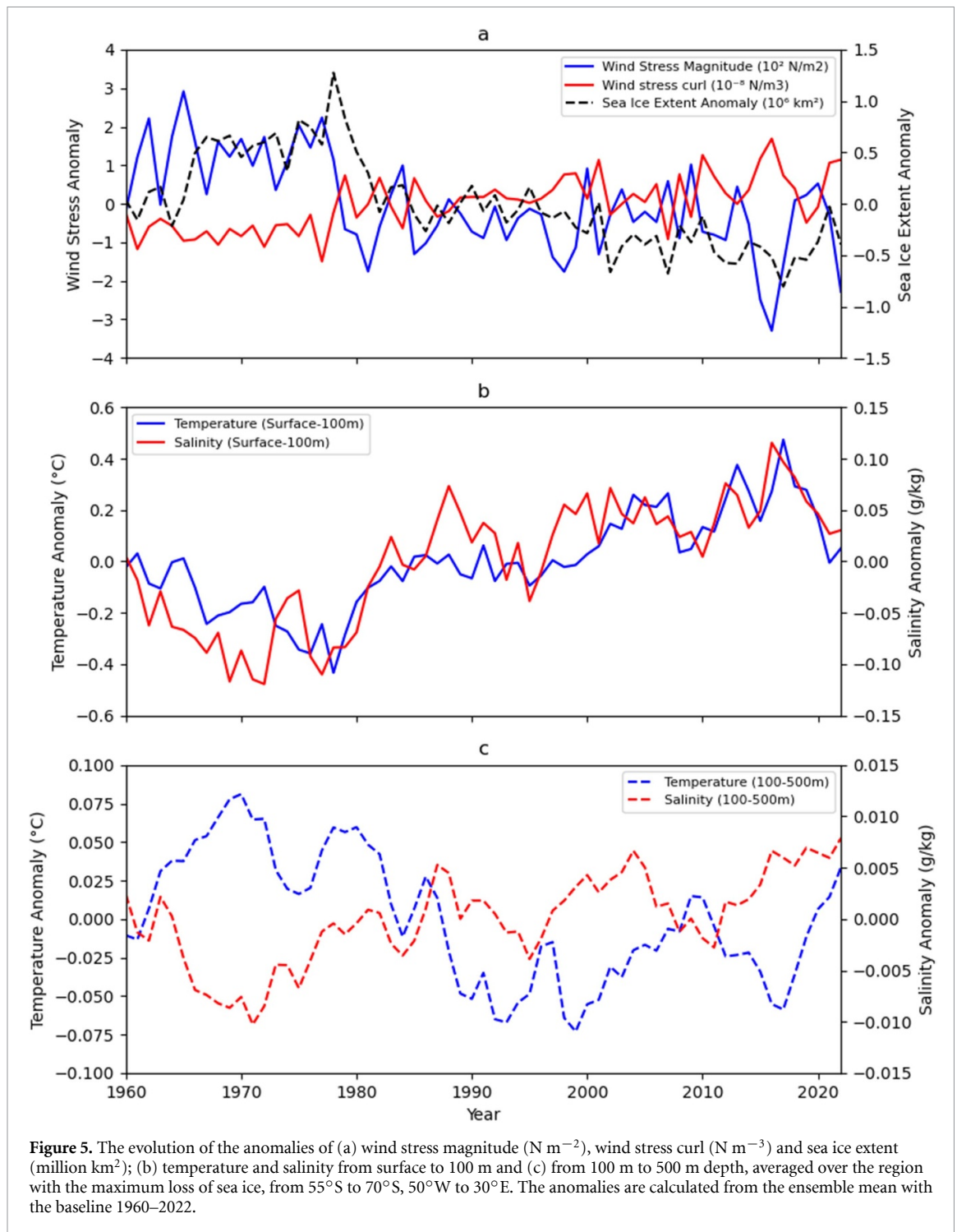
Considering the experimental design, forcing the ocean with the wind stress anomalies, the role of winds is to be expected. The exact mechanisms driving the increased salinity and temperatures at the surface and the sea ice loss are explored in the next section.

3.3. The role of the winds

All the ensemble members are forced with the same wind stress anomalies; therefore, any changes consistently observed across all the members, as seen for the EWS sector, can be attributed to wind-driven processes. The wind stress anomalies can impact the vertical exchanges in the ocean in two main ways.

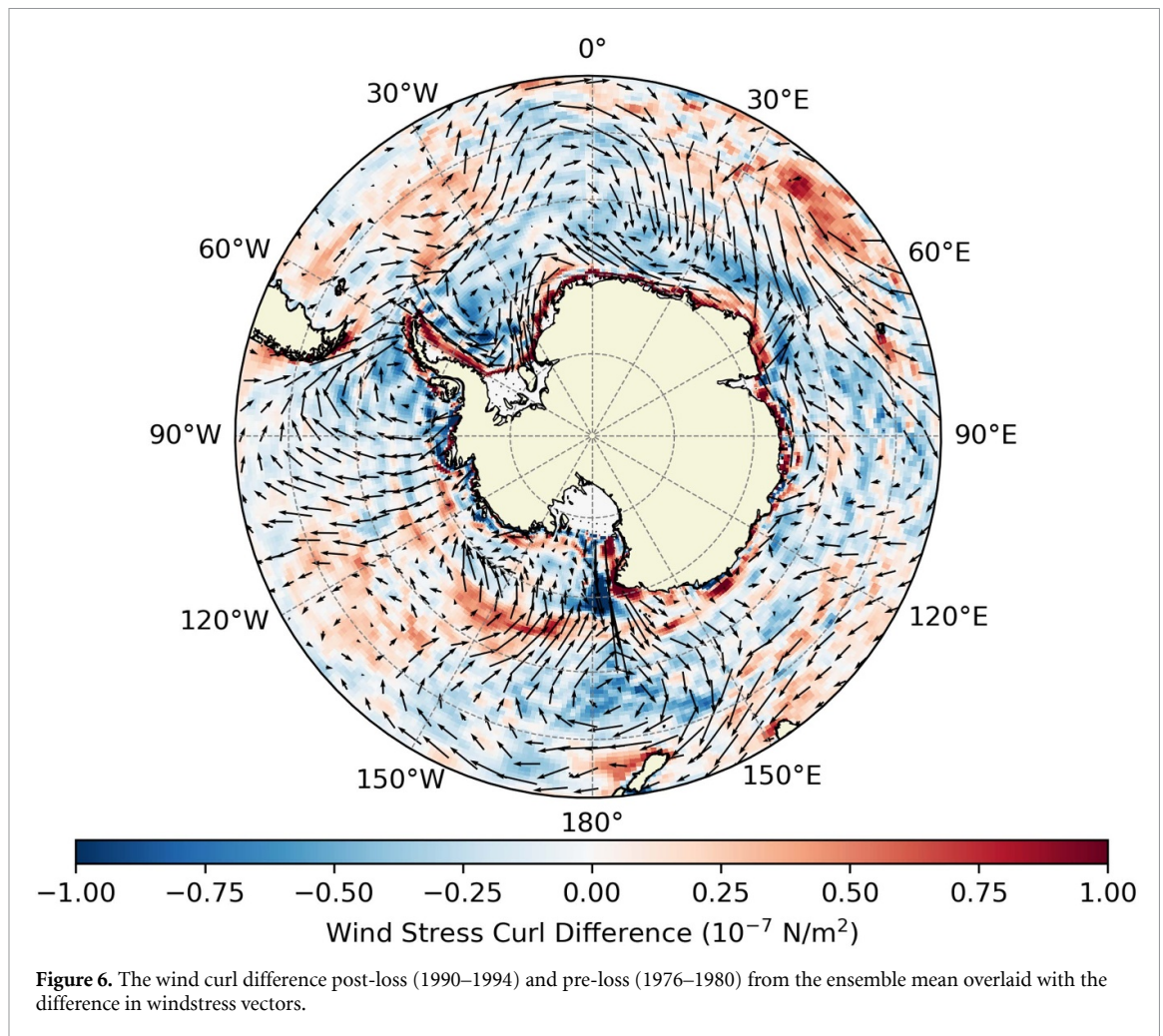
Firstly, the perturbations modify the WSC (a measure of the local rotation of the wind), affecting the vertical velocity in the ocean through Ekman transport and mass conservation. In the Southern Hemisphere, a positive (i.e. counter-clockwise) WSC indicates a convergence and causes an Ekman downwelling. The surface waters at high latitudes are generally colder and fresher than the subsurface waters. As most of the Southern Ocean, particularly the EWS, is a region of Ekman upwelling (annual mean state, supplementary figure 9), the anomalous positive WSC observed from 1960 to the late 1970s indicates a weakened upwelling. The weakened upwelling may have contributed to the lower surface temperature at that time, and then to the increase of SIE for over a decade during the late 1970s (figure 5(a)). In the late 1970s, the WSC over the ESW sector became anomalously negative (figure 6), driving a stronger Ekman upwelling. The upwelled waters bring salts and warmer waters from the subsurface to the surface, contributing to the loss of SIE, the increase in surface temperature, and salinity during the same period.

The second impact of the imposed wind anomalies is through their influence on vertical mixing, along with a larger wind stress magnitude, inducing a deeper mixed layer and the entrainment of warmer and saltier water at depth in the mixed layer. From the 1960s to the end of the 1970s, the



winds were weaker (anomalously negative magnitude) and then shifted to a stronger phase. This drove a stronger vertical mixing, increasing the surface temperature and salinity at the same time as the decrease in SIE.

The combined effects of these two wind-driven mechanisms force a deepening of the mixed layer, a warming and salinification of the surface and a decrease in the SIE in most of the Southern Ocean and specifically the large sea ice loss in the EWS sector. However, the contribution of those two effects cannot be separated in our experiments. Considering the differences in vertical velocity fields across the two periods reaffirms that regions of SIE loss co-occur with zones of upwelling (supplementary figure 10), though it is difficult to quantify precisely the contribution of each of the two effects individually. The upwelling modified the stratification of the water column and is likely responsible for the positive salinity trend starting at the end of the 1970s. The higher magnitude of the wind stress at the end of the



1970s triggered deeper mixing and a net salt input from below in the surface layer, increasing the surface density and favouring a deep mixed layer in the following years. At the same time, this larger mixing induced a large temperature decrease at depth between the late 1970s and the 1980s, providing part of the heat required to reduce the SIE at that time, with the heat input from a larger upwelling partly compensating for this oceanic heat loss.

4. Conclusion

In this study, we examine the impact of wind changes on the loss of SIE in the Southern Ocean at the end of the 1970s. We use the ESM, EC-Earth to conduct a control run and then impose, in a six-member ensemble of sensitivity experiments, wind stress monthly anomalies derived from the ERA5 reanalysis. All 6 ensemble members are initialised at different ocean states and run with constant pre-industrial CO₂, to separate the anthropogenic influences. Our results from all the ensemble members unanimously confirm that the sea ice loss at the end of the 1970s was driven by the wind stress perturbation, although the magnitudes differ across different regions. The strengthened wind stress and larger WSC at that time drive a larger upwelling, stronger vertical mixing, warming the surface and decreasing the SIE.

Many factors can influence the evolution of the SIE, but our results indicate that changes in vertical exchanges in the ocean alone can be responsible for major modifications in the SIE. The changes in atmospheric circulation explain the imposed wind stress perturbation in our experiments, and the atmosphere sets the timing of the events. Nevertheless, the initial energy at the origin of the SIE decrease comes from the ocean, not from the atmosphere. Of course, when the temperature perturbation reaches the surface and the SIE is modified, the positive feedback with the atmosphere can amplify and sustain the response, but this comes only in a second step.

Finally, while our sensitivity experiments suggest a mechanistic causal relationship between the dynamical wind forcing and the sea ice decline, the corresponding mechanism in the real system may involve additional processes. Our experiment design is highly idealised and does not include many elements important for the SIE, such as changes in large-scale atmospheric heat transport, teleconnections from the tropics, and modification of freshwater fluxes towards the Southern Ocean. We thus cannot reproduce the exact details of the interannual variability of the observed SIE extent. The simulated decrease in SIE at the end of the 1970s is also similar to the reconstructions, including its spatial pattern. However, the decrease is larger and less abrupt in our simulations.

The sea ice loss at the end of the 1970s obtained in our simulations can be compared with the SIE shift after 2015 by considering the possible contribution from anthropogenic factors, which we have not discussed here. The wind anomalies have some similarities between the two periods, with larger wind-driven mixing and upwelling around 2015 (figure 5(a)), which has likely contributed to the SIE extent drop at that time (Meehl *et al* 2019, Spira *et al* 2026, Wilson *et al* 2026). Another major common feature is the increase in salinity at the surface since 2015 as shown in recent satellite observations, contradicting the expected freshening due to melting sea ice (Silvano *et al* 2025). Our analysis also shows a salinification at the surface towards the end of the 1970s (figure 5), and similar mechanisms may be at play in both periods.

On the other hand, a noticeable difference between the 1970s sea ice loss and the recent events is in the subsurface temperatures. The ocean temperatures from 100 to 500 metres have warmed in recent years, which has become one of the factors contributing to the sea ice loss along with other atmospheric factors (Zhang *et al* 2022). This is in contrast to our studies, where the subsurface has cooled during the sea ice loss. This difference may also explain why in our simulations, the sea ice loss in 2015 is smaller than the one at the end of the 1970s. Further exploration and understanding of the similarities and differences between the two events would require us to run an additional multi-member ensemble, forced with identical monthly anomalies but with greenhouse gas forcings activated (similar to CMIP historical runs). Unfortunately, this is beyond the scope of the present study.

This study demonstrates that, even in the absence of atmospheric warming or changes in radiative forcing, and thus no imposed change in heat fluxes from the atmosphere, oceanic changes driven by wind stress anomalies can lead to significant changes in sea ice. The ocean is thus not just a passive player in SIE changes but can play an active role. Further investigating the influence of winds in different regions of the Southern Ocean and how the ocean responds to them would be beneficial for a better understanding of past and future changes in SIE.

Acknowledgments

This work was performed in the framework of the PDR project T.0101.22 ‘Role of WINDS and oceanic interactions on Sea ice Changes in the SOuthern Ocean over the Past millennium (WindSCOOP)’ of the FRS-FNRS. FF, as a postdoctoral fellow, was supported by the same project. HG is a Research Director within the F.R.S.-FNRS (Belgium). FM is an F.R.S.-FNRS Research Associate (Belgium). Computational resources have been provided by the supercomputing facilities of the Université catholique de Louvain (CISM/UCLouvain) and the Consortium des Equipements de Calcul Intensif en Fédération Wallonie Bruxelles (CECI) funded by F.R.S.-FNRS, under convention 2.5020.11 and by the Walloon Region.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://zenodo.org/records/17624705> (Feba 2025).

Supplementary Figures available at: <https://doi.org/10.1088/2752-5295/ae7597/data1>.

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