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Analysis of the Unprecedented Reduction in Antarctic Sea Ice During the Years 2022–2023

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ABSTRACT

This study analyses the unprecedented decline in Antarctic sea ice extent during 2022 and 2023. The results reveal that the minimum records in Antarctic sea ice, observed in both summer (February) and winter (September), display inhomogeneous spatial patterns and may be linked to intricate air-sea interactions, including internal climate variability and changes in wind patterns. Events such as the positive southern annular mode, intensification of the Amundsen Sea Low and La Niña played a critical role during September 2022, driving atmospheric and oceanic conditions that enhanced reduction and limited ice formation, particularly in the Weddell and Amundsen Seas. Conversely, in September 2023, characterised by a negative southern annular mode, a weakened Amundsen Sea Low and El Niño conditions, the Ross Sea exhibits pronounced negative sea ice concentration anomalies. The results suggest that internal climate variability can contribute to changes in Antarctic sea ice, primarily through wind pattern variations associated with changes in the Amundsen Sea Low. However, the recent decline of the Antarctic sea ice remains a subject of debate and lacks conclusive answers.

1 | Introduction

In recent years, the Antarctic region has witnessed alarming changes in sea ice extent (SIE), with unprecedented minimum levels recorded in 2022 and 2023 (Turner et al. 2022; Yadav et al. 2022; Roach and Meier 2024; Mezzina et al. 2024). Antarctic sea ice is essential to the Earth's system and has a significant impact on the regulation of global climate. Its high albedo makes the ice cover crucial for maintaining the global energy balance by reflecting a large portion of incoming solar radiation, contributing to the cooling of the planet (Parkinson and Cavalieri 2012). Additionally, sea ice plays a significant role in atmosphere–ocean interactions in polar regions, affecting the exchange of heat, moisture and gases. These interactions are vital for the global thermohaline circulation, as the formation and melting of sea ice contribute to deep water formation, driving oceanic currents that redistribute heat worldwide (Roach et al. 2018). Furthermore, sea ice impacts oceanic and atmospheric circulation patterns, influencing weather systems far beyond the polar regions (Eicken 1992; Eayrs et al. 2019, 2021; Yadav et al. 2022; Casagrande et al. 2023). Changes in Antarctic sea ice can lead to feedback mechanisms that amplify or dampen global warming, making its recent decline a critical concern for future climate stability (Goosse et al. 2018). Moreover, changes in Antarctic sea ice have significant consequences for marine ecosystems, affecting the distribution and abundance of key species, primary productivity and the structure of polar food webs (Smetacek and Nicol 2005; Steiner et al. 2021; Swadling et al. 2023).

The Arctic region has experienced a consistent decline in sea ice since the beginning of satellite records, as reported by Roach and Meier (2024). They highlighted that increases in the length of the open-water season, along with reductions in ice age and thickness, are associated with these declines in SIE. Gorenstein et al. (2022) emphasise that there is a scientific consensus attributing these Arctic changes to anthropogenic forcing. Over the past three decades, this decline has been both rapid and unprecedented, with the annual mean sea ice area decreasing by approximately 2×10^6 km^2 between 1979 and 2020, and with significant impacts on mid-latitude weather and circulation (Meredith et al. 2019; Docquier and Koenigk 2021; Vihma 2014). In contrast, Antarctic sea ice showed a modest increase from 1979 until about 2015, followed by a sharp and persistent decline starting in 2016, culminating in unprecedented minima in 2022 and 2023 (Suryawanshi et al. 2023; Yang et al. 2024; Mezzina et al. 2024). There are some hypotheses that in Antarctica, recent SIE trends can be attributed to internal variability, but there is an ongoing debate about why models fail to accurately capture the spatial patterns of these changes (Blanchard-Wrigglesworth et al. 2021; Gorenstein et al. 2022; Liu et al. 2023).

Several studies have addressed the limitations and challenges of modeling Antarctic sea ice, particularly in representing minimum extremes such as those observed in 2022 and 2023 (Roach et al. 2018; Casagrande et al. 2023; Diamond et al. 2024; Holmes et al. 2024). The biases found in climate models related to observational datasets may be attributed to the complexity of the coupled ocean–atmosphere–cryosphere system in the Southern Ocean. These discrepancies may stem from unrealistic representations of key physical processes and properties, including air-sea temperature gradients, surface air-sea heat fluxes, shortwave radiation, westerly wind patterns, clouds, mesoscale ocean dynamics and the influence of freshwater input from ice sheet melt on sea ice formation (Bintanja et al. 2015; Bracegirdle et al. 2018; Roach et al. 2018; Hyder et al. 2018; Beadling et al. 2019, 2020; Rackow et al. 2022; Holmes et al. 2024; Moura et al. 2024).

Global sea ice is steadily declining due to a combination of internal variability and anthropogenic forcing. While long-term trends were previously driven mainly by reductions in Arctic sea ice, rapid shifts in Antarctic sea ice are now playing a significant role. Record lows in the Antarctic and global sea ice have coincided with record highs in global mean surface air temperature, ocean heat content and sea surface temperature (SST) (Suryawanshi et al. 2023; Roach and Meier 2024; Goosse et al. 2024; Sahoo et al. 2025).

Several drivers contributed to this decrease: the influence of ozone depletion (Turner et al. 2009; Sigmond and Fyfe 2010; Bitz and Polvani 2012), the Pacific Decadal Oscillation (PDO) (Meehl et al. 2016), dynamic processes related to the ocean's mesoscale (Rackow et al. 2022), changes in precipitation, winds and sea surface temperature (SST) (Thompson and Solomon 2002; Liu and Curry 2010; Purich et al. 2016; Blanchard-Wrigglesworth et al. 2021; Hou et al. 2025), as well as the impact of meltwater from the Antarctic ice sheet and ice shelves on the rate of sea ice formation (Bintanja et al. 2013, 2015; Bronselaer et al. 2018; Schloesser et al. 2019).

Liu et al. (2023) also pointed out that several modes of climate variability might have contributed to this new minimum record: the persistent positive southern annular mode (SAM) during 2022, intensifications in the Amundsen Sea Low (ASL), a moderate La Niña event in 2022, the negative phase of the Interdecadal Pacific Oscillation and the positive phase of the Atlantic Multidecadal Oscillation, which strengthened the ASL.

This study aims to analyse the record low sea ice extents observed in February and September of 2022 and 2023, using observational satellite and reanalysis datasets. These 2 years correspond to the lowest Antarctic SIE minima ever recorded, representing unprecedented consecutive extremes that stand out from the historical variability. Investigating these events is therefore particularly important for advancing the scientific community's understanding of the processes driving the recent abrupt decline in Antarctic sea ice and for assessing their potential implications for future trends. This paper is structured as follows: Section 2 offers a detailed overview of the data and methods employed, along with a description of SAM. In Section 3, we present the seasonal cycle, the SIE trends and the findings about the loss of sea ice concentration (SIC). Finally, Section 4 presents concluding remarks and discusses the implications of our work.

2 | Data and Method

2.1 | Data

To carry out this work, satellite Sea Ice Concentration (SIC) data were used, obtained from the Scanning Multichannel Microwave Radiometer (SSMR) on board the Nimbus-7 satellite and the Special Sensor Microwave/Imager (SSM/I) on board the Defense Meteorological Satellite Program's (DMSP), available for the period from October 1978 to present, at the National Snow and Ice Data Center (NSIDC 2023; https://nsidc.org/data/g02135/versions/3 last access: January 2025) (Fetterer et al. 2017).

The SIC satellite data are provided in the polar stereographic projection with a spatial resolution of 25 km × 25 km. The Sea Ice Extent (SIE) was determined by calculating the total area of satellite pixels where the SIC was 15% or higher. These data were used to compute the SIC anomaly, calculated using the reference period from 1980 to 2023, and to analyse the SIE seasonal cycle.

The ERA5 Global Reanalysis (Hersbach et al. 2020) was used in order to evaluate the sea level pressure (SLP) and winds in February and September for both years, 2022 and 2023. It has a grid resolution of 31 km and provides hourly estimates of a large number of atmospheric, land and oceanic climate variables.

2.2 | Southern Annular Mode

The Southern Annular Mode (SAM), also known as the Antarctic Oscillation (AAO), is the primary mode of natural climate variability in the extratropical circulation of the Southern Hemisphere. This oscillation is characterised by zonally

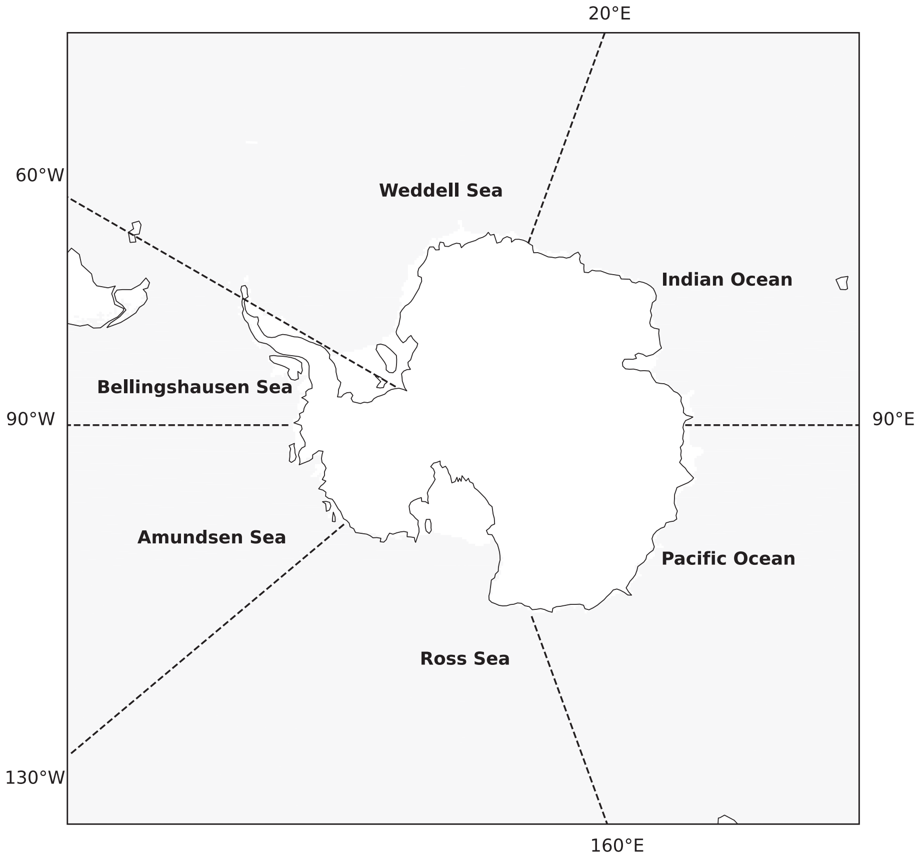

FIGURE 1 | The Antarctica continent and Southern Ocean from 50°S to the South Pole. Dashed lines show the boundaries of the Weddell Sea, Bellingshausen Sea, Amundsen Sea, Ross Sea, Pacific Ocean sector and Indian Ocean sector. Adapted from Ludescher et al. (2019). [Colour figure can be viewed at wileyonlinelibrary.com]

symmetric perturbations in geopotential height, with opposite signs over Antarctica and around 45°S (Marshall 2003; Reboita et al. 2009; Fogt and Marshall 2020).

SAM modulates the position of the westerly winds, shifting them northward during negative phases and southward during positive phases. These phases can be determined using the GW99 SAM Index (Gong and Wang 1999), which is calculated as the difference between normalised monthly mean sea level pressure anomalies at 40°S ($P^*_{40°S}$) and 65°S ($P^*_{65°S}$) latitudinal belts:

$$\mathrm{GW99} = P^*_{40°\mathrm{S}} - P^*_{65°\mathrm{S}} \tag{1}$$

Beyond the westerlies, SAM also influences the position of the polar jet stream and, consequently, the trajectories of cold fronts. Its impacts extend to key climate features such as SIE, ocean currents and the South Atlantic Convergence Zone (SACZ), and it can also interact with other modes of variability, including El Niño and La Niña (Fogt and Marshall 2020).

The combined phases of SAM and ENSO play a crucial role in shaping atmospheric circulation patterns over the Southern Ocean. Studies have shown that when La Niña coincides with a positive SAM, this configuration favors a deepening of the ASL, which is a semi-permanent low-pressure system located in the Pacific sector of the Southern Ocean, while the occurrence of El Niño combined with a negative SAM leads to a weakening of the ASL (Fogt and Marshall 2020; Wang, Luo, et al. 2023).

In addition to their influence on atmospheric circulation, the combined phases of SAM and ENSO contribute to pronounced changes in Antarctic sea ice conditions. Wang, Liu, et al. (2023) demonstrated the impact of these combined modes on sea ice by analysing in-phase and out-of-phase episodes between 1979 and 2020. During this period, the authors identified 54 months characterised by the combination of La Niña and positive SAM, and 45 months with El Niño and negative SAM. The results showed that, during the winter period, the La Niña/SAM+ combination tends to increase SIC in the Ross Sea and reduce it in the Amundsen and Bellingshausen Seas, which is associated with the intensification of the ASL. In contrast, the El Niño/SAM- combination is linked to a reduction in sea ice in the Amundsen Sea and an increase in concentration in the Bellingshausen and Weddell Seas.

2.3 | Study Area

The study focuses on the Antarctic continent and the Southern Ocean, as shown in Figure 1. For clarity, the sectors of the Southern Ocean are defined as follows: Weddell Sea (60°W–20°E), Bellingshausen Sea (60°W–90°W), Amundsen Sea (90°W–130°W), Ross Sea (160°E–130°W), Pacific Ocean sector (90°E–160°E) and Indian Ocean sector (20°E–90°E).

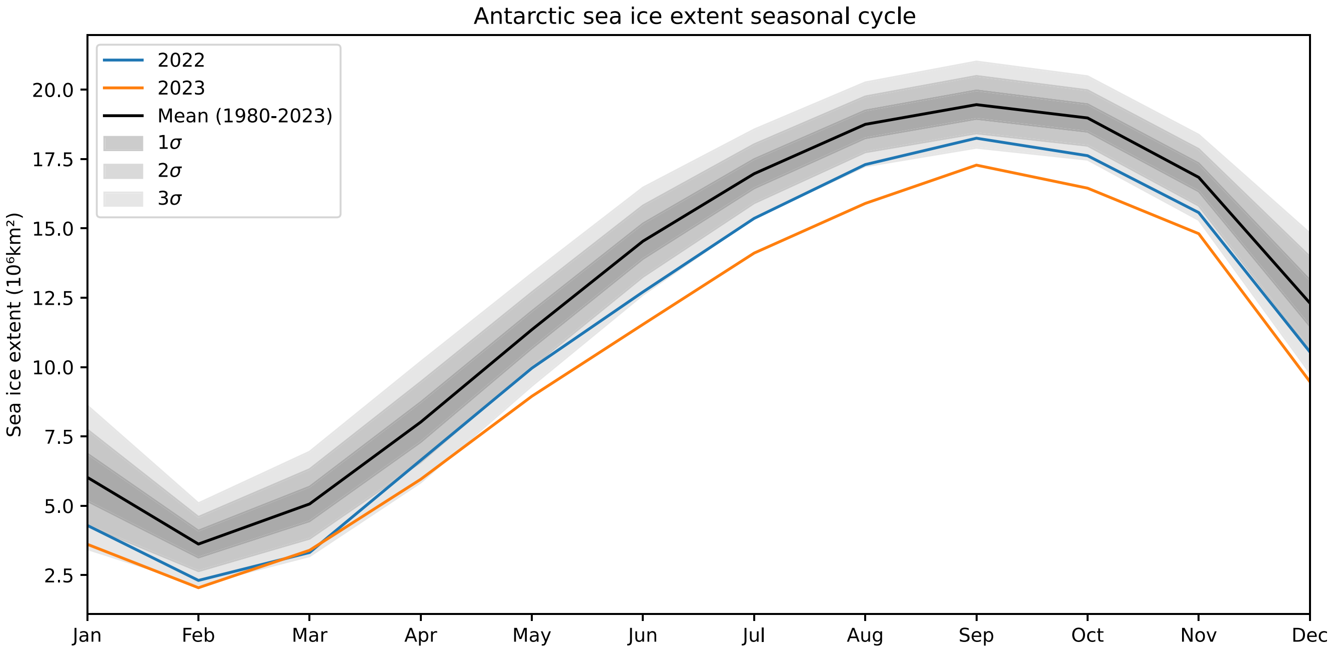

FIGURE 2 | Seasonal cycle of the monthly Antarctic SIE. The dark line shows the mean SIE from 1980 to 2023, while the grey-shaded areas indicate its standard deviations. The blue and orange lines show the SIE for 2022 and 2023, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

Anomalies were calculated using the reference period from 1980 to 2023.

3 | Results and Discussion

3.1 | The Antarctic Sea Ice Seasonal Cycle

The Antarctic seasonal cycle of SIE is a critical component of the polar climate system. Each year, the Antarctic sea ice reaches its maximum extent during the austral winter (in September) and retreats to its minimum extent during the austral summer (in February). This cycle plays a key role in modulating the Earth's energy balance by reflecting sunlight (through the high albedo of ice) and controlling the heat exchange between the ocean and the atmosphere. During the winter months, sea ice formation contributes to the production of dense cold water that drives global ocean circulation, while in the summer months, ice melts, releasing fresh water into the Southern Ocean, influencing stratification and nutrient distribution. The sea ice seasonal expansion and retreat also regulate gas exchanges and impact marine ecosystems by providing habitats for various species, from algae to large mammals (Arrigo and Thomas 2004; Massom and Stammerjohn 2010; Eayrs et al. 2019).

Figure 2 illustrates the seasonal cycle of Antarctic SIE for 2022 and 2023, compared to the long-term mean from 1980 to 2023. The black line represents the mean SIE over this period, while the shaded areas in grey indicate the standard deviation around the mean (1σ, 2σ and 3σ), showing the variability of SIE throughout the year. The 2022 and 2023 data (represented by blue and orange lines, respectively) reveal that both years followed the general seasonal pattern but remained consistently below the SIE mean, particularly in 2023, which shows a more pronounced deviation. For instance, in September, the SIE mean reaches 19.46 million km^2, while in 2022 it is 18.25 million km^2 and in 2023 it is 17.28 million km^2. This highlights the ongoing reduction in Antarctic sea ice in recent years, with 2022 and 2023 displaying particularly low values, marking them as anomalous years.

3.2 | Sea Ice Trends

Since the beginning of satellite data, a trend of increasing SIE has been observable in February and September from 1980 until 2014 (Parkinson and Cavalieri 2012; Parkinson 2019). Figure 3 shows the temporal evolution of Antarctic SIE in February (top panel) and September (bottom panel), highlighting trends between 1980 and 2014 (blue dashed line) and from 2014 to 2023 (orange dashed line).

It is possible to observe in Figure 3 that, for both months, from 1980 to 2014, there was a tendency for SIE to increase by approximately 15.000 km^2 per year (in February) and 25.000 km^2 per year (in September). However, from 2014 to 2023, there was a decline of 142.000 km^2 per year (in February) and 145.000 km^2 per year (in September). A Mann–Kendall trend test indicates that only the September trend from 1980 to 2014 is statistically significant ($p = 0.001$), while the other trends do not meet significance at the 5% level: February 1980–2014 ($p = 0.069$), February 2014–2023 ($p = 0.152$) and September 2014–2023 ($p = 0.283$). These results imply that although the recent downward trends appear marked, they are statistically uncertain due to the short duration of the record and considerable interannual variability.

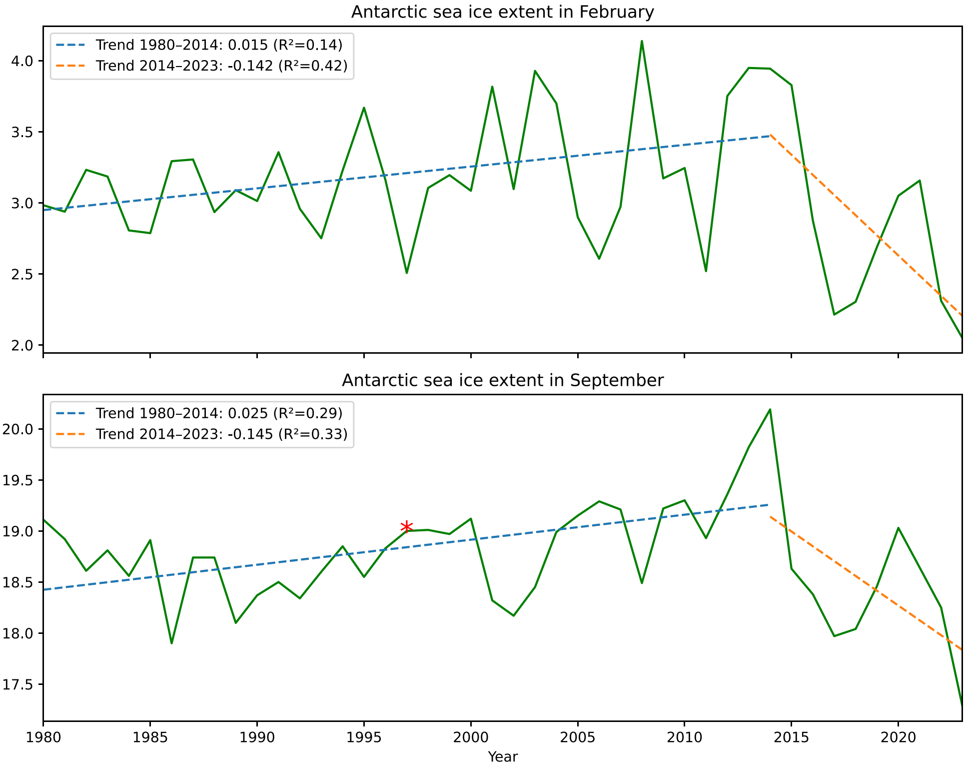

FIGURE 3 | Time series of Antarctic annual mean SIE for February (top panel) and September (bottom panel). The blue dashed line represents the linear trend from 1980 to 2014, and the orange dashed line represents the linear trend from 2014 to 2023. The slope of each trend (in 10^6 km^2 per year) and the corresponding R^2 are indicated in the legend. Statistically significant trend ($p < 0.05$, Mann–Kendall test) is marked with a red asterisk. [Colour figure can be viewed at wileyonlinelibrary.com]

Liu et al. (2023) provide trend values for SIE minimums (February) from 1979 to 2014, which align with the values shown in Figure 3. Additionally, they include trend values up to 2017, 2022 and 2023. According to them, the linear trend between 1979 and 2014 was an increase of 13.800 km^2 per year. From that year onwards, the rate began to decline. In 2017, the first record of minimum SIE values occurred, changing the trend to 9.500 km^2 per year for the period from 1979 to 2017. The trend during the second minimum (2022) was 200 km^2 per year (1979–2022). Until that year, the trend remained positive. However, in 2023, with a new record low, the trend turned negative, reaching −2.800 km^2 per year (1979–2023). In the years 2022 and 2023, record minimum values of sea ice were recorded, both in the minimum (February) and maximum (September) periods. According to the National Snow and Ice Data Center (NSIDC), during 2022, the minimum SIE observed was 1.976 million km^2 on February 25th. This value was even smaller in the next year (2023): 1.788 million km^2 on February 21th. This is the SIE record minimum register to date. During the maximum period of SIE, the NSIDC recorded in 2022 was 18.245 million km^2 on September 16th, but on September 10th, 2023, a new record was observed: 16.956 million km^2.

A decreasing SIE trend begins after 2014, despite earlier record-high SIE values. These patterns indicate a shift in the behaviour of Antarctic SIE, with an increase until 2014 followed by a reversal thereafter, reflecting the recent and abrupt decreases in sea ice observed in recent years. This suggests a significant change in climatic and oceanic conditions in Antarctica, the causes and impacts of which remain under investigation. The lowest recorded SIE values have been observed since 2016, coinciding with the warmest years on record since 1979 (Suryawanshi et al. 2023). The year 2014 marks a turning point in air and SST trends, as well as SIE. During that year, temperatures shifted from a negative to a positive trend, while SIE exhibited the opposite behaviour. According to Suryawanshi et al. (2023), from 2015 to 2022, the annual mean of the SAM index was positive, coinciding with an extended La Niña period.

The loss in SIE during 2016/2017 has been attributed to several factors, including an unusually strong atmospheric zonal wave 3 (ZW3), associated with stronger-than-usual meridional winds; a negative SAM in the spring of 2016; a deep ASL; and teleconnections to the tropical Pacific (Schloesser et al. 2018; Meehl et al. 2019; Wang et al. 2019; Hobbs et al. 2024).

3.3 | Sea Ice Anomaly

As discussed, 2022 and 2023 are critical years for recording minimal sea ice values. This anomalous behaviour is examined in detail using data on sea ice concentration and extent. The SIC anomaly was calculated using the reference period between 1980 and 2023. Figure 4 shows the SIC anomaly for both years, 2022 (on the top) and 2023 (on the bottom), for February (a and c) and September (b and d). In February, when the SIC reached

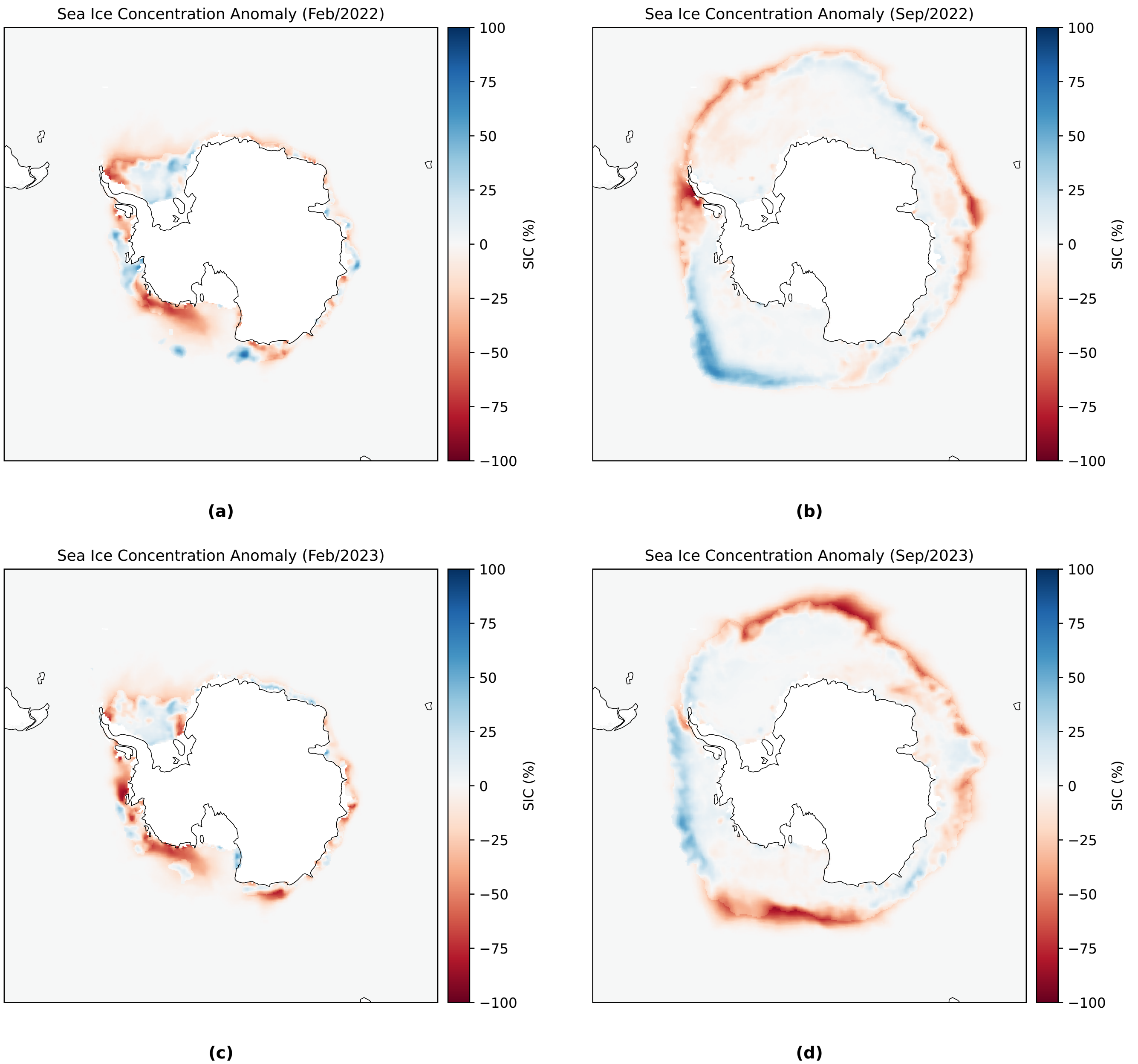

FIGURE 4 | Sea ice concentration anomaly (%) for February 2022 (a), September 2022 (b), February 2023 (c) and September 2023 (d). The reference period is 1980–2023. [Colour figure can be viewed at wileyonlinelibrary.com]

its minimum value, negative SIC anomalies were observed in all sectors of the Southern Ocean. Figure 4a,c shows a reduction in SIC in several regions around Antarctica. Significant reductions are observed in the Weddell Sea, Amundsen Sea and Ross Sea for the year 2022, while in 2023, there was also a significant decrease in the Bellingshausen Sea. Although some specific increases in sea ice were observed in certain sectors, February showed an average decrease in sea ice across all sectors in both years.

In both cases, the SAM was in a positive phase (Ciências Atmosféricas Unifei—available at https://meteorologia.unifei.edu.br/teleconexoes/indice?id=aao, last access: 27 January 2025), while the ENSO remained in a neutral state—conditions that did not occur in September. Wang, Liu, et al. (2023) show that the decrease in February 2022 is related to the ASL, which contributed 60% to this reduction. The authors also highlighted that La Niña conditions and a strong stratospheric polar vortex in 2021 contributed to the deepest ASL. Yadav et al. (2022) also point out that a positive SAM helps intensify the ASL. These mechanisms also contributed to the decrease observed in February 2023. Yang et al. (2024) add that strong winds caused by the more intense ASL in spring contributed to severe sea ice melt in December, while also triggering the ice-albedo feedback on land through coastal divergence. This ice-albedo feedback was unusually active at the end of 2022 and favoured accelerated melt towards the minimum.

TABLE 1 | Sea ice extent observed (10^6 km^2) for February and September of 2022 and 2023, along with climatological values and anomalies for each month in the following sectors: Weddell Sea (WS), Bellingshausen Sea (BS), Amundsen Sea (AS), Ross Sea (RS), Pacific Ocean sector (PO) and Indian Ocean (IO).

	SIE observed				Climatology		Anomaly			
	Feb/22	Set/22	Feb/23	Set/23	Feb	Set	Feb/22	Set/22	Feb/23	Set/23
WS	1.12	6.20	1.15	5.97	1.54	6.78	−0.42	−0.58	−0.39	−0.81
BS	0.10	0.59	0.01	0.97	0.21	0.93	−0.12	−0.34	−0.21	0.04
AS	0.31	1.44	0.29	1.64	0.43	1.46	−0.12	−0.02	−0.14	0.19
RS	0.32	4.65	0.26	3.54	0.79	4.35	−0.47	0.31	−0.53	−0.81
PO	0.33	1.95	0.19	1.91	0.42	2.15	−0.09	−0.21	−0.24	−0.25
IO	0.13	3.43	0.15	3.26	0.23	3.80	−0.10	−0.37	−0.08	−0.54

The albedo-sea ice feedback is a crucial mechanism influencing the sea ice dynamics. Sea ice (with its high albedo) reflects solar radiation, preventing the ocean from absorbing radiation and isolating it from the atmospheric conditions. As sea ice melts, it exposes darker (and low-albedo) ocean water that absorbs more solar radiation, increasing the air-sea temperatures and further accelerating the initial sea ice melting. Consequently, the projected warming in the Southern Ocean is expected to intensify the sea ice albedo feedback, contributing to more rapid sea ice melting and potentially leading to a transition towards sea ice-free conditions during the austral summer, as pointed out by Casagrande et al. (2019) and Casagrande et al. (2021).

During the period of maximum SIC (September), the most significant variations concerning the climatological average were observed in regions close to the polar front. For the year 2022 (Figure 4b), predominant positive anomalies were recorded in the Ross Sea, in contrast with the negative anomalies in the other sectors. In 2023 (Figure 4d), there is a change in the anomaly patterns compared to the year 2022, with negative SIC anomalies in the Ross and Weddell Seas (except near the peninsula) and positive ones in the Bellingshausen and Amundsen seas. In these cases, 2022 had a positive SAM and a La Niña period, whereas in 2023 the opposite was observed, with a negative SAM and an El Niño period. Wang, Liu, et al. (2023) refer to these combinations as in-phase events. The authors pointed out that SIC anomalies are mainly affected by atmospheric anomalies driven by SAM and oceanic anomalies driven by ENSO. SIC anomalies also present a dipole between the Weddell/Bellingshausen seas and the Amundsen/Ross Seas. This means that, for La Niña and positive SAM (El Niño and negative SAM), negative (positive) anomalies are seen in the Weddell and Bellingshausen Seas, and positive (negative) anomalies are seen in the Amundsen and Ross seas. This pattern is seen in September 2022.

Table 1 summarises the SIE observed in February and September of 2022 and 2023, compared to climatological values and their respective anomalies for each sector of Antarctica. The sectors include the Weddell Sea (WS), Bellingshausen Sea (BS), Amundsen Sea (AS), Ross Sea (RS), Pacific Ocean sector (PO) and Indian Ocean (IO). The observed SIE values show significant variations compared to the climatological averages, as evidenced by the negative anomalies in almost all sectors. In February 2022 and 2023, negative anomalies were observed in all regions. The most pronounced anomalies were recorded in the Ross Sea, with −0.47 and −0.53 million km^2, respectively, indicating a substantial reduction in SIE in this sector. In September, it was observed that some regions experienced an increase in SIE, such as the Ross Sea, which experienced an increase of 0.31 million km^2 in 2022, and the Bellingshausen and Amundsen Seas, which recorded increases of 0.03 and 0.19 million km^2, respectively, in 2023.

Figure 5 shows the mean SLP and the 10 m wind mean for September 2022 (a) and 2023 (b). The positive SAM contributes to the intensification of winds near the Antarctic continent, causing the ASL to become more intense, as observed in Figure 5a. On the one hand, this wind pattern contributes to positive SIC anomaly values on one side of the ASL and negative values on the other. Winds blowing from the ocean towards the continent typically carry warmer air, leading to negative anomaly values in the Weddell and Bellingshausen Seas. On the other hand, winds blowing from the continent towards the ocean carry colder air, enhancing ice formation in these regions, as observed in the Amundsen and Ross seas. The pattern observed in the SIC anomaly, mean SLP and 10 m wind for September 2022 (Figures 4b and 5a) closely aligns with what Wang, Liu, et al. (2023) described for in-phase La Niña and positive SAM conditions.

Additionally, the analysis of mean SLP anomaly (Figure 6a,b), air temperature anomaly at 850 hPa (Figure 6c,d) and SST anomaly (Figure 6e,f) for September 2022 and 2023 reinforces this interpretation. In 2022, a negative pressure anomaly over the Amundsen and Bellingshausen seas (Figure 6a) corresponds to the intensification of the ASL. During the same period, the temperature anomaly pattern at 850 hPa (Figure 6c) shows colder-than-average conditions over the Amundsen and Ross Seas, reflected in negative SST anomalies in the same region (Figure 6e), corroborating the pattern observed by Wang, Liu, et al. (2023). In contrast, warmer-than-average air persisted over the Antarctic Peninsula and Bellingshausen Sea.

In 2023, the mean SLP anomaly (Figure 6b) shows a distinct dipole pattern, with positive anomalies over the Bellingshausen and Amundsen Seas and negative anomalies over the Ross Sea. This configuration reflects a displacement and weakening of the ASL, which may have altered regional wind patterns and

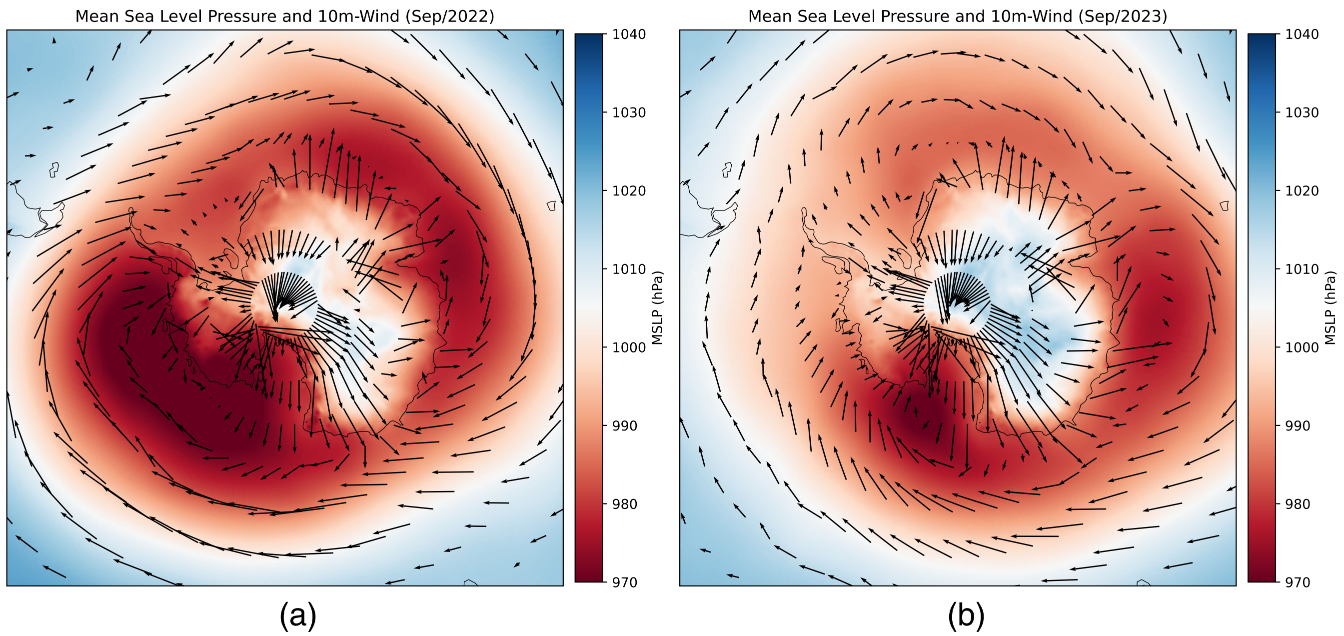

FIGURE 5 | Mean sea level pressure and 10 m wind for September 2022 (a) and 2023 (b). [Colour figure can be viewed at wileyonlinelibrary.com]

sea ice distribution. The air temperature anomaly at 850 hPa (Figure 6d) reveals colder-than-average conditions over the Weddell Sea. The SST anomaly (Figure 6f) shows positive anomalies in the Bellingshausen and Amundsen seas, and negative anomalies in the Ross Sea, following the same pattern observed in SIC (Figure 5b), likely associated with changes in atmospheric circulation and ice advection. These results demonstrate that the observed atmospheric and oceanic conditions, including SLP, air temperature and SST anomalies, are consistent with the spatial patterns of sea ice increase or reduction in different regions.

4 | Conclusion

We have investigated the significant reduction of Antarctic sea ice that occurred in 2022 and 2023. Our focus included specific areas as Weddell Sea, Bellingshausen Sea, Amundsen Sea, Ross Sea, as well as the Pacific and Indian sectors of the Southern Ocean. This study reveals that the seasonal cycles of the SIE in 2022 and 2023 show extreme differences compared to the mean seasonal cycle from 1980 to 2023, particularly with lower values in September and February. When we examine the interannual variability of the Sea Ice Extent (SIE) for these months from 1980 to 2023, both years recorded the lowest minimum levels, highlighting a continued and accelerating decline in Antarctic sea ice. Although Antarctic SIE was also notably low in 2024, it did not surpass the record minima observed in 2023. According to the NSIDC, the SIE reached 2.029 million km^2 on February 20th and 17.256 million km^2 on September 16th 2024. These trends represent a significant shift from the increasing SIE noted until 2014, followed by a sharp decline after that year. We observed that in February (September), between 1980 and 2014, the trend was positive, at 15.000 km^2 per year (25.000 km^2 per year). From 2014 to 2023, the trend shifted to negative, at 142.000 km^2 per year (145.000 km^2 per year).

To support the robustness of these observations, we applied a Mann–Kendall trend test to the SIE time series. The analysis confirmed that the increasing trend observed in September from 1980 to 2014 is statistically significant ($p = 0.001$), whereas the trends in other periods are not statistically significant. This discrepancy may be attributed to the short evaluation period and the strong interannual variability. These findings emphasise the need for ongoing monitoring.

The study confirms that the recent decreases in Antarctic sea ice are the result of complex interactions between atmospheric and oceanic processes. In February (2022 and 2023), a reduction in sea ice was observed across all sectors. The positive phase of the SAM and La Niña conditions, particularly in September 2022, intensified winds and led to significant reductions in SIC and SIE in regions like the Amundsen, Bellingshausen and Weddell Seas, and an increase in the Ross Sea. In contrast, in September 2023, the combination of a negative SAM and El Niño reversed some regional patterns of anomalies, showing an increase in the concentration and extent of sea ice in the Amundsen and Bellingshausen Seas. Conversely, a decrease was noted in the Ross Sea and parts of the Weddell Sea. However, the mechanisms driving regional changes in Antarctic sea ice and their teleconnections to climate modes (e.g., SAM and ENSO) still lack conclusive explanations and remain a topic of ongoing debate within the scientific community.

These changes have serious implications for global climate regulation, ocean circulation and marine ecosystems, as Antarctic sea ice serves as a critical indicator of our rapidly changing climate system. Future research should explore the causes of these anomalies further and evaluate the long-term consequences of the observed trends for both the Antarctic environment and the global climate.

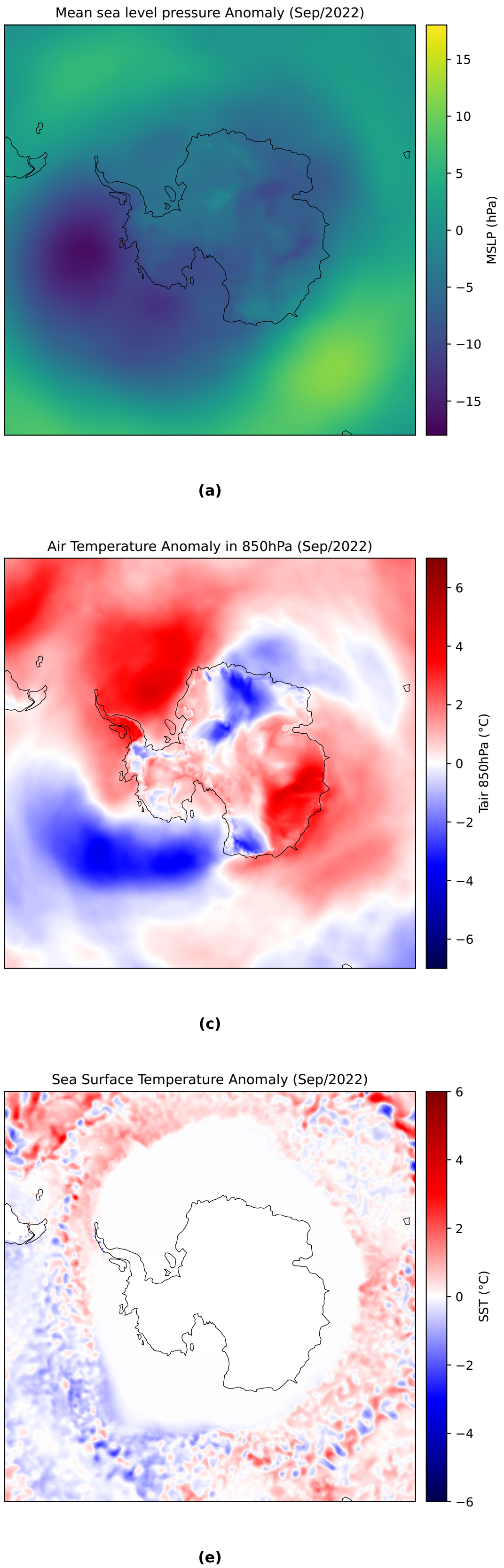

FIGURE 6 | Mean sea level pressure anomalies for September 2022 (a) and 2023 (b), air temperature in 850 hPa anomalies for September 2022 (c) and 2023 (d), and sea surface temperature anomalies for September 2022 (e) and 2023 (f). [Colour figure can be viewed at wileyonlinelibrary.com]

Author Contributions

Helena Barbieri de Azevedo: investigation, writing – original draft, methodology, visualization, writing – review and editing, formal analysis, data curation, conceptualization. **Fernanda Casagrande:** conceptualization, investigation, methodology, writing – review and editing, formal analysis, data curation. **Sofia Allende:** writing – review and editing, formal analysis, investigation, data curation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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