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REVIEW

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Antarctic sea ice variability and monsoonal precipitation: a review of reported teleconnections, associations and uncertainties

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Abstract

Antarctic sea ice variability is increasingly recognized as a potentially important component of the coupled Southern Hemisphere climate system. Growing observational, reanalysis, and modeling evidence suggests that Antarctic sea ice anomalies are associated with large-scale atmospheric circulation changes that may contribute to climate variability in tropical and subtropical regions. However, the relative contribution of Antarctic sea ice variability compared with established climate drivers such as the El Niño–Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) remains incompletely understood. At the sectoral scale, asymmetric sea ice variability associated with wind-driven Ekman transport, air–sea heat flux anomalies, and ocean–ice interactions has been linked to dipole-like patterns of atmospheric and oceanic variability that may alter jet streams, storm tracks, and large-scale circulation. Proposed teleconnection pathways involving Rossby wave propagation and circulation adjustments suggest that sea ice variability in the Indian Ocean, Pacific, and Atlantic sectors may be associated with changes in cross-equatorial moisture transport, subtropical jet position, and regional pressure systems, with potential implications for precipitation variability across South Asia, East Asia, and Africa. Collectively, the available evidence indicates that Antarctic sea ice variability may represent one component of a broader interconnected climate system influencing hydroclimatic variability across multiple regions, while also highlighting substantial uncertainties regarding the magnitude, mechanisms, and regional expression of these relationships. Improved understanding of Southern Ocean–ice–atmosphere interactions and their representation in climate models will be important for evaluating the potential role of Antarctic sea ice variability in seasonal-to-decadal climate variability and hydroclimatic predictability.

Keywords Antarctica, Sea ice, Teleconnection, Southern annular mode, El Niño–Southern Oscillation, Monsoon variability

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1 Introduction

The Earth's climate system functions as a dynamic and interconnected network in which interactions among different latitudinal zones play a fundamental role in shaping weather and climate variability across the globe. Understanding how variability originating in one region propagates through the climate system and manifests elsewhere remains a central challenge in climate research. Atmospheric circulation, ocean currents, heat redistribution, temperature gradients, precipitation variability, and extreme weather events are governed by exchanges of energy and momentum between the tropics, mid-latitudes, and polar regions (Chiang and Friedman 2012). Substantial environmental changes have been documented in both polar regions, including changes in sea ice concentration and extent, increasing oceanic and atmospheric temperatures, and modifications to large-scale circulation patterns (Hastenrath 1985; Trewin 2014). These high-latitude changes have been associated with climate variability beyond the polar regions and have encouraged increasing investigation of potential polar–lower-latitude climate linkages (Beadling et al. 2024; Bilgili et al. 2024).

Much of the current understanding of polar–mid-latitude and polar–tropical climate linkages originate from studies of the Arctic, where persistent sea ice decline since 1979 has been extensively documented (Budikova 2009; NSIDC 2024b). Arctic sea ice variability has been associated with changes in atmospheric circulation, including modifications of storm tracks, Rossby wave activity, and jet-stream characteristics, often discussed in the context of Arctic amplification (Francis and Vavrus 2015; Cohen et al. 2020; Smith et al. 2022; Ye et al. 2024). A reduction in the meridional temperature gradient between the Arctic and mid-latitudes has been proposed as a mechanism capable of modifying jet-stream strength and waviness, potentially contributing to more persistent mid-latitude weather patterns (Francis and Skific 2015; Coumou et al. 2018; England et al. 2020; Dai and Deng 2021; Cohen et al. 2023; Geen et al. 2023). However, the extent and robustness of these linkages remain debated because of the important roles played by internal atmospheric variability and tropical forcing (Blackport and Screen 2020; Sun et al. 2022). Arctic sea ice anomalies have also been linked to tropical climate variability through coupled atmosphere–ocean and stratosphere–troposphere processes, including potential modulation of El Niño–Southern Oscillation (ENSO) through atmospheric wave trains and ocean–atmosphere feedbacks (Sun et al. 2015; Tomas et al. 2016; Smith et al. 2017; Yuan et al. 2018; Kim et al. 2020; Chen et al. 2020, 2024a, 2025; Chen et al. 2024b). Collectively, these studies demonstrate that sea ice variability can form part of broader climate teleconnection pathways and provide a useful conceptual framework for examining analogous processes in the Antarctic.

In contrast, the potential role of Antarctic sea ice variability in climate variability beyond the high southern latitudes has received comparatively less attention despite the distinctive characteristics of Southern Hemisphere climate dynamics. Teleconnection pathways in the Southern Hemisphere differ from those in the Northern Hemisphere because of the predominance of oceanic surfaces and comparatively weaker meridional temperature gradients (Feulner et al. 2013; Cabré et al. 2017). Variability in Southern Ocean convection can modify sea surface temperatures, pressure gradients, and atmospheric circulation patterns, thereby affecting meridional heat transport and large-scale climate variability (Cabré et al. 2017), although the atmospheric response to deep convection remains unclear and highly uncertain because the composite anomalies reported were not subjected to statistical significance testing. Within this framework, Antarctic sea ice variability has been proposed as one component of a coupled atmosphere–ocean–cryosphere system that may contribute to climate variability in mid- and low-latitude regions.

Recent studies have highlighted statistically significant associations between Antarctic sea ice variability and atmospheric circulation variability across the Southern Hemisphere. However, establishing the direction and magnitude of causality remains challenging because Antarctic sea ice and atmospheric circulation are strongly coupled through large-scale climate modes such as the Southern Annular Mode (SAM) and ENSO (Thompson and Wallace 2000; Pezza et al. 2012; Fogt and Marshall 2020). Variations in SAM are known to influence storm tracks, westerly wind patterns, and precipitation regimes across the Southern Hemisphere and may provide an important pathway through which Antarctic sea ice variability and lower-latitude climate variability become linked (Thompson and Wallace 2000; Gillett et al. 2006; Fogt and Marshall 2020). ENSO further modulates these relationships and contributes to the complexity of Antarctic sea ice–climate interactions (Yuan and Martinson 2000; Schneider et al. 2012; Chandra et al. 2022). Antarctic sea ice is also closely connected to Southern Ocean processes, including Antarctic Bottom Water formation and large-scale ocean circulation, which influence oceanic heat storage and redistribution (Golledge et al. 2019; Lago and England 2019; Zhang et al. 2024). In addition, Antarctic sea ice variability has been associated with fluctuations in the Antarctic Circumpolar Wave, Rossby wave propagation, and major modes of climate variability such as the Indian Ocean Dipole (IOD) and Pacific Decadal Oscillation (Khare 2022; Raghuvanshi and Agarwal

2024). Taken together, these studies suggest that Antarctic sea ice variability should be viewed within the broader context of coupled Southern Hemisphere climate variability rather than as an isolated forcing mechanism.

The significance of Antarctic sea ice variability has become increasingly apparent in light of recent rapid and spatially heterogeneous changes. Between 1979 and 2014, Antarctic sea ice exhibited a modest increasing trend, culminating in a record-high annual mean extent in 2014 (Turner et al. 2015; Eayrs et al. 2021). This pattern changed markedly after 2016, with several subsequent years, including 2017, 2023, and 2024, recording historically low or near-record-low sea ice extents (Purich and Doddridge 2023; Gilbert and Holmes 2024; Josey et al. 2024; Raphael et al. 2025). The 2024 Antarctic sea ice extent was the second lowest on record, approximately 30% below the 1981–2010 climatological mean (NSIDC 2024a). Furthermore, Antarctic sea ice variability exhibits pronounced regional and seasonal contrasts among different sectors of the Southern Ocean, reflecting the combined influences of atmospheric, oceanic, and cryospheric processes operating across multiple spatial and temporal scales (Eayrs et al. 2019; Bocquet et al. 2024). Given the pronounced regional heterogeneity of Antarctic sea ice, its variability is commonly divided into five broad sectors: the Ross Sea (160–130°W), Bellingshausen–Amundsen Seas (130–60°W), Weddell Sea (60°W–20°E), Indian Ocean (20–90°E), and West Pacific (90–160°E). These sectors differ in their atmospheric and oceanic environments and consequently exhibit distinct patterns of sea ice variability. This sectoral framework is adopted throughout this review to describe the spatially heterogeneous relationships between Antarctic sea ice variability and monsoonal precipitation.

Although a growing body of literature has documented relationships between Antarctic sea ice variability and atmospheric circulation anomalies extending into mid- and low-latitude regions, current understanding remains fragmented across observational analyses, modeling studies, and region-specific investigations. In particular, the mechanisms through which Antarctic sea ice variability may be linked to precipitation variability in tropical and extratropical regions, particularly monsoonal precipitation, have not been comprehensively synthesized. This review addresses that gap by examining current understanding of Antarctic sea ice variability, the large-scale atmospheric and oceanic pathways associated with Antarctic climate variability, and the reported precipitation responses across different regions. By integrating evidence across spatial scales, seasons, and timescales, this review aims to provide a balanced synthesis of proposed Antarctic sea ice–climate linkages, identify areas of consensus and uncertainty within the existing literature, and highlight priorities for future research. Given the recent rapid decline and pronounced regional variability of Antarctic sea ice, such a synthesis is timely and may contribute to improved understanding of Southern Hemisphere climate variability and its broader climatic implications.

2 Influences of antarctic sea ice on monsoon-dominated regions

Growing evidence suggests that Antarctic sea ice variability is associated with precipitation variability across several monsoon-dominated regions, including South Asia, East Asia, and parts of Africa. Numerous observational, reanalysis, and modeling studies have reported statistically significant relationships between Antarctic sea ice anomalies and regional monsoon rainfall, although the physical interpretation and relative importance of these relationships remain areas of active research (Xue et al. 2003; Blamey and Reason 2007; Prabhu et al. 2009, 2021, 2022; Azhar et al. 2020, 2023; Zhou et al. 2021; Makula and Zhou 2023; Wu et al. 2023; Xiao et al. 2024). Proposed teleconnection pathways involve large-scale atmospheric circulation adjustments, including meridional wave trains, jet-stream variability, and changes in cross-equatorial moisture transport.

Figure 1 presents a conceptual synthesis of mechanisms proposed in the literature to explain observed associations between Antarctic sea ice variability and precipitation variability across South Asia, East Asia, and Africa. The schematic illustrates how sector-specific Antarctic sea ice anomalies may be associated with changes in Southern Hemisphere atmospheric circulation, Rossby wave activity, subtropical jet variability, and large-scale moisture-transport pathways. These circulation anomalies can extend beyond the Southern Hemisphere through interactions with large-scale overturning circulations and cross-equatorial atmospheric exchanges. Because many of these processes are closely linked with SAM, ENSO, and other modes of climate variability, the pathways shown in the figure should be interpreted as conceptual representations of proposed climate linkages rather than definitive causal relationships.

2.1 Antarctic sea ice and precipitation in the Indian subcontinent

Several observational and modeling studies have reported significant associations between Antarctic sea ice variability and Indian Summer Monsoon (ISM) precipitation, with both the strength and sign of the relationship varying among Antarctic sectors (Dugam and Kakade 2004; Prabhu et al. 2009, 2021, 2022; Azhar et al. 2020, 2023; Bajish et al. 2021; Tewari et al. 2023). Positive relationships have generally been reported for the Indian Ocean and western Pacific sectors, whereas sea ice variability

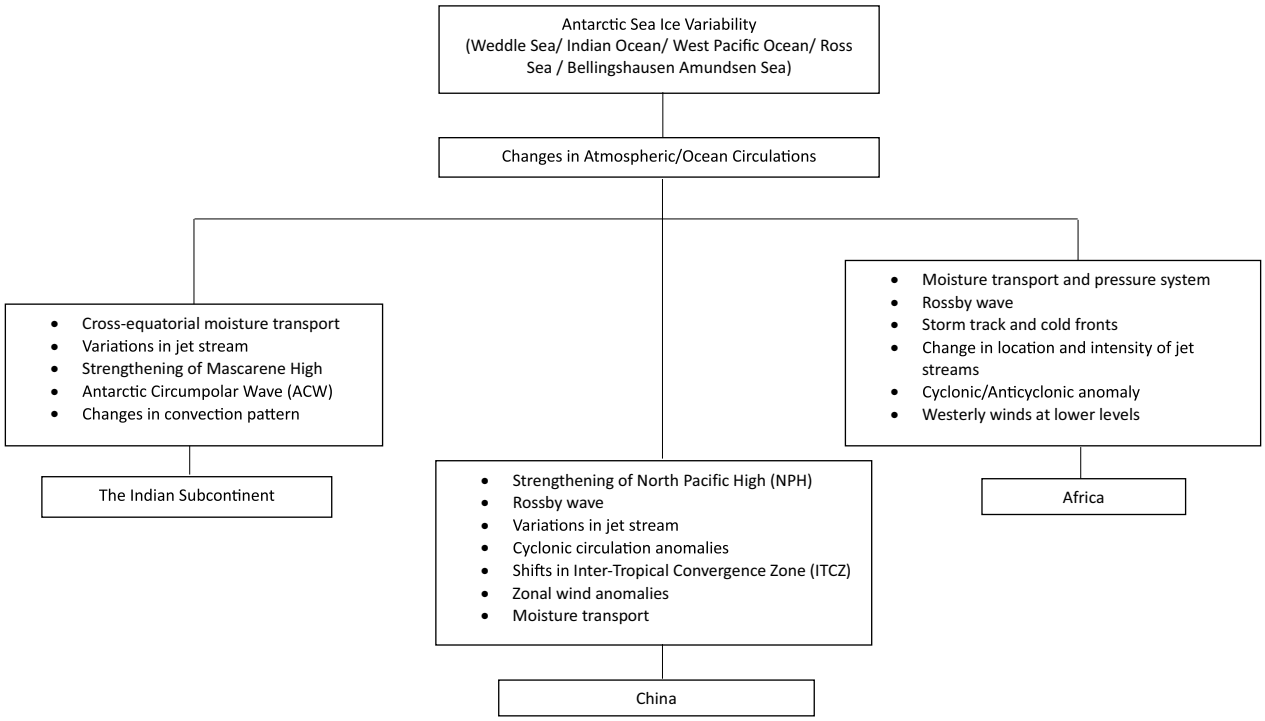


Fig. 1 The schematic representation illustrating the association of Antarctic Sea Ice on monsoon-dominated regions

in the Bellingshausen and Amundsen Sea sector (BASS) has often been associated with reduced ISM rainfall (Prabhu et al. 2009, 2010, 2021, 2022; Bajish et al. 2021). These contrasting regional responses highlight the spatial complexity of Antarctic sea ice variability and suggest that Antarctic–tropical climate linkages may depend on sector-specific circulation anomalies and broader hemispheric climate interactions (Simmonds and King 2004; Turner et al. 2009; England et al. 2014).

Evidence supporting Antarctic sea ice–ISM relationships originates from a combination of observational analyses, reanalysis datasets, and climate-model experiments. Observational and reanalysis studies provide evidence for statistically significant associations between Antarctic sea ice anomalies and monsoon rainfall variability, while modeling studies have been used to investigate potential dynamical pathways linking Southern Hemisphere high-latitude variability with tropical circulation changes (Prabhu et al. 2009, 2021, 2022; Azhar et al. 2020, 2023; Tewari et al. 2023). However, because Antarctic sea ice variability is closely coupled with large-scale climate modes such as the SAM, ENSO, and Southern Ocean variability, the extent to which Antarctic sea ice exerts an independent influence on ISM precipitation remains an active area of investigation.

Antarctic sea ice variability has been associated with changes in large-scale Southern Hemisphere atmospheric circulation; however, the mechanisms through which these high-latitude anomalies may influence lower-latitude climate remain uncertain. While planetary wave dynamics are known to contribute to climate teleconnections, direct evidence linking Antarctic sea ice anomalies to the generation and propagation of such waves is limited (Hoskins and Karoly 1981; Ding et al. 2014). Within this broader context, Azhar et al. (2020, 2023) reported statistical associations between Antarctic sea ice variability in the Indian Ocean sector and changes in large-scale atmospheric circulation, including variations in the Hadley and Ferrel circulations and upper-level zonal winds. However, these relationships are primarily based on observational and model-based correlations, and the mechanisms through which Antarctic sea ice variability may influence such circulation features remain uncomprehended. Changes in the polar front jet have also been proposed as a potential pathway linking Southern Hemisphere high-latitude variability with tropical atmospheric circulation through modifications in cross-equatorial energy and moisture transport (Lau and Nath 2003; Dugam and Kakade 2004; Trenberth et al. 2006; Azhar et al. 2023). Collectively, these studies point to several possible mechanisms that may contribute to the observed Antarctic sea ice–ISM relationships. Nevertheless, their relative importance remains uncertain, with different studies emphasizing planetary wave dynamics,

modifications of large-scale overturning circulations, or ocean–atmosphere feedbacks. This diversity of interpretations suggests that the reported teleconnections may arise from multiple interacting processes rather than a single dominant mechanism.

Low-level circulation anomalies provide an additional pathway through which Antarctic sea ice variability may be linked to ISM variability. High sea ice conditions have been associated with a strengthening of the Mascarene High and enhanced anticyclonic circulation over the southern Indian Ocean, potentially favoring stronger cross-equatorial flow and Somali jet activity (Azhar et al. 2020, 2023). These circulation anomalies may contribute to increased moisture transport into the Indian subcontinent and enhanced moisture convergence over parts of peninsular India (Fig. 2) (Webster et al. 1998; Azhar et al. 2020). While these relationships have been identified in both observational and modeling studies, the extent to which they represent a direct response to Antarctic sea ice variability remains an area of continuing investigation.

Figure 1 provides a conceptual synthesis of the atmospheric circulation responses and associations reported in the literature between Antarctic sea ice variability and ISM precipitation. Enhanced sea ice conditions in the Indian Ocean and western Pacific sectors have been associated with variations in large-scale atmospheric circulation over the southern Indian Ocean, including changes in the strength and position of the Mascarene High (Azhar et al. 2020). Previous studies have also reported concurrent variations in cross-equatorial flow, the Somali jet, and Indian monsoon rainfall during periods of anomalous Antarctic sea ice conditions (Azhar et al. 2020, 2023). However, these relationships are generally moderate in strength, and in several studies the strongest correlations occur over the Arabian Sea and adjacent oceanic regions rather than directly over the Indian subcontinent. This spatial pattern suggests that Antarctic sea ice variability may be more closely related to regional circulation and moisture-transport processes than to direct modulation of ISM rainfall. The dynamical links among these circulation features remain unexplained, and much of the available evidence is based on statistical associations rather than process-based attribution or targeted modeling experiments (Azhar et al. 2020, 2023; Tewari et al. 2023). In addition, Antarctic sea ice anomalies in different sectors have been associated with contrasting atmospheric responses, indicating that the reported relationships may depend on the location of the sea ice anomaly and its interaction with broader climate variability, including ENSO and SAM. Accordingly, the figure should be interpreted as a conceptual synthesis of the atmospheric circulation features and associations reported in previous studies, rather than as evidence of a definitive or direct causal pathway between Antarctic sea ice variability and ISM precipitation.

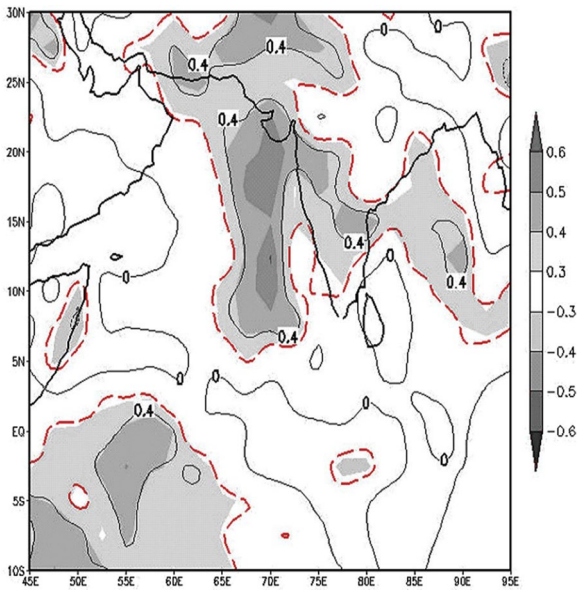


Fig. 2 Correlation between the April–May–June (AMJ) sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall over India region from 1979 to 2013. Dashed line in red is statistically significant at 95% (Azhar et al. 2020)

Sea ice variability in the western Pacific sector has also been linked to ISM variability through its potential influence on Indo-Pacific atmosphere–ocean interactions. Enhanced sea ice, together with elevated western Pacific SSTs, has been associated with increased ascending motion and modifications of Walker-type circulation patterns that may favor monsoon convection over India (Prabhu et al. 2009, 2021, 2022; Cai et al. 2021). Oceanic processes, including brine rejection, deep-water formation, and large-scale ocean circulation, have been proposed as potential mechanisms through which Antarctic sea ice variability may interact with broader climate variability (Gordon 2009; Prabhu et al. 2009; Rintoul 2018). Nevertheless, the influence of these processes on tropical sea surface temperatures and monsoon circulation remains unresolved, and the proposed oceanic teleconnections have yet to be firmly established through observational and modeling studies. In contrast, increased sea ice in the Bellingshausen and Amundsen Sea sector has frequently been associated with weaker monsoon circulation and reduced ISM precipitation (Prabhu et al. 2010, 2021, 2022; Bajish et al. 2021). These relationships have been interpreted in the context of Antarctic Circumpolar Wave variability, SAM-related circulation anomalies, and associated changes in upper-tropospheric heat transport (Thompson and Wallace 2000; Lau and Nath 2003; Marshall 2003; Prabhu et al. 2010). Concurrent SST

anomalies in the eastern and central Pacific may further contribute to these relationships through well-established ENSO–monsoon interactions (Kumar et al. 1999; Prabhu et al. 2010, 2021). The contrasting responses associated with different Antarctic sectors highlight the spatial heterogeneity of Antarctic sea ice variability and indicate that regional sea ice anomalies may interact with tropical climate systems through distinct circulation pathways. Consequently, Antarctic sea ice–monsoon relationships are unlikely to be spatially uniform and may depend on the location, magnitude, and persistence of sea ice anomalies as well as the prevailing background climate state.

The reported relationships between Antarctic sea ice variability and ISM precipitation are strongly modulated by broader modes of climate variability, particularly ENSO and SAM, which influence the background atmospheric circulation and introduce substantial nonlinearity into polar–tropical teleconnections (Prabhu et al. 2010, 2021, 2022; Bajish et al. 2021; Cai et al. 2021). On longer timescales, warming over eastern Antarctica has been associated with declining ISM precipitation and broader changes in large-scale atmospheric circulation (Frierson et al. 2013; Lakshmi et al. 2025). Proposed explanations include modifications in Southern Hemisphere wave activity and circulation patterns, potentially involving changes in the Mascarene High and tropical overturning circulations. However, the dynamical pathways linking Antarctic climate variability to Indian monsoon changes remain inexplicable and require further investigation. Likewise, projected reductions in Antarctic sea ice have been suggested to modify monsoon precipitation through changes in the strength of the Hadley and Ferrel circulations, shifts in jet-stream position, and adjustments in the Inter-Tropical Convergence Zone (Cabré et al. 2017; Tewari et al. 2023; Chandra and Sandeep 2024). Climate-model simulations further indicate that Antarctic sea ice decline may influence large-scale ocean circulation, including the Atlantic Meridional Overturning Circulation, with potential implications for vertical wind shear over the Bay of Bengal and the development of synoptic-scale monsoon systems (Rahmstorf et al. 2015; Chandra et al. 2022).

Some studies have suggested that Antarctic sea ice variability may function primarily as an indicator of broader Southern Hemisphere climate variability rather than as an independent forcing mechanism. Under this interpretation, the reported associations between Antarctic sea ice anomalies and ISM rainfall may partly reflect the combined influence of SAM, ENSO, Southern Ocean variability, and associated atmosphere–ocean interactions that simultaneously affect both Antarctic and tropical climate systems. Distinguishing the direct effects of Antarctic sea ice variability from those of the broader climate system remains a major challenge for future research.

The literature reviewed suggests that Antarctic sea ice variability is associated with ISM precipitation variability through a combination of proposed atmospheric teleconnections, circulation adjustments, and ocean–atmosphere interactions. However, the relative importance of these mechanisms varies among studies, and substantial uncertainty remains regarding the extent to which Antarctic sea ice exerts an independent influence compared with established climate drivers such as ENSO, SAM, and tropical ocean variability. Most available evidence is derived from observational analyses and reanalysis datasets, making attribution challenging within a highly coupled climate system. Nevertheless, Antarctic sea ice variability may provide useful predictive information for understanding seasonal-to-interannual monsoon variability and its potential response to future climate change, although its independent predictive value relative to established climate drivers remains uncertain (Prabhu et al. 2009, 2010, 2022). Despite increasing evidence for Antarctic sea ice–Indian monsoon linkages, the reported strength, timing, and spatial expression of these relationships vary among studies. Such differences likely reflect variations in the Antarctic sector considered, analysis period, datasets employed, and interactions with other climate drivers, particularly ENSO, SAM, and Indian Ocean variability. Consequently, the relative contribution of Antarctic sea ice variability to Indian monsoon variability is a subject requiring further study.

2.2 Antarctic sea ice extent and precipitation over china

A number of observational, reanalysis, and modeling studies have reported statistically significant associations between Antarctic sea ice variability and precipitation over China, although the strength and spatial expression of these relationships vary considerably among regions and seasons (Xue et al. 2003; Ma et al. 2006; Zhou et al. 2021; Xiao et al. 2024). The reported precipitation responses are strongly dependent on Antarctic sector, seasonal timing, and the prevailing atmospheric circulation background. Rather than representing a simple hemispheric forcing, Antarctic sea ice variability has been linked to Chinese rainfall through a combination of proposed dynamical and thermodynamical pathways involving hemispheric pressure redistribution, meridional energy transport, and planetary-scale wave propagation (Yuan and Martinson 2000; Clem et al. 2020). However, because Antarctic sea ice variability is closely coupled with large-scale modes of climate variability, including the SAM and ENSO, the extent to which Antarctic sea ice exerts an independent influence on East Asian monsoon variability is an emerging field.

Observational evidence indicates that enhanced Antarctic sea ice during boreal summer is often associated with increased precipitation over North China, particularly within the lower Yellow River basin (Peng and Domrös 1987; Xue et al. 2003), whereas reduced sea ice in certain Antarctic sectors has been linked to enhanced rainfall over Northeast China and parts of Xinjiang (Ma et al. 2006). Lagged relationships have also been reported. For example, Zhou et al. (2021) showed that June–August sea ice variability in the Southern Indian Ocean and Pacific sectors was associated with precipitation anomalies over western China during the subsequent autumn (Fig. 3). In contrast, precipitation responses over southern China and the Yangtze River Basin appear more complex and, in some cases, exhibit opposite responses depending on the location and timing of Antarctic sea ice anomalies (Xue et al. 2003; Ma et al. 2006; Xiao et al. 2024). These contrasting responses suggest that Antarctic sea ice–East Asian monsoon relationships are regionally heterogeneous and may depend on sector-specific circulation pathways and background climate conditions.

Figure 1 synthesizes the reported relationships between Antarctic sea ice variability, large-scale atmospheric circulation, moisture transport, and precipitation variability over China. Antarctic sea ice anomalies have been associated with changes in the North Pacific High, Rossby wave activity, jet-stream characteristics, cyclonic and anticyclonic circulation anomalies, shifts in the ITCZ, zonal wind patterns, and associated moisture transport. These circulation anomalies may influence the delivery, convergence, and redistribution of atmospheric moisture over China, thereby contributing to regional precipitation variability. The reported relationships suggest that Antarctic sea ice variability may be connected to hydroclimatic conditions over China through a sequence of large-scale atmospheric responses rather than through a simple direct linkage. However, these associations are primarily based on statistical covariability and should therefore not be interpreted as evidence of a definitive causal teleconnection. The observed relationships may also reflect the influence of broader coupled climate modes and ocean–atmosphere variability that can simultaneously affect Antarctic sea ice, atmospheric circulation, and precipitation over China. These reported associations indicate that Antarctic sea ice variability may influence precipitation variability over China through interconnected atmospheric circulation and moisture-transport processes, with the resulting response varying across regions and seasons.

Several studies have proposed a range of mechanisms through which Antarctic sea ice variability may be linked to East Asian climate. These include changes in Southern Ocean surface heat fluxes, meridional temperature gradients, and large-scale atmospheric circulation. However, the physical pathways connecting Antarctic sea ice variability and East Asian climate remain unaccountable and are subject to considerable uncertainty. Previous studies have also highlighted the importance of planetary-scale circulation variability and its influence on key East Asian circulation systems, including the North Pacific High and upper-tropospheric jet structure, which can affect moisture transport and vertical motion over China (Hoskins and Ambrizzi 1993; Ma et al. 2006; Ding et al. 2012). Nevertheless, the extent to which Antarctic sea ice anomalies independently contribute to these circulation changes, as opposed to reflecting the influence of larger-scale climate modes, warrants further study. Thermodynamic processes have also been proposed as contributing

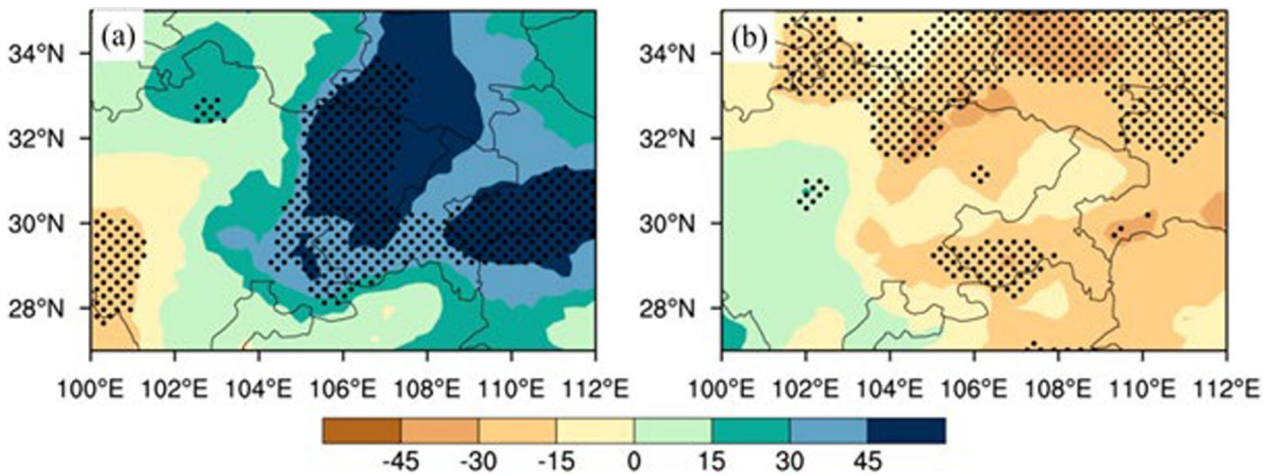


Fig. 3 Composite anomalies of autumn precipitation (mm/year) in West China during **a** high and **b** low sea ice concentration (SIC) years in the Southern Indian and Pacific Ocean basins (Zhou et al. 2021). (dots indicate statistical significance at 95%)

mechanisms. Enhanced Antarctic sea ice has been associated with reduced turbulent heat fluxes and lower-tropospheric cooling over high southern latitudes (Xiao et al. 2024). These thermodynamic anomalies may alter meridional temperature gradients and high-latitude atmospheric circulation, potentially generating large-scale wave-train or teleconnection patterns that extend into the Indo-Pacific region. Through their influence on large-scale circulation, these anomalies have been linked to changes in zonal winds, moisture transport, moisture convergence, and regional precipitation patterns across different parts of China. However, the precise pathways connecting Antarctic sea ice variability to East Asian climate remain unresolved and may be influenced by other large-scale climate modes, including ENSO and SAM.

Antarctic sea ice variability has also been linked to changes in the Western Pacific Subtropical High (WPSH), a key component of East Asian monsoon circulation. Several studies suggest that Antarctic sea ice anomalies, particularly in the Ross and Bellingshausen Sea sectors, may be associated with variations in the position and intensity of the WPSH, thereby affecting moisture-transport pathways and frontal activity over China (Peng and Domrös 1987; Bian and Lan 2010). These circulation anomalies have been associated with variations in cross-equatorial flow, shifts in the position of the Inter-Tropical Convergence Zone (ITCZ), and changes in the timing and intensity of Mei-Yu frontal activity, which may contribute to regional differences in monsoonal precipitation (Bian and Lan 2010). However, the physical mechanisms linking Antarctic sea ice variability to these tropical and subtropical circulation responses remain unelucidated, and the relative importance of these processes is difficult to isolate because similar circulation anomalies can also arise from tropical forcing, internal atmospheric variability, and other large-scale climate modes.

The reported Antarctic sea ice–East Asian monsoon relationships are further influenced by interactions with other modes of climate variability. ENSO modifies tropical circulation patterns and may either strengthen or weaken the teleconnections associated with Antarctic sea ice variability (Dash et al. 2013; Lim et al. 2023). Similarly, SAM influences zonal wind anomalies and large-scale meridional circulation patterns across the Southern Hemisphere and may provide an important pathway linking Southern Ocean variability with East Asian climate conditions (Fogt et al. 2011; Sun et al. 2015). Because both ENSO and SAM can affect Antarctic sea ice variability as well as regional atmospheric circulation and precipitation patterns, distinguishing the independent contribution of Antarctic sea ice remains challenging. Consequently, many of the reported relationships likely reflect the combined influence of Antarctic sea ice variability, large-scale climate modes, and broader atmosphere–ocean interactions operating across multiple spatial and temporal scales. Further progress will require targeted modeling experiments and attribution studies designed to isolate Antarctic sea ice signals from those associated with dominant climate drivers.

Some studies have suggested that Antarctic sea ice variability may act primarily as an indicator of broader Southern Hemisphere climate variability rather than as an independent forcing mechanism. Under this interpretation, the reported associations between Antarctic sea ice anomalies and East Asian precipitation may partly arise from the influence of coupled climate modes that simultaneously affect both Antarctic and East Asian climate systems. Distinguishing the independent contribution of Antarctic sea ice variability from that of SAM, ENSO, and other large-scale circulation processes remains an important challenge for future research. Taken together, studies from both South Asia and East Asia indicate that Antarctic sea ice variability may be linked to monsoon precipitation through a range of atmospheric and oceanic pathways, although the relative importance of these mechanisms remains uncertain and is strongly influenced by interactions with other modes of climate variability.

2.3 Antarctic sea ice extent and precipitation in Africa

Several observational studies have reported statistical associations between Antarctic sea ice variability and seasonal precipitation variability across parts of Africa, particularly over southern and East Africa. In particular, variations in sea ice concentration within sectors such as the Weddell Sea and Ross Sea have been linked to regional precipitation anomalies on monthly to seasonal timescales (Turner et al. 2009). However, the physical mechanisms underlying these relationships remain uncertain, and it is often difficult to distinguish potential sea-ice-related influences from the effects of larger-scale climate modes, such as the SAM and ENSO, which can affect both Antarctic sea ice variability and African rainfall. However, the strength, spatial expression, and physical interpretation of these relationships vary among regions and seasons.

The reported associations suggest that Antarctic sea ice variability occurs within a broader framework of hemispheric climate variability that may influence African rainfall through interconnected atmosphere–ocean processes. Consequently, Antarctic sea ice anomalies may represent one component of a coupled climate system involving Southern Ocean variability, SAM, ENSO, and regional ocean–atmosphere interactions. The spatial heterogeneity of the observed precipitation responses further indicates that the relationship

depends on Antarctic sector, regional circulation patterns, and the prevailing climate background. Although several studies have reported associations between Antarctic sea ice variability and African precipitation, the mechanisms responsible for these relationships remain incompletely understood. In particular, it is difficult to separate the influence of Antarctic sea ice from that of larger-scale climate modes such as ENSO and the SAM, both of which affect atmospheric circulation and precipitation across the Southern Hemisphere (Fogt and Marshall 2020).

Over southern Africa, several studies have reported relationships between Antarctic sea ice variability and winter rainfall. Blamey and Reason (2007), for example, found that increased sea ice concentration in the Weddell Sea and Drake Passage during 1982–2004 was associated with enhanced precipitation over western South Africa during the May–September (MJJAS) season. The observed relationship was linked to cyclonic circulation anomalies over southern Africa and the adjacent South Atlantic, which may favor stronger low-level westerlies and increased moisture transport from the South Atlantic (Fogt et al. 2011). A northward displacement of the mid-latitude storm track has also been proposed as a contributing factor through its influence on frontal activity and winter rainfall variability (Hoskins and Hodges 2005). In addition, changes in the organization of the subtropical and polar jets have been suggested as mechanisms capable of modifying the frequency and intensity of frontal systems affecting southern Africa (Thompson and Wallace 2000).

Interestingly, reduced sea ice concentration in parts of the eastern Weddell Sea has also been associated with enhanced winter precipitation over western South Africa (Blamey and Reason 2007). This apparent contrast suggests that precipitation responses may depend less on whether Antarctic sea ice anomalies are positive or negative and more on the location of the anomaly and the associated atmospheric circulation configuration. However, these relationships should be interpreted with caution because southern African rainfall is strongly influenced by other large-scale climate drivers, including ENSO, SAM, and variability in the Indian and South Atlantic Oceans (Richard 2000; Behera and Yamagata 2001; Fauchereau et al. 2003; Reason and Rouault 2005). Consequently, the observed associations between Antarctic sea ice and rainfall may partly reflect shared responses to broader climate variability rather than a direct sea-ice influence. These findings highlight the complexity of Antarctic sea ice–African precipitation relationships and suggest that multiple interacting circulation pathways, operating alongside dominant climate modes, may contribute to the observed rainfall variability.

Evidence for Antarctic sea ice–precipitation linkages has also been reported in tropical East Africa. Makula and Zhou (2023) identified statistically significant inverse relationships between Antarctic sea ice variability and Tanzanian rainfall during the March–May (MAM) season, with increased Weddell Sea ice associated with reduced precipitation over northern Tanzania and enhanced Ross Sea ice linked to suppressed rainfall over southern and eastern Tanzania during 1978–2017 (Fig. 4).

Figure 1 provides a conceptual representation of reported relationships between Antarctic sea ice variability, large-scale atmospheric circulation, and African precipitation. Increased sea ice concentration in the Weddell Sea and Drake Passage has been associated with circulation anomalies over the southeast Atlantic that may coincide with enhanced moisture transport and winter rainfall variability over western South Africa. Over East Africa, Antarctic sea ice anomalies have also been associated with circulation variations that may affect moisture transport from the Indian Ocean and Congo Basin, contributing to regional precipitation variability. These relationships are based primarily on statistical associations and contemporaneous correlation analyses and therefore should not be interpreted as evidence of a direct causal influence of Antarctic sea ice on African precipitation. The observed covariability may also reflect the influence of large-scale climate modes, including the SAM and ENSO, which can affect both Antarctic sea ice conditions and African rainfall. Accordingly, the figure is intended as a conceptual synthesis of the circulation features and statistical relationships reported in the literature, rather than as a definitive representation of a physically established teleconnection pathway. Further lead–lag analyses, process-based investigations, and targeted climate-model experiments are needed to better constrain the direction, mechanisms, and magnitude of these relationships.

Several studies have proposed that these relationships may be mediated through Rossby wave activity extending from the Southern Ocean and the high-latitude South Pacific near the Amundsen Sea Low region into the southwestern Indian Ocean region. The resulting circulation anomalies have been associated with changes in upper-level and lower-level atmospheric flow, potentially affecting moisture transport from the Indian Ocean and Congo Basin and influencing regional moisture convergence (Hoskins and Ambrizzi 1993; Cook and Vizy 2013; Makula and Zhou 2023). However, the relative contribution of Antarctic sea ice variability compared with regional ocean–atmosphere interactions remains uncertain. At the same time, East African rainfall is strongly influenced by variability in the Indian Ocean, including the Indian Ocean Dipole and ENSO-related circulation

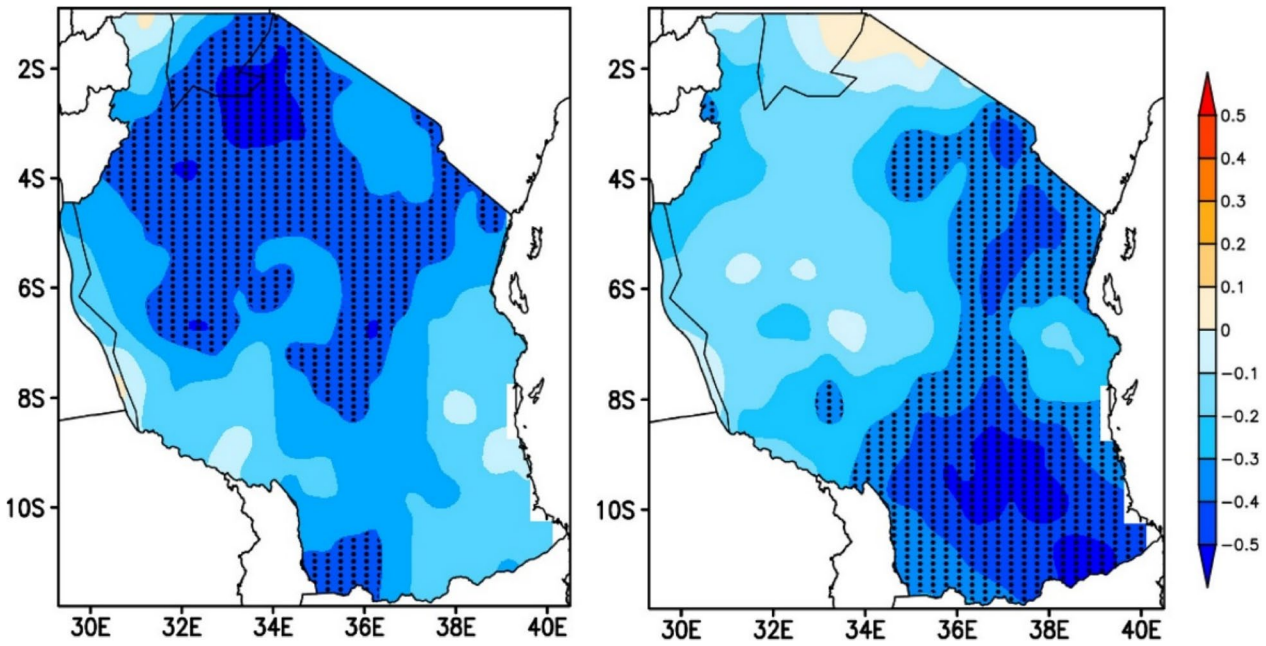


Fig. 4 Correlation map of March–April–May (MAM) precipitation in Tanzania with MAM sea ice concentration (SIC) anomalies over the Weddell Sea and Ross Sea during 1978–2017 (dots indicate statistical significance at 95%) (Makula and Zhou 2023)

changes. Consequently, the independent contribution of Antarctic sea ice variability remains difficult to quantify and may vary among seasons and regions.

The reported Antarctic sea ice–African precipitation relationships are further influenced by interactions with dominant modes of climate variability, particularly ENSO and SAM. These climate modes affect large-scale atmospheric circulation and may either strengthen or weaken the teleconnections associated with Antarctic sea ice variability. Consequently, many of the observed relationships likely reflect the combined influence of Antarctic sea ice variability, tropical climate variability, and internal atmospheric dynamics operating across multiple spatial and temporal scales. Under this interpretation, Antarctic sea ice may act both as a component of the coupled climate system and as an indicator of broader Southern Hemisphere climate variability rather than as an isolated forcing mechanism.

The available literature provides evidence for statistically significant associations between Antarctic sea ice variability and precipitation variability across southern and East Africa, although the physical mechanisms responsible for these relationships remain incompletely resolved. Much of the current evidence is derived from observational and reanalysis studies, while relatively few modeling studies have explicitly isolated the role of Antarctic sea ice from other sources of climate variability. Proposed mechanisms include changes in jet-stream behavior, storm-track variability, Rossby wave propagation, and large-scale moisture transport, although the relative importance of these processes remains uncertain. The reported precipitation responses vary substantially among regions and Antarctic sectors and are strongly influenced by interactions with ENSO, SAM, and other atmosphere–ocean processes. While these findings suggest potential links between Antarctic climate variability and African hydroclimate, further observational, modeling, and attribution studies are needed to clarify the physical mechanisms involved and to evaluate the predictive value of Antarctic sea ice variability for African rainfall.

A consolidated synthesis of sector-specific Antarctic sea ice teleconnections and their reported hydroclimatic associations across tropical and mid-latitude regions is presented in Table 1. The studies reviewed indicate that Antarctic sea ice variability is associated with precipitation variability across South Asia, East Asia, and Africa through a range of proposed atmospheric and oceanic pathways, including Rossby wave propagation, jet-stream variability, SAM-related circulation changes, and interactions with tropical climate modes such as ENSO and IOD. However, the strength, spatial expression, and confidence of these reported relationships vary considerably among regions, seasons, and Antarctic sectors. Teleconnections involving the ISM are generally supported by both observational and modeling evidence, whereas relationships identified over East Africa and some parts of East Asia remain comparatively less constrained. The

Table 1 Summary of reported relationships between Antarctic sea ice variability and regional hydroclimatic variability, including proposed teleconnection pathways, evidence types, confidence levels, and major uncertainties

Antarctic sea ice sector	Dominant season	Affected region	Reported association with hydroclimatic variability	Proposed physical mechanism	Evidence type	Confidence level	Key uncertainties and competing drivers	Key references
Indian Ocean Sector (20–90°E)	Austral winter–spring/Boreal summer	Indian Subcontinent	Positive association with ISM rainfall reported in several studies	SAM-related circulation anomalies, strengthening of the Mascarene High and Somali Jet, enhanced cross-equatorial moisture transport, Hadley circulation adjustments	Observational + Reanalysis Observational + Reanalysis + Model	Moderate–High	Difficult to separate from ENSO, Indian Ocean variability, and SAM influences	Azhar et al. (2020) Azhar et al. (2023)
Indian Ocean Sector (20–90°E)	Austral spring	East Asia	Positive association with autumn precipitation over northern China and the Yangtze River Basin	Rossby wave propagation, subtropical jet variability, enhanced moisture convergence	Observational + Reanalysis Observational + Reanalysis + Model	Moderate	Relative contribution of Antarctic variability versus regional atmospheric processes remains uncertain	Zhou et al. (2021) Xiao et al. (2024)
Western Pacific Sector (90–160°E)	Austral winter–spring	Indian Subcontinent	Positive association with monsoon circulation strength and ISM rainfall	Meridional wave trains, tropical overturning circulation adjustments, upper-level divergence anomalies	Observational + Reanalysis	Moderate	Strong interaction with ENSO-related Indo-Pacific variability	Prabhu et al. (2009, 2021, 2022)
Ross Sea Sector (160°E–130°W)	Austral spring	East Asia	Negative association with summer precipitation over parts of southern and northeastern China	Variability in the North Pacific High, mid-latitude trough activity, and jet-stream position	Observational + Reanalysis	Moderate	Potential influence of tropical Pacific variability and unresolved teleconnection pathways	Ma et al. (2006)
Ross Sea Sector (160°E–130°W)	Austral winter–spring	Eastern Africa	Negative association with boreal spring rainfall in parts of East Africa	Rossby wave-related circulation anomalies affecting western Indian Ocean moisture transport	Observational + Reanalysis	Low–Moderate	Possible confounding effects from IOD, ENSO, and regional SST variability	Makula and Zhou (2023)
Bellingshausen–Amundsen Seas (130–60°W)	Austral winter	Indian Subcontinent	Negative association with ISM rainfall reported in several studies	Antarctic Circumpolar Wave variability, Pacific SST anomalies, weakened monsoon circulation	Observational + Reanalysis	Moderate	Strong overlap with ENSO-related Pacific variability and SAM influences	Prabhu et al. (2010, 2021, 2022); Bajish et al. (2021)

Table 1 (continued)

Antarctic sea ice sector	Dominant season	Affected region	Reported association with hydroclimatic variability	Proposed physical mechanism	Evidence type	Confidence level	Key uncertainties and competing drivers	Key references
Weddell Sea Sector (60°W–20°E)	Austral winter	Southern Africa	Positive association with winter rainfall over western South Africa	Storm-track variability, cyclonic circulation anomalies, enhanced westerly moisture transport	Observational + Reanalysis	Moderate	Sensitive to storm-track dynamics and Southern Hemisphere circulation variability	Blamey and Reason (2007)
Weddell Sea Sector (60°W–20°E)	Austral spring	Eastern Africa	Negative association with seasonal rainfall in parts of East Africa	Wave-related circulation anomalies affecting Indian Ocean and Congo Basin moisture transport	Observational + Reanalysis	Low–Moderate	Influence of Tropical Indian Ocean variability remains uncertain	Makula and Zhou (2023)
Circumpolar/Multi-sector Anomalies	Seasonal to Decadal	Multiple Monsoon Regions	Increased precipitation variability and circulation changes reported under Antarctic sea ice decline scenarios	Large-scale circulation reorganization, Hadley and Ferrel cell adjustments, subtropical jet variability	Model	Moderate	Limited observational validation; future response depends on climate-change scenario and model structure	Cabré et al. (2017); Tewari et al. (2023); Chandra and Sandeep (2024)
Circumpolar/Multi-sector Anomalies	Seasonal to Decadal	Global	Associations with enhanced hydroclimatic variability and extremes reported in several studies	Interhemispheric coupling, Rossby wave propagation, large-scale circulation adjustment	Observational + Model	Low–Moderate	Attribution remains challenging because multiple climate modes operate simultaneously	Chandra et al. (2022); Wu et al. (2023)

synthesis further highlights that many proposed mechanisms operate within a highly coupled climate system in which Antarctic sea ice variability coexists with other sources of climate variability, making attribution challenging. Although many studies report statistically significant relationships, differences in the strength, spatial pattern, and seasonality of these relationships likely reflect variations in datasets, analysis periods, methodologies, and interactions with other modes of climate variability. Consequently, the relationships summarized in Table 1 should be interpreted primarily as reported associations and proposed teleconnection pathways supported by varying levels of observational, reanalysis, and modeling evidence, rather than as universally established causal mechanisms. These findings underscore the potential climatic relevance of Antarctic sea ice variability while highlighting the need for further observational, modeling, and attribution studies to better quantify its role in regional hydroclimatic variability.

3 Climate modes and other drivers of Antarctic sea ice variability

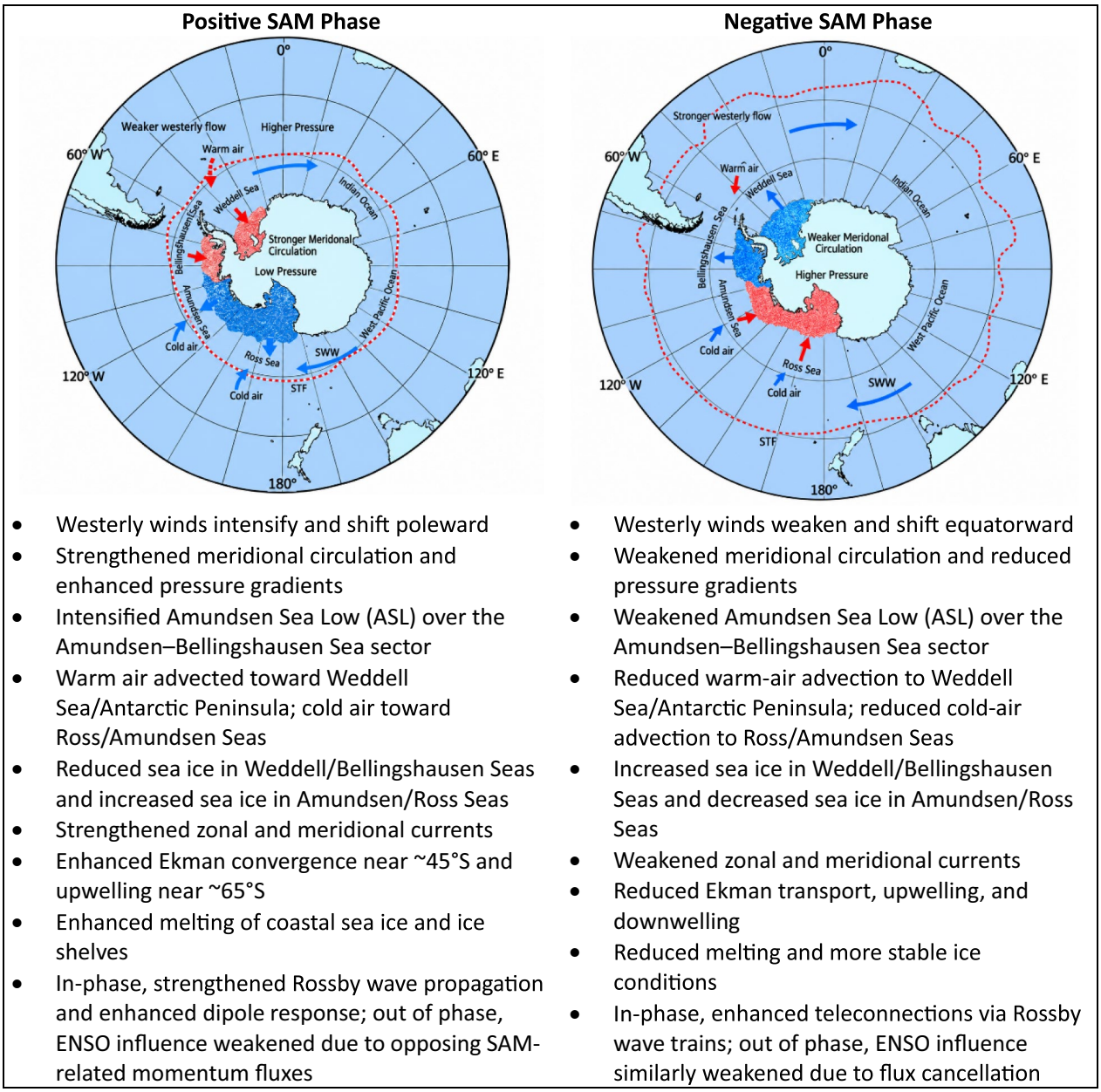
3.1 Climate modes and Antarctic sea ice variability

Antarctic sea ice variability is governed by several interacting climate modes and large-scale atmospheric and oceanic processes operating across different spatial and temporal scales. Although SAM is a major mode of Southern Hemisphere climate variability, other processes, including ENSO, the Pacific–South American (PSA) pattern, Southern Ocean sea surface temperature anomalies, the Antarctic Circumpolar Wave, and internal atmospheric variability, also contribute to sea ice variability. Their combined effects contribute to the pronounced spatial and temporal heterogeneity of Antarctic sea ice and should be considered when interpreting associations between Antarctic sea ice variability and precipitation anomalies at lower latitudes.

Among these climate modes, SAM is one of the most extensively documented modes associated with Antarctic sea ice variability, particularly through its influence on the strength and latitudinal position of the circumpolar westerly winds. Variations in SAM influence surface wind stress, meridional heat transport, and air–sea–ice interactions, contributing to pronounced regional differences in Antarctic sea ice concentration and extent. These responses vary among Antarctic sectors because of differences in regional atmospheric circulation, oceanic conditions, and sea-ice dynamics. SAM-related circulation anomalies interact with regional pressure systems, such as the Amundsen Sea Low, and oceanic processes associated with the Antarctic Circumpolar Current (ACC), which contributes to the redistribution of heat around Antarctica (Alder et al. 2017; Rintoul 2018; Eabry et al. 2024). Seasonal variability further modulates these processes, with sea ice advancing during austral autumn and winter and retreating during spring and summer in response to variations in solar radiation, wind-driven ice transport, and air–sea heat exchange (Simpkins et al. 2012; Doddridge and Marshall 2017; Yadav et al. 2022; Wang et al. 2023).

During the positive phase of SAM, intensified and poleward-shifted westerly winds modify meridional circulation and interact with low-pressure systems over the Amundsen and Bellingshausen Seas. These circulation anomalies have been associated with enhanced warm-air advection toward the Weddell Sea and Antarctic Peninsula and increased cold-air transport toward the Ross and Amundsen Sea sectors. Observational and modeling studies indicate that positive SAM conditions are commonly associated with a dipole-like pattern of Antarctic sea ice variability, characterized by reduced sea ice concentration in the Weddell and Bellingshausen Seas and increased sea ice concentration in the Amundsen and Ross Sea sectors, particularly during austral winter and spring (Lefebvre et al. 2004; Liu et al. 2004; Lefebvre and Goosse 2005; Sen Gupta and England 2006; Simpkins et al. 2012; Wang et al. 2023). Ocean–atmosphere interactions may further reinforce these patterns. Strengthened wind stress during positive SAM conditions has been linked to enhanced Ekman transport, promoting convergence and downwelling near 45°S and divergence-driven upwelling around 65°S. The resulting upwelling of relatively warm and saline subsurface waters may increase oceanic heat availability near the Antarctic continental margin, thereby contributing to sea ice reduction and ice-shelf melt in some regions (Lefebvre et al. 2004; Lefebvre and Goosse 2005).

Negative SAM conditions are characterized by weakened and equatorward-shifted westerly winds and a weaker Amundsen–Bellingshausen low. These circulation changes are generally associated with a reversal of the sea ice dipole pattern, with increased sea ice concentration in the Weddell and Bellingshausen Seas and reduced sea ice concentration in the Amundsen and Ross Sea sectors (Pezza et al. 2012; Doddridge and Marshall 2017; Eabry et al. 2024). Reduced zonal and meridional circulation under negative SAM conditions has also been associated with weaker Ekman-driven vertical exchange and reduced oceanic heat transport into the sea ice zone. The contrasting atmospheric circulation patterns and associated Antarctic sea ice responses during positive and negative SAM phases are summarized schematically in Fig. 5. These contrasting responses illustrate how large-scale climate modes can generate regionally distinct patterns of Antarctic sea ice variability.



- Westerly winds intensify and shift poleward
- Strengthened meridional circulation and enhanced pressure gradients
- Intensified Amundsen Sea Low (ASL) over the Amundsen–Bellingshausen Sea sector
- Warm air advected toward Weddell Sea/Antarctic Peninsula; cold air toward Ross/Amundsen Seas
- Reduced sea ice in Weddell/Bellingshausen Seas and increased sea ice in Amundsen/Ross Seas
- Strengthened zonal and meridional currents
- Enhanced Ekman convergence near ~45°S and upwelling near ~65°S
- Enhanced melting of coastal sea ice and ice shelves
- In-phase, strengthened Rossby wave propagation and enhanced dipole response; out of phase, ENSO influence weakened due to opposing SAM-related momentum fluxes

- Westerly winds weaken and shift equatorward
- Weakened meridional circulation and reduced pressure gradients
- Weakened Amundsen Sea Low (ASL) over the Amundsen–Bellingshausen Sea sector
- Reduced warm-air advection to Weddell Sea/Antarctic Peninsula; reduced cold-air advection to Ross/Amundsen Seas
- Increased sea ice in Weddell/Bellingshausen Seas and decreased sea ice in Amundsen/Ross Seas
- Weakened zonal and meridional currents
- Reduced Ekman transport, upwelling, and downwelling
- Reduced melting and more stable ice conditions
- In-phase, enhanced teleconnections via Rossby wave trains; out of phase, ENSO influence similarly weakened due to flux cancellation

Fig. 5 Schematic comparison of positive and negative Southern Annular Mode (SAM) phases and their associated atmospheric circulation patterns and Antarctic sea ice responses (Red dotted line—Subtropical front (STF); Red and blue shaded regions indicating decreasing and increasing sea ice extent; Red arrows—Warm air; Blue arrow—Cold air)

Interactions between SAM and ENSO provide an important example of this broader climate-system variability. ENSO can modulate the propagation of Rossby wave trains from the tropics into high southern latitudes, thereby influencing regional atmospheric circulation and sea ice conditions around Antarctica. In-phase combinations of SAM and ENSO (positive SAM with La Niña or negative SAM with El Niño) have been associated with stronger pressure anomalies over the Amundsen and Bellingshausen Seas and more pronounced sea ice anomalies in the Amundsen, Ross, Bellingshausen, and Weddell Sea sectors (Wang et al. 2023). Conversely, out-of-phase combinations tend to weaken these teleconnection signals, contributing to greater sea ice variability in the Indian Ocean and West Pacific sectors and reducing the influence of ENSO on Southern Hemisphere mid-latitude circulation through opposing transient eddy momentum fluxes associated with SAM and

ENSO (Fogt et al. 2011; Wilson et al. 2016; Wang et al. 2023). Importantly, SAM has also been linked directly to monsoon variability through large-scale atmospheric circulation changes that do not necessarily require Antarctic sea ice anomalies as an intermediary. Previous studies have reported relationships between SAM variability and monsoon circulation over South and East Asia through modifications of subtropical jet streams, meridional circulation, and tropical–extratropical interactions (Prabhu et al. 2016; Liu et al. 2018). Thus, Antarctic sea ice–monsoon relationships should be considered within the broader context of interacting Southern Hemisphere climate modes and atmospheric processes rather than interpreted as evidence of an independent sea ice forcing.

3.2 Other atmospheric and oceanic drivers of Antarctic sea ice variability

Beyond the influence of major climate modes, Antarctic sea ice variability is influenced by a range of interacting atmospheric and oceanic processes operating across multiple spatial and temporal scales. The observed regional and seasonal heterogeneity of Antarctic sea ice reflects the combined effects of tropical teleconnections, internal atmospheric variability, ocean–atmosphere interactions, regional circulation and oceanic processes and large-scale climate modes beyond SAM (Pezza et al. 2012; Schneider et al. 2012; Fogt and Marshall 2020; Eayrs et al. 2021).

Among these processes, ENSO exerts a substantial influence on Antarctic climate through atmospheric teleconnections linking tropical and high-latitude circulation systems. ENSO-related convection anomalies in the tropical Pacific can generate Rossby wave trains that propagate into the Southern Hemisphere through the PSA pattern, thereby modifying atmospheric pressure fields, storm tracks, and surface wind anomalies around Antarctica (Yuan and Martinson 2000; Schneider et al. 2012; Stuecker et al. 2017). These circulation changes influence sea ice concentration and extent in a regionally dependent manner, particularly within the Amundsen–Bellingshausen Sea and Ross Sea sectors. However, the influence of ENSO varies according to season, background circulation state, and its interaction with SAM, contributing to interannual variability in Antarctic sea ice conditions (Pezza et al. 2012; Fogt and Marshall 2020).

Antarctic sea ice variability is also associated with the Antarctic Circumpolar Wave (ACW), a coupled ocean–atmosphere mode characterized by eastward-propagating anomalies in sea surface temperature, sea-level pressure, winds, and sea ice concentration around the Southern Ocean. The ACW contributes to regional fluctuations in Antarctic sea ice by modulating oceanic and atmospheric conditions across different sectors of Antarctica and has been linked to variability in Southern Hemisphere climate on interannual timescales (White and Peterson 1996; Prabhu et al. 2010; Khare 2022). In addition, zonal-wave 3 (ZW3) variability represents an important feature of Antarctic climate, characterized by three alternating ridges and troughs distributed around the Southern Ocean. The ZW3 pattern influences atmospheric circulation, sea ice distribution, and regional climate variability through interactions with planetary-scale wave activity and Southern Ocean circulation. Raphael (2007) demonstrated that ZW3 variability contributes substantially to regional asymmetries in Antarctic sea ice and atmospheric circulation, helping to explain differences among Antarctic sectors that cannot be attributed solely to SAM.

Oceanic processes provide an additional source of Antarctic sea ice variability. Variations in Southern Ocean sea surface temperatures, upper-ocean heat content, mixed-layer dynamics, and ocean circulation influence the growth, persistence, and decay of sea ice through modifications in oceanic heat fluxes and air–sea interactions (Liu et al. 2004; Rintoul 2018). Changes in ocean stratification and heat transport can either promote or suppress sea ice formation depending on regional conditions. Recent studies have also emphasized the importance of ocean–ice feedbacks in explaining the abrupt decline in Antarctic sea ice observed since 2016 (Eayrs et al. 2021; Purich and Doddridge 2023; Raphael et al. 2025). Furthermore, internal atmospheric variability and short-term fluctuations in synoptic-scale circulation patterns contribute to Antarctic sea ice variability and may generate substantial year-to-year changes in sea ice extent independent of long-term climate trends (Pezza et al. 2012; Fogt and Marshall 2020). Taken together, these findings indicate that Antarctic sea ice variability reflects the combined influence of atmospheric and oceanic processes rather than a single dominant forcing. Consequently, relationships between Antarctic sea ice variability and lower-latitude precipitation should be interpreted within the broader context of interactions among SAM, ENSO, PSA variability, Southern Ocean processes, and internal climate variability.

4 Conclusions and future perspectives

This review synthesizes observational, reanalysis, and modeling evidence concerning the relationships between Antarctic sea ice variability and precipitation variability across monsoon-dominated and seasonally wet regions, with particular emphasis on South Asia, East Asia, and Africa. By integrating findings from diverse regional studies, the review highlights emerging evidence for Antarctic sea ice–precipitation linkages while identifying key areas of agreement, uncertainty, and future research

priorities. The literature suggests that Antarctic sea ice variability is associated with a range of atmospheric and oceanic processes that may contribute to hydroclimatic variability beyond the high southern latitudes. Unlike the Arctic, where long-term sea ice decline has been relatively consistent, Antarctic sea ice exhibits pronounced regional, seasonal, and interannual variability, resulting in substantial spatial heterogeneity in the reported climate responses. This complexity has stimulated growing interest in understanding the potential teleconnection pathways through which Antarctic sea ice variability may be linked to climate variability in lower latitudes.

A key finding emerging from the literature is that reported Antarctic sea ice–precipitation relationships are strongly sector-dependent and do not represent a uniform hemispheric response. Sea ice variability in the Ross Sea, Weddell Sea, Indian Ocean, Western Pacific, and Bellingshausen–Amundsen Sea sectors has been linked to different hydroclimatic responses across South Asia, East Asia, and Africa. Several mechanisms have been proposed to explain these relationships, including changes in meridional temperature gradients, Rossby wave propagation, jet-stream variability, storm-track adjustments, and modifications of large-scale circulation systems such as the Mascarene High and the Western Pacific Subtropical High. Collectively, these studies suggest that Antarctic sea ice variability may be associated with changes in atmospheric circulation and moisture transport that are relevant to regional precipitation variability.

SAM is frequently identified as an important component of the proposed teleconnection framework because of its influence on Southern Hemisphere westerly winds, atmospheric circulation, and Antarctic sea ice distribution. Interactions between SAM and other large-scale climate modes, particularly ENSO, appear to influence the strength, timing, and spatial expression of many reported Antarctic sea ice–precipitation relationships. These findings highlight the importance of considering Antarctic sea ice variability within the broader context of a coupled climate system in which tropical, mid-latitude, and polar processes interact across multiple spatial and temporal scales. However, substantial uncertainties remain regarding the physical mechanisms responsible for these relationships and the extent to which Antarctic sea ice exerts an independent influence relative to other modes of climate variability. In particular, interactions among Antarctic sea ice variability, SAM, ENSO, and regional ocean–atmosphere processes complicate attribution and make it difficult to isolate individual contributions to observed precipitation variability.

Across the Indian subcontinent, East Asia, and Africa, the reviewed studies collectively indicate that Antarctic sea ice variability has been associated with both enhanced and reduced precipitation, depending on the Antarctic sector, season, and prevailing climate conditions. Furthermore, much of the available evidence is derived from observational and reanalysis analyses, while comparatively few studies have explicitly isolated the contribution of Antarctic sea ice variability through targeted modeling experiments. Consequently, the robustness of some reported teleconnections and the relative importance of competing climatic drivers remain areas of ongoing investigation. Some studies suggest that Antarctic sea ice variability may contain information relevant to seasonal-to-interannual hydroclimatic variability and therefore warrants consideration alongside more widely recognized climate drivers such as ENSO. However, substantial uncertainties remain regarding the physical mechanisms responsible for these relationships, the relative importance of atmospheric and oceanic pathways, and the extent to which Antarctic sea ice exerts an independent influence relative to other modes of climate variability. Furthermore, much of the available evidence is derived from observational and reanalysis analyses, while comparatively few studies have explicitly isolated the contribution of Antarctic sea ice variability through targeted modeling experiments.

Recent declines in Antarctic sea ice extent and the emergence of historically low sea ice conditions have renewed interest in understanding the climatic implications of Antarctic change. However, the consequences of future Antarctic sea ice variability for regional precipitation remain uncertain because the underlying teleconnection mechanisms may evolve under changing climate conditions. Continued changes in Southern Hemisphere circulation, ocean–atmosphere interactions, and large-scale climate modes could alter the strength, structure, and persistence of the relationships identified in the present literature, potentially affecting the applicability of historical relationships under future climates.

Overall, the literature reviewed here suggests that Antarctic sea ice variability may contribute to interhemispheric climate variability and regional precipitation variability, although the magnitude, mechanisms, and robustness of these relationships remain unresolved. In particular, distinguishing an independent Antarctic sea ice signal from the influence of interacting climate drivers such as ENSO and SAM remains a major challenge. Addressing this uncertainty will require longer-term observations and reanalysis datasets, together with targeted and coordinated modeling experiments capable of isolating the contribution of Antarctic sea ice and evaluating the underlying processes. Future research should give particular attention to sector-specific and seasonally resolved sea ice anomalies, Southern Ocean–atmosphere interactions, and the stability

of reported teleconnections under ongoing climate change. Such efforts will be essential for determining the extent to which Antarctic sea ice variability contributes to regional precipitation variability and whether these relationships have meaningful implications for seasonal predictability.

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Data availability
All datasets used in this research were collected from open-access sources and digital libraries.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
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