



The variability of Antarctic fast ice extent related to tropical sea surface temperature anomalies

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Abstract. While numerous studies have examined the influence of meteorological variables on fast ice, the mechanistic linkages between fast-ice variability and large-scale climatic oscillations have remained inadequately explored. Empirical Orthogonal Function (EOF) analysis is applied to circumpolar Antarctic fast-ice extent data (March 2000-February 2018) to
15 investigate seasonal-scale teleconnections between fast ice anomalies and tropical sea surface temperature (SST) variability. Results demonstrate a fluctuating but increasing trend in fast-ice extent during austral winter and spring, with spatially predominant anomalies concentrated in the West Antarctic. A physical pathway linking tropical and subtropical SST anomalies to fast-ice variability is elucidated through multiscale interactions: SST anomalies modulate outgoing longwave radiation (OLR), subsequently perturbing the 200 hPa geopotential height field and triggering atmospheric Rossby wave trains. These
20 planetary waves propagate from the tropics towards the Antarctic coastal zone, generating anomalies in the Southern Annular Mode (SAM) and other patterns of mean-sea-level pressure (MSLP) and surface wind field. These atmospheric adjustments directly regulate fast-ice mechanical formation/disintegration processes while indirectly influencing thermodynamic ice evolution through air temperature modifications. Tropical SST anomalies predominantly exciting planetary waves during austral autumn, whereas the subtropical South Pacific SST dipole mode emerges as the primary forcing mechanism during
25 austral winter and spring. Seasonal variations in atmospheric forcing on fast ice are identified. By tracing how remote SST forcing propagates through atmospheric wave dynamics to influence regional fast-ice conditions, this study advances process-level understanding of tropical and subtropical impacts on the Antarctic.

Keywords: Antarctic, Fast-ice extent, Empirical Orthogonal Function (EOF), Sea surface temperature (SST), Atmospheric teleconnections



30 1 Introduction

Fast ice, defined as sea ice that remains immobilized along coastlines, ice shelves, or iceberg margins, is present throughout the coastal regions of Antarctica. It occurs for periods ranging from weeks to several decades. The maximum width of Antarctic fast-ice zone is approximately 200 km, covering an area of up to 600,000 km² (Fraser et al., 2021). Based on morphological characteristics and formation mechanisms, fast ice is categorized into two primary types: level fast ice and deformed fast ice.

35 Level fast ice, which dominates in areal extent in the Antarctic (Fedotov et al., 1998), forms in situ through thermodynamically driven processes and is typically thinner. In contrast, deformed fast ice results from the dynamic stacking of drifting ice under wind or wave forcing, being thicker and exhibiting greater stability than level fast ice (Inall et al., 2022). The relative proportion of these two types is governed by coastal geomorphology (Porter-Smith et al., 2021) and advective barriers such as glacier tongues and grounded icebergs (Fraser et al., 2012). On the basis of its persistence, fast ice is further divided into seasonal fast
 40 ice, which melts during austral spring or summer, and multi-year fast ice, predominantly occurring in embayments or associated with grounded icebergs (Fraser et al., 2021). The mechanical strength of multi-year fast ice significantly exceeds that of seasonal fast ice (Kharitonov & Borodkin, 2022).

Fast ice plays critical roles in the cryosphere and Earth system. First, it provides mechanical stabilization for vulnerable ice shelves and glacier tongues (Massom et al., 2018) and can respond rapidly to environmental forcing (Leonard et al., 2021).

45 Secondly, fast ice modulates the size of coastal polynya and dense water production (Fraser et al., 2019), which influences the formation rate of Antarctic Bottom Water (Ohshima et al., 2013). Second, fast ice serves as a seasonal reservoir of nutrients and its breakup and offshore advection potentially fertilize the ocean (Grotti et al., 2005). Third, fast ice also provides a substrate for early-stage primary production (Meiners et al., 2018), which fuels coastal marine food webs, and supports key ecosystem processes (Bluhm et al., 2017).

50 The formation of fast ice in austral autumn is influenced by oceanic factors including SST variability (Li et al., 2024), vertical oceanic heat flux (Maksym, 2019; Hu et al., 2023), and salinity (Brett et al., 2020). The primary mechanisms for fast ice shrink in late spring include break-out events (Squire, 2020), internal melt (Zhao et al., 2022), and tensile failure caused by wind and storm-driven waves (Crocker & Wadhams, 1989a; Voermans et al., 2021).

The atmospheric forcing factors also influence the variability of Antarctic fast ice across time scales ranging from microscale
 55 to synoptic, regional, seasonal, and interannual. Major atmospheric drivers include air temperature (Heil, 2006), wind speed and direction, storms and cyclones (Crocker & Wadhams, 1989a), and snowfall (Kawamura et al., 1997; Ushio, 2006). However, most research on atmospheric impacts has so far been conducted regionally. In Prydz Bay, Heil (2006) analyzed five decades (1950s–2003) of fast-ice records at Australia’s Davis Station and found that the duration of seasonal fast ice depends on winter and spring temperatures, while interannual variability is primarily controlled by wind and storms. Yu et al.
 60 (2017) and Liu et al. (2023) identified ice surface temperature as the primary determinant of seasonal fast ice near China’s Zhongshan Station. Zhao et al. (2019) demonstrated through measurements during 2012–2016 that local fast-ice thickness decreases with increasing snow accumulation. Zhai et al. (2019) reported that low air temperatures and wind speeds promote



fast-ice expansion in the vicinity of Inexpressible Island. In the Ross Sea, Leonard et al. (2021) observed that the extent and duration fast ice near the McMurdo station are influenced by seasonal storm intensity; winter storm intensity additionally affects the following summer's fast ice conditions. On the Antarctic Peninsula and the Weddell Sea, Massom et al. (2018) and Wille et al. (2022) demonstrated the importance of persistent warm northerly winds in triggering anomalous break-up of fast ice near ice shelves, where wind-driven pack ice movement facilitates wave-induced fracturing. Herman et al. (2021) emphasized the role of ocean wave action in fast ice fragmentation near ice shelves. Arndt et al. (2020) identified snow accumulation as a major factor controlling fast ice formation in Atka Bay of the Weddell Sea, with strong easterly winds redistributing snow on fast ice and contributing to its summer break-up.

In addition to synoptic-scale processes, numerous studies have examined the roles of large-scale atmospheric and oceanic forcing factors on the formation and decay of regional fast ice. Extensive research has noted linkages between total Antarctic sea ice and large-scale climate modes (Clem & Fogt, 2013; Coggins & McDonald, 2015; Meehl et al., 2016; Baba & Renwick, 2017; Clem et al., 2017; Chung et al., 2022; Yu et al., 2022), while less studies have assessed their relationships in process level. Using ice records from the South Orkney Islands, Murphy et al. (2014) identified the non-stationary relationship between Weddell Sea fast-ice extent and climate modes, such as the El Nino - Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). Aoki (2017) observed a significant positive correlation between the latitude of fast-ice edges in Lützow-Holm Bay, East Antarctica and eastern equatorial Pacific SST during 1997–2016. However, their studies only focused on a specific region, not the entire Antarctic fast-ice zone. In this study we employ Empirical Orthogonal Function (EOF) analysis to obtain the main modes of Antarctic fast ice variability and analyze SST and atmospheric variables related to the modes to build the relationship between seasonal Antarctic fast ice and climate modes (tropical Pacific SST) for the 2000–2018 period.

2 Data and methods

The monthly Antarctic fast ice dataset was derived from the Antarctic sea ice distribution data publicly released by Fraser (2022) in the Australian Antarctic Data Centre website. This dataset classifies sea ice in National Aeronautics and Space Administration Moderate Resolution Imaging Spectroradiometer (NASA MODIS) imagery, covering an 18-year period from March 2000 to February 2018, with a spatial resolution of 1 km and a temporal resolution of 15 days. This dataset was utilized to extract the monthly boundaries of fast ice. The latitude of the fast-ice edge at each longitude (1 degree resolution) was identified by determining the boundary between fast ice and drifting ice or open ocean. The latitudinal difference between the fast ice outer boundary and the corresponding Antarctic continental coastline was calculated to generate a time series of fast ice edge anomalies across all longitudes around Antarctica.

Oceanic and atmospheric datasets were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation reanalysis (ERA5) (Hersbach et al., 2020), which has a spatial resolution of $0.25^\circ \times 0.25^\circ$. Due to its high resolution and advanced data-assimilation system, ERA5 performs well with respect to variables that are of key importance in

our study: upper-tropospheric geopotential height fields in the tropics (Hoffmann and Spang, 2022) and MSLP and wind fields
 95 in the Southern Ocean (McErlich et al., 2023).

Monthly averaged sea surface temperature (SST), MSLP, 2-m air temperature, 10-m wind fields, and 200-hPa geopotential
 height fields from ERA5 were employed. In addition, we used the monthly top-of-the-atmosphere (TOA) outgoing longwave
 radiation (OLR) data provided by the National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA
 CPC) (Xie et al., 2023). These oceanic and atmospheric datasets were used to investigate the relationship between fast ice
 100 variability and atmospheric circulation anomalies.

The four austral seasons here refer to spring: September, October and November (SON); summer: December, January and
 February (DJF); autumn: March, April and May (MAM); winter: June, July and August (JJA). Seasonal anomalies were
 obtained by subtracting the climatological seasonal cycle from each time series. To visualize the spatiotemporal variations in
 fast ice offshore distance, Empirical Orthogonal Function (EOF) analysis was performed on the processed data. This method
 105 decomposes the variability of fast ice anomalies into spatial patterns (EOFs) and their associated temporal coefficients, called
 as Principal Components (PCs). The EOFs and PCs are mutually orthogonal, with the variance contribution of each mode
 indicating the percentage of total variance explained by the mode. The contribution of the mode to the total trend for each
 season is calculated by the product of the trend in the PCs of the mode and the EOFs of the mode.

Regression analysis was employed to establish relationships between meteorological variables and fast ice variability.
 110 Regression coefficients were calculated by regressing the time series of each meteorological variable at every spatial grid point
 onto the standardized PCs of fast ice variability. A two-tailed Student's t-test is used to assess the confidence level of all
 regression results..

3 Results

EOF analysis of seasonal Antarctic fast-ice extent anomalies from 2000 to 2017 revealed distinct seasonal differences. The
 115 variance contributions of every EOF mode for each season are shown as Table 1. The first mode accounted for a substantial
 proportion of the total variance, with the largest percentage of 41% in austral winter and the smallest of 31% in austral summer.
 The percentage of variance explained by the second mode ranges from 13% in austral autumn to 22% in summer.

Table 1: Variance contributions (%) of each mode from the EOF of fast ice extent anomalies in each season.

	Mode1	Mode2	Mode3	Mode4
MAM	36.58%	13.43%	11.07%	8.45%
JJA	36.06%	20.61%	12.66%	7.85%
SON	41.28%	18.03%	10.09%	9.57%
DJF	31.36%	21.77%	12.21%	6.75%



120 3.1 EOF analysis of seasonal Antarctic fast-ice extent anomalies

As shown in the left panels of Figure 1, the PC1 over the 18-year period revealed distinct seasonal differences. Austral winter and spring exhibited a gradual increasing trend in fast-ice extent superimposed on interannual fluctuations, whereas austral summer and autumn exhibited a gradual decreasing trend and interannual and decadal variability with maximum positive anomalies in 2007 (summer) and 2009 (autumn).

125 The EOF1 (Figure 1, right panel) highlights pronounced fast ice anomalies in West Antarctica, particularly in the Ross Sea, the Bellingshausen Sea, the Weddell Sea, and regions surrounding the Antarctic Peninsula. These areas are characterized by complex coastlines and offshore islands, which promote the formation of extensive fast ice at greater distances from the coast. Variations in island-associated fast ice strongly influence fast ice edge anomalies. In contrast, East Antarctica, with its smoother coastline along the Indian Ocean sector, exhibited smaller anomalies, except for localized variability near Prydz Bay.

130 In austral autumn (MAM), significant positive fast ice anomalies were observed at the Ross Sea (170°E–150°W) and west of the Weddell Sea (45°W–60°W), while negative anomalies dominated the Bellingshausen Sea and the middle Atlantic sector (0°–30°W). The Indian Ocean sector displayed a west-positive, east-negative anomaly pattern, with pronounced negative anomalies near Prydz Bay (60°E–90°E). During austral winter (JJA), the midwest of Ross Sea (170°E–170°W) exhibited negative anomalies, whereas the western Weddell Sea (45°W–60°W) showed strong positive anomalies. The Bellingshausen

135 Sea remained anomalously low, while the middle of southern Atlantic sector (0°–30°W) displayed slight positive anomalies. The Indian Ocean sector was predominantly positive, with localized reductions. During austral spring (SON), the western Ross Sea (160°E–180°) featured negative anomalies, contrasting with positive anomalies in the eastern Ross Sea (150°W–180°). The Bellingshausen Sea and Antarctic Peninsula regions experienced large-amplitude variability, with overall positive anomalies. The Weddell Sea exhibited significant negative anomalies, while the Atlantic sector (0°–30°E) showed slight

140 increases. In austral summer, the Ross Sea displayed overall negative anomalies with high variability. The Amundsen Sea showed slight positive anomalies, whereas the Bellingshausen Sea remained anomalously low. The Weddell Sea and Atlantic sector exhibited positive anomalies, while Prydz Bay experienced reductions.

Figure 2 shows the results of second mode of seasonal Antarctic fast ice variability. The left panel illustrates the PC2 over 18 years (2000–2017). The time series for all four seasons exhibited an noticeably interannual fluctuations, but their trends are

145 not significant. Spatially, the eastern Antarctic Peninsula experienced significantly reduced fast ice across all seasons, while the western Antarctic Peninsula showed marked increases in autumn and spring. In the Ross Sea region of the Pacific sector, fast ice anomalies were pronouncedly positive in austral autumn and winter. During austral spring (SON), a west-to-east dipole pattern emerged (low in the west, high in the east), reversing to an east-to-west dipole in summer. The Amundsen Sea exhibited slight reductions in autumn but modest increases in other seasons. The Bellingshausen Sea displayed positive anomalies year-

150 round. In the Indian Ocean sector, anomalies were predominantly positive in winter, spring, and summer, with large variability observed in autumn.

Figure 3 presents the contributions of the first two modes to the total linear trends for each season. PC1 demonstrated marginally better agreement with the linear trend compared to PC2. Seasonally, the austral spring exhibited poorer trend fitting, while the other three seasons showed robust correlations. Spatially, both modes displayed superior fitting performance over East Antarctica relative to West Antarctica.

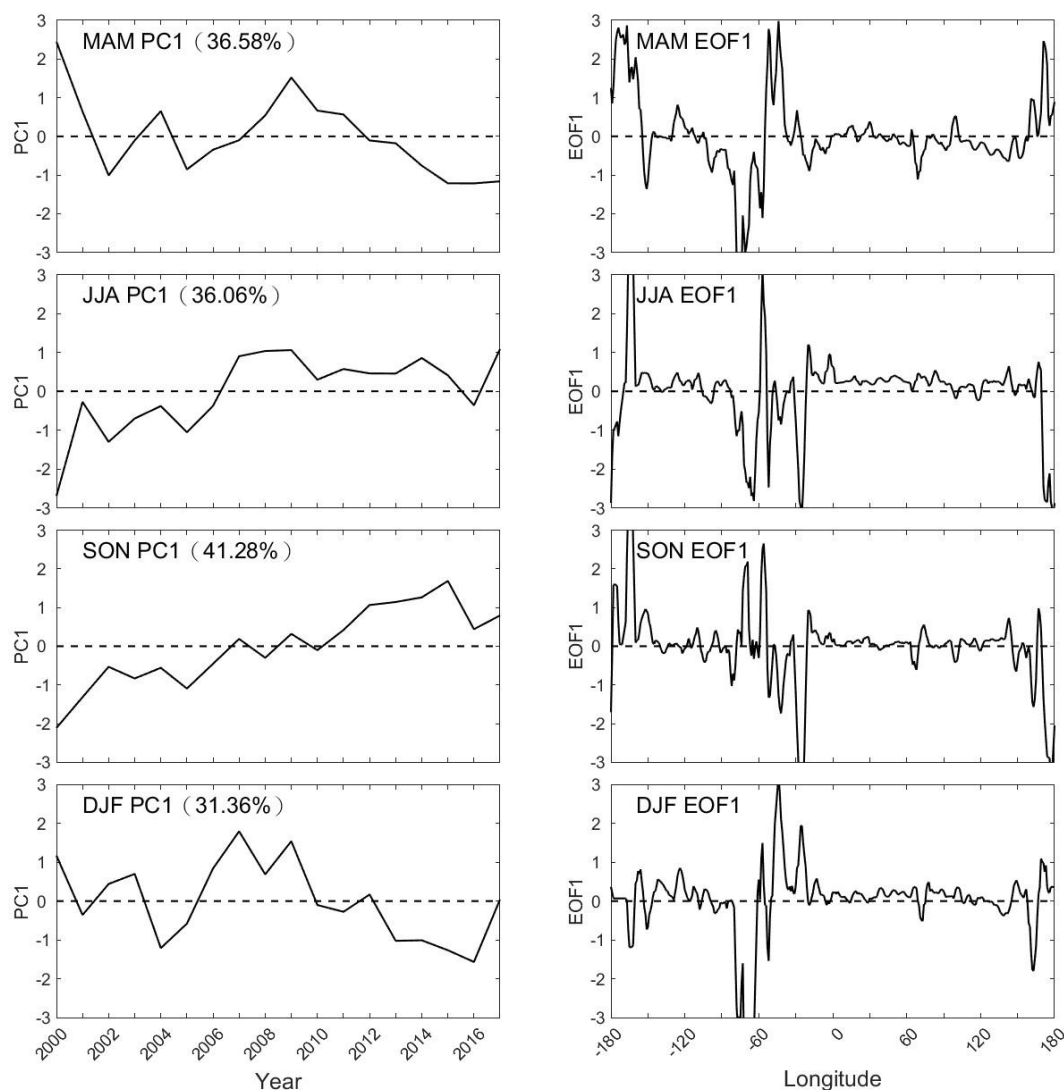
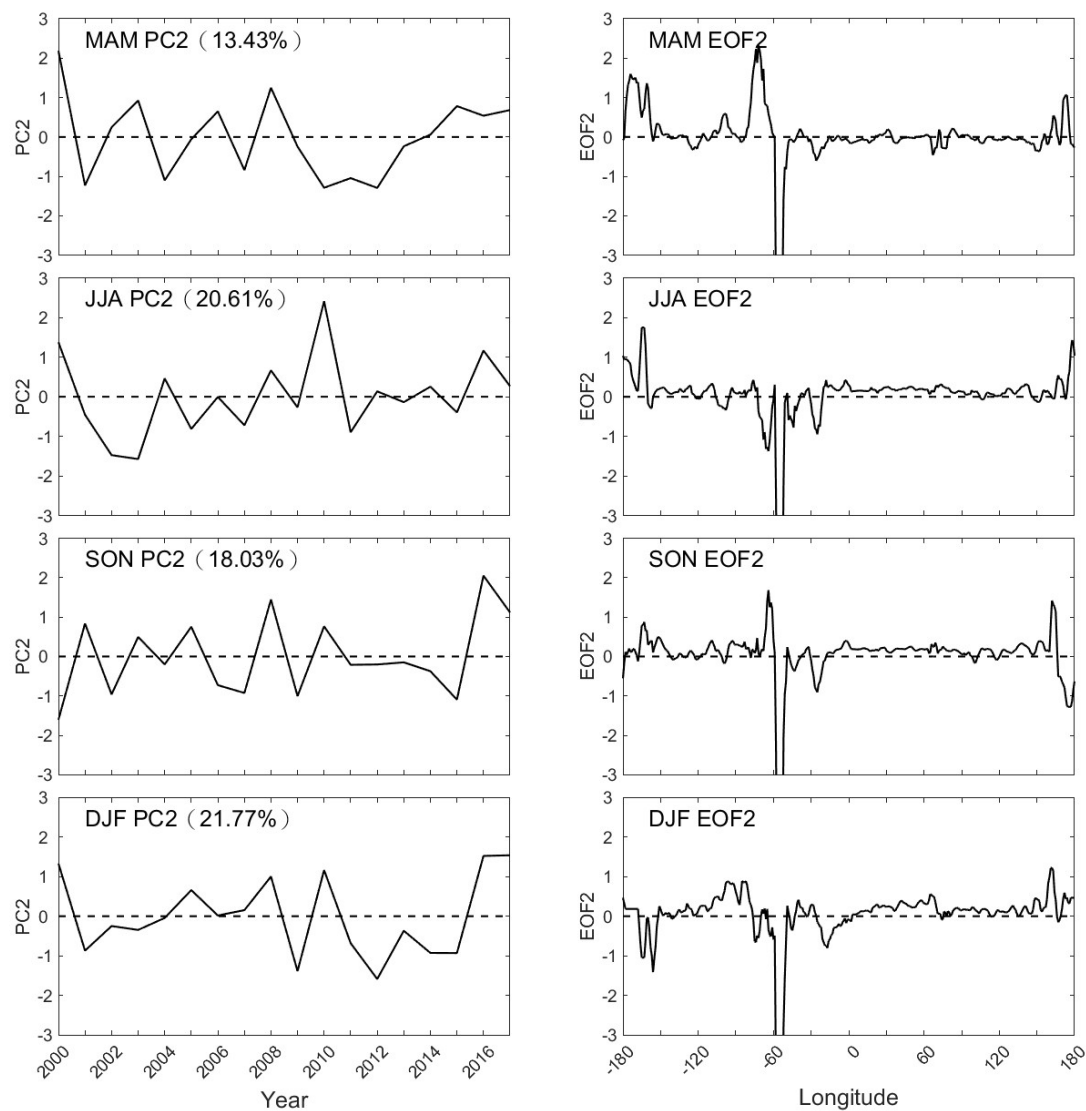


Figure 1: The PC1s and EOF1s of first EOF mode of Antarctic fast ice extent anomalies (2000–2018) for each season: temporal principal component (PC1, left) and spatial pattern (EOF1, right). Numbers in parentheses indicate the percentage of the variance explained by each mode.



160 **Figure 2: The same as figure 1 but for the second EOF mode.**

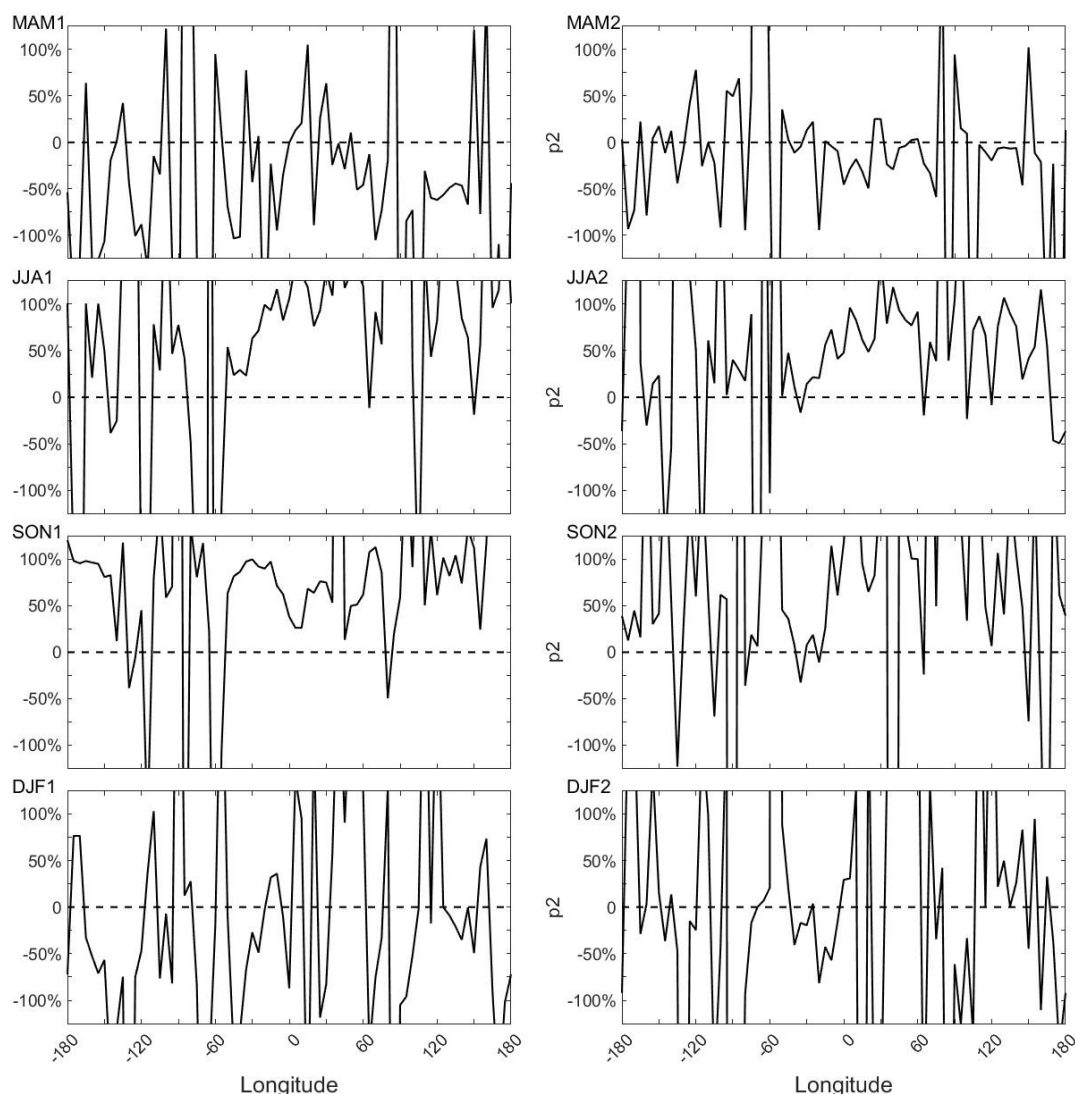


Figure 3: Longitudinal distribution of the ratio of trend explained by the mode to the total trend in Antarctic fast ice. Left: the ratio of the first mode to the total trend. Right: the ratio of the second mode to the total trend.

3.2 Multiscale analysis of fast-ice anomalies in each seasons

165 To explain the spatial patterns of the first modes, we make the regression of oceanic and meteorological variables (SST, air temperature, MSLP, and wind fields) onto the PC1s.

During austral autumn, the regression coefficient map for SST (Figure 4a) reveals significant positive anomalies in the tropical western Pacific and negative anomalies in the central-eastern Pacific, the values in center of anomalies area are 0.4°C and -0.6°C, respectively, resembling the SST pattern associated with La Niña events. These SST anomalies enhance convective activity in the western Pacific, resulting in high, cold cloud tops, manifested as negative TOA OLR anomalies. The anomalies

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in this area are almost as low as -8 Wm^{-2} (Figure 5a), and establish atmospheric teleconnections. Concurrently, negative SST anomalies in the central-eastern Pacific and tropical Indian Ocean correspond to positive OLR anomalies. A mid-latitude SST dipole in the central Pacific (positive anomalies south and north of the equatorial negative region) induces negative OLR anomalies. They are indicative of enhanced convective activity, which results in an increase in high-level clouds with cold tops and divergence in the upper troposphere, then generate strong positive 200 hPa geopotential height anomaly (the maximum values are higher than 20gpm) southeast of Australia (Figure 6a). This anomaly propagates eastward as an atmospheric wave train, amplifying the Amundsen Sea Low (ASL) through a trough over the southeastern Pacific, the negative pressure anomalies in the centre of ASL is lower than -2 hPa (Figure 7c). The intensified ASL creates asymmetric pressure patterns over Antarctica, with lower pressures in West Antarctica and higher pressures in the Atlantic sector. Wind fields (Figure 7d) exhibit a strong clockwise circulation around the ASL, driving northerly winds along the western Antarctic Peninsula. These northerly winds promote onshore ice stacking (dynamic effect) but also elevate temperatures (thermal effect), leading to ice melt. In the Amundsen Sea, easterly winds may favour fast-ice formation farther west, resulting in a west-positive, east-negative distribution. Over the southeastern Indian Ocean, negative SST and air temperature anomalies dominate, inversely correlating with fast ice variability (Figure 7b). Thus, autumn fast ice anomalies are driven by atmospheric wave-induced circulation changes in the Pacific and Atlantic sectors, while thermal factors prevail in the Indian Ocean sector.

During austral winter, SST regression coefficients (Figure 4b) show an insignificant tropical signal but a significant mid-latitude dipole off eastern Australia, with southwest-negative and northeast-positive anomalies, the values in center of anomalies area are 0.4°C and -0.4°C . Corresponding OLR anomalies (Figure 5b) display a southwest-positive and northeast-negative pattern, alongside a negative OLR anomaly over the Drake Passage. The 200 hPa geopotential height field (Figure 6b) exhibits a wave train propagating eastward from the southern Indian Ocean to the South Atlantic, alternating between positive and negative anomalies. This wave train influences MSLP, generating high-pressure anomalies over the southeastern Indian Ocean (higher than 1 hPa) and southeastern Atlantic (higher than 1 hPa), and low-pressure anomalies over the southeastern Pacific (lower than -1 hPa) and Drake Passage (Figure 8c). The eastward-shifted ASL induces strong northeasterly winds along the Antarctic Peninsula (Figure 8d), causing onshore ice accumulation along the eastern coast and offshore ice dispersal along the western coast of the peninsula. In East Antarctica, southerly winds associated with a high-pressure system over the southeastern Indian Ocean enhance cooling, promoting fast ice growth. Convergent winds near Prydz Bay facilitate ice formation, while divergent winds at 110°E lead to ice fragmentation. Air temperature regressions (Figure 8a, b) indicate an inverse relationship with fast ice anomalies, underscoring the dominance of thermodynamic processes in winter.

During the austral spring (SON), the regression coefficient distribution of SST in Figure 4c reveals a reversed pattern in tropical SST compared to autumn and winter, with significant negative anomalies in the eastern Indian Ocean and western Pacific and positive regression coefficients in the eastern Pacific. The magnitudes of anomalies reach approximately 0.3°C , being smaller than in autumn and winter. The corresponding OLR (Figure 5c) exhibits significant positive anomalies (8 Wm^{-2}) over the eastern Indian Ocean and western Pacific and negative anomalies (-8 Wm^{-2}) over the eastern Pacific. The anomalies of OLR are more significant than winter. This reversed tropical SST distribution maintains the SST dipole in the mid-latitude Pacific



205 during austral spring, though its position shifts southward to 50°S, with its orientation changing from a wintertime positive southwest-northeast gradient to a springtime positive west-east gradient (Figure 4c). The anomalous geopotential height distribution at 200 hPa (Figure 6c) shows that both high and low geopotential height centers shift southward to the margins of the Antarctic continent and the Southern Ocean. Negative anomalies dominate from the eastern Indian Ocean to the western Pacific, while positive anomalies prevail over the eastern Pacific and Drake Passage, and negative anomalies re-emerge over
 210 the Atlantic. The magnitudes of both positive and negative geopotential height anomalies exceed 20 gpm, and the spatial coverage of large anomalies expands compared to autumn and winter.

The upper-level anomalies influence MSLP, with the MSLP distribution in Figure 9c characterized by a high-pressure anomaly over most of the Antarctic continent and large parts of the Southern Ocean, exceeding 1 hPa over most of East Antarctica and western Amundsen Sea. Low-pressure anomalies occur over the Antarctic Peninsula and surrounding seas, as well as over the
 215 western Pacific sector. The negative anomalies of MSLP have smaller magnitudes than the positive anomalies. The pressure anomalies drive wind anomalies (Figure 9d), with strong southerly wind anomalies over the Bellingshausen Sea and around the Antarctic Peninsula. These result in lower temperatures, promoting fast-ice expansion. In contrast, the Amundsen Sea lies between two low-pressure centers under a high-pressure ridge, where divergent winds induce fast ice fracturing. However, lower temperatures in this region simultaneously favor fast ice retention, leading to a large variability in fast ice coverage.
 220 Over the Weddell Sea, northerly wind anomalies dominate, inhibiting fast ice preservation and resulting in reduced coverage. In the Atlantic and western Indian Ocean, zonal easterly winds prevail, causing fast ice variability to depend heavily on topography and wind convergence/divergence.

The Prydz Bay (70°E) experiences northerly winds and elevated temperatures, leading to reduced fast ice coverage. Near 110°E in the eastern Indian Ocean sector of the Southern Ocean, wind divergence promotes fast ice fracturing and reduction,
 225 while wind convergence near 150°E enhances fast ice accumulation. Notably, a comparison between fast ice and temperature anomalies (Figures 9a and 9b) indicates a weaker correlation in spring than in winter, with opposing temperature-fast ice relationships occurring in the eastern Ross Sea, Amundsen Sea, Bellingshausen Sea, and parts of the eastern Indian Ocean sector of the Southern Ocean. This suggests that dynamic factors, rather than thermal conditions, dominate fast ice variability during the spring breakup season.

230 During the austral summer, the SST regression coefficients in Figure 4d show overall negative values (about -0.2°C) across the tropical Pacific, with pronounced negative anomalies in the western Pacific, weak positive anomalies (less than 0.2°C) in the Indian Ocean, and negligible coefficients in the Atlantic. The OLR (Figure 5d) displays positive anomalies near New Guinea and significant negative anomalies (lower than -8 Wm⁻²) in the south of Australia and east of the Australian coast. The mid-latitude eastern Pacific exhibits strong positive OLR anomalies (4 Wm⁻²). These zonal variations in OLR anomalies
 235 generate spatially varying 200-hPa geopotential height anomalies (Figure 6d), with alternating positive and negative anomaly centers aligned along 60°S, forming a circumpolar atmospheric wave train. Correspondingly, the Southern Ocean MSLP (Figure 10c) adopts a tripole structure: high-pressure centers over the South Atlantic, central Indian Ocean, and Ross Sea, and low-pressure centers over the Bellingshausen Sea, eastern Indian Ocean, and western Indian Ocean. The wind field (Figure



10d) aligns with the pressure anomalies, with easterly winds on both sides of the Antarctic Peninsula driving onshore winds
240 in the eastern side and offshore winds in the western side, resulting in a higher fast-ice coverage east of the Peninsula and a
lower one west of it. Strong southerlies over the Amundsen Sea lower temperatures, locally increasing the fast-ice cover. In
the Ross Sea, northerly winds elevate temperatures, but wind convergence introduces variability in fast ice (Heil, 2006). Over
the Weddell Sea, southerly winds enhance fast ice accumulation. The Atlantic sector, situated between high and low-pressure
anomalies, experiences southerly winds with localized convergence/divergence, leading to substantial fast ice fluctuations.
245 Temperature regression coefficients (Figures 10a and 10b) reveal that the correlation between fast ice and temperature is
stronger in summer than in spring. Inverse relationships between temperature and fast ice occur in the Amundsen Sea,
Bellingshausen Sea, eastern Weddell Sea, and eastern Indian Ocean sector.

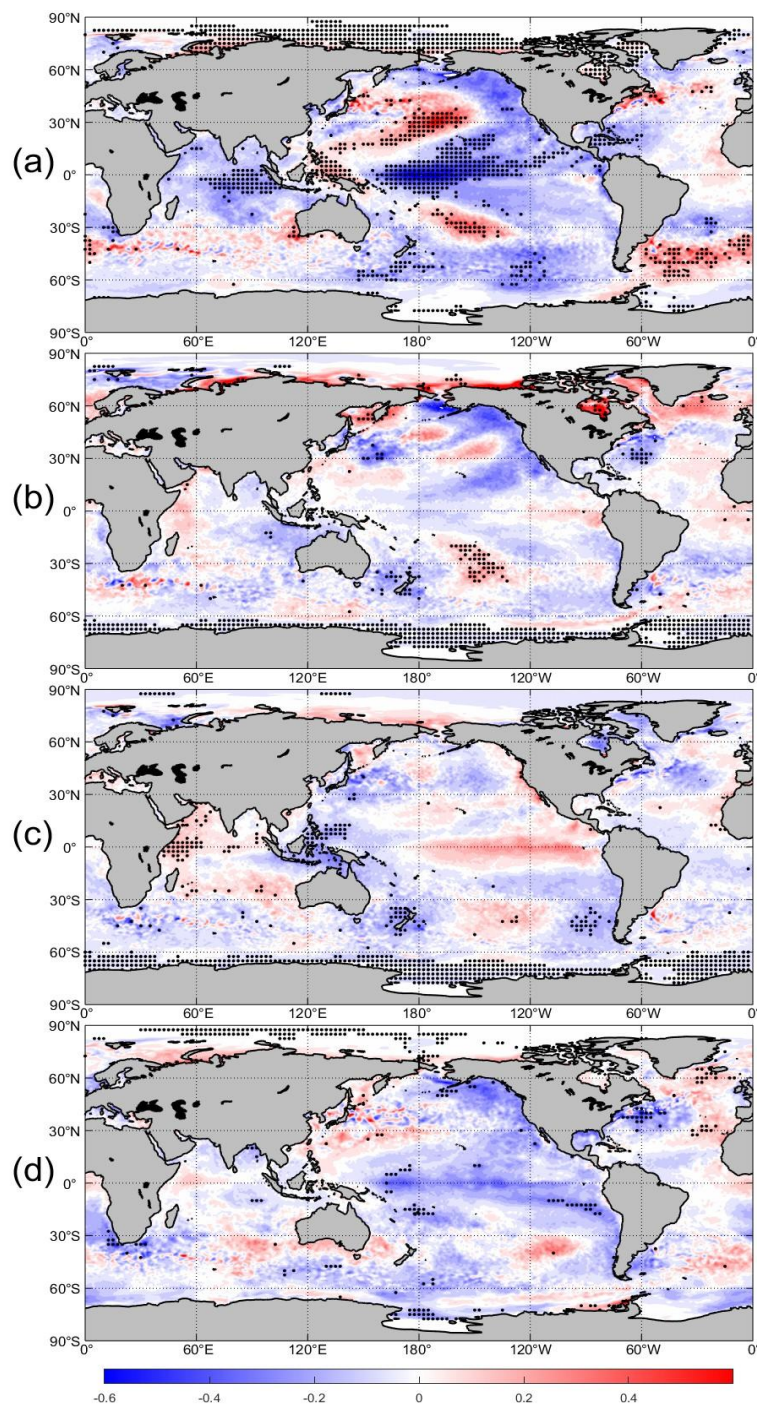


Figure 4: Regression of SST (in °C) onto the PC1: (a) austral autumn (MAM), (b) austral winter (JJA), (c) austral spring (SON), and (d) austral summer (DJF). Regions with black dots indicate areas passing the 95% confidence level.

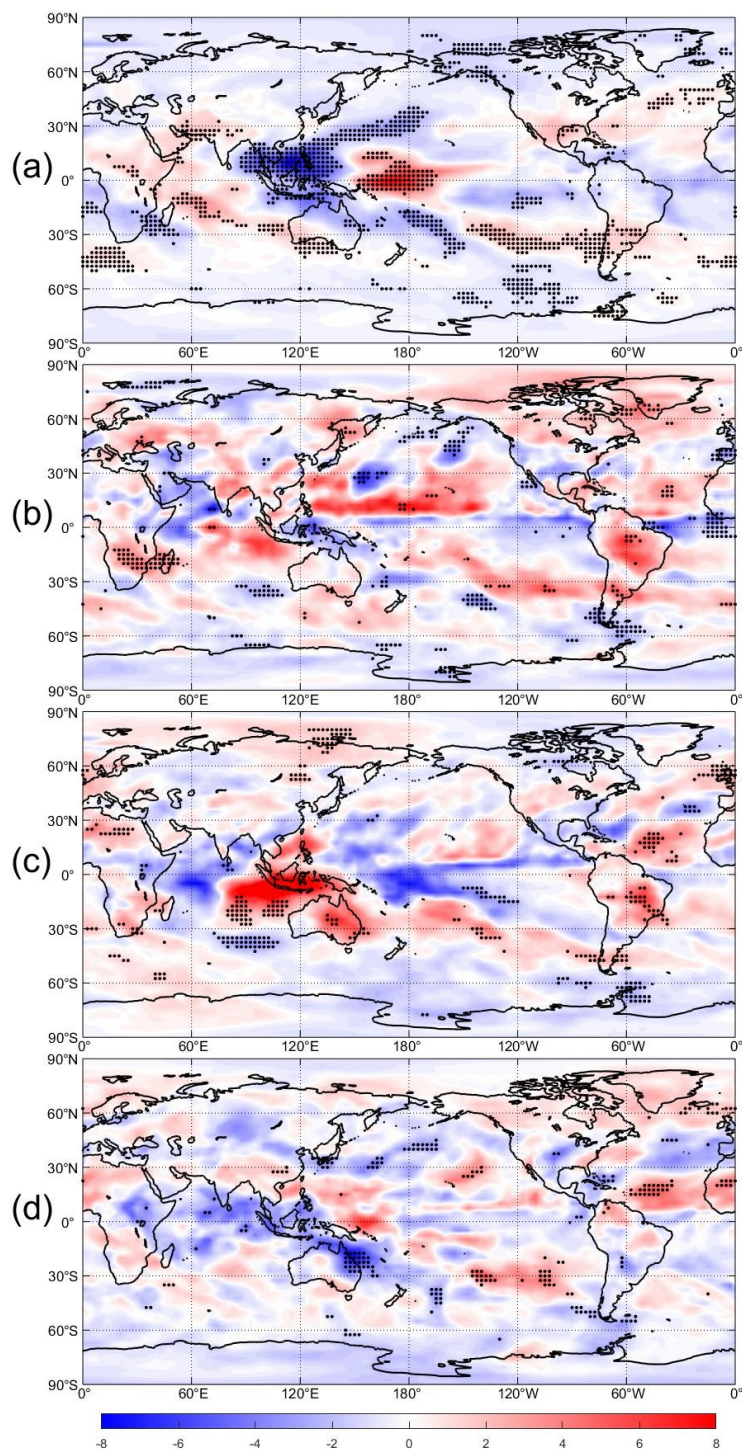


Figure 5: Regression of OLR (in W m^{-2}) onto the PC1: (a) austral autumn (MAM), (b) austral winter (JJA), (c) austral spring (SON), and (d) austral summer (DJF). Regions with black dots indicate areas passing the 95% confidence level.

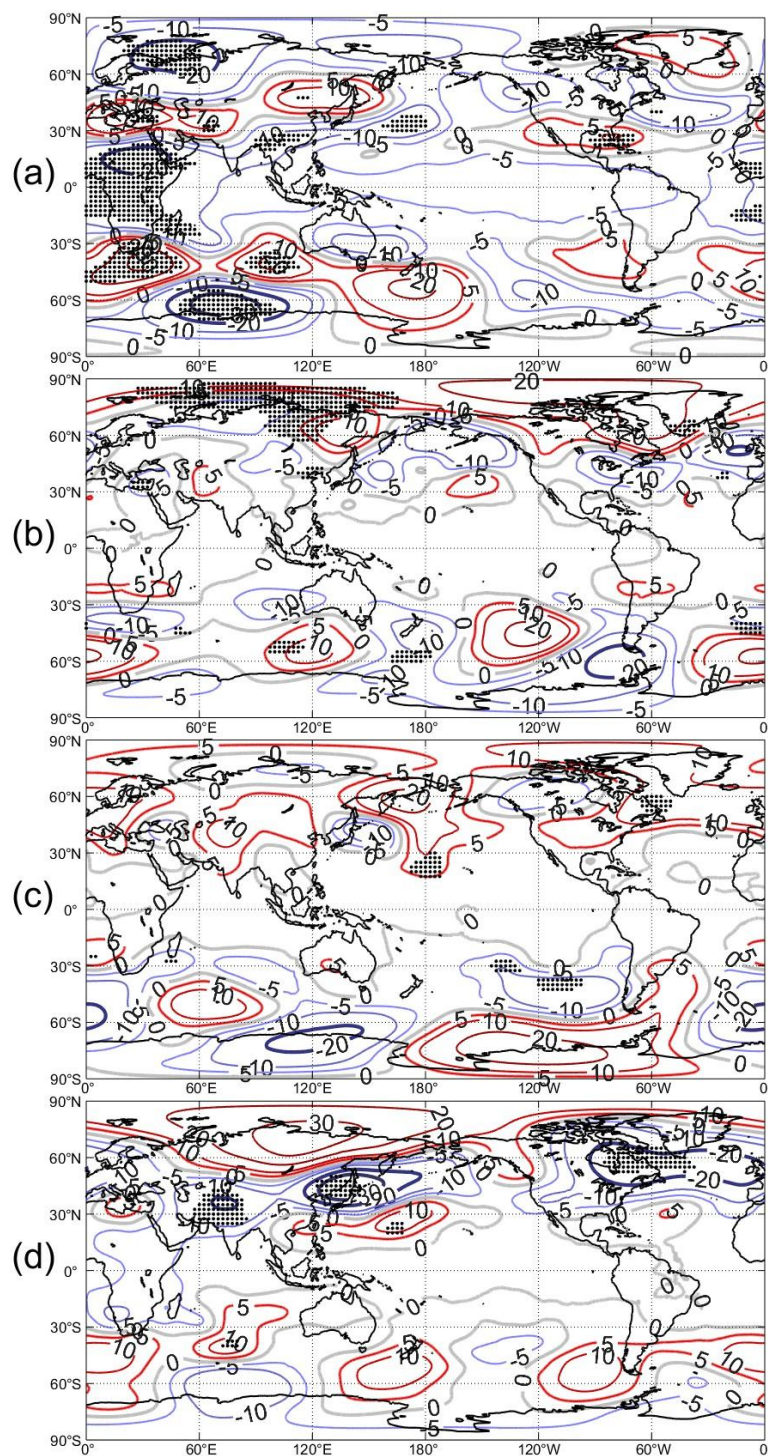


Figure 6: Regression of 200 hPa geopotential height (in gpm) onto the PC1: (a) austral autumn (MAM), (b) austral winter (JJA), (c) austral spring (SON), and (d) austral summer (DJF). Regions with black dots indicate areas above 95% confidence level.

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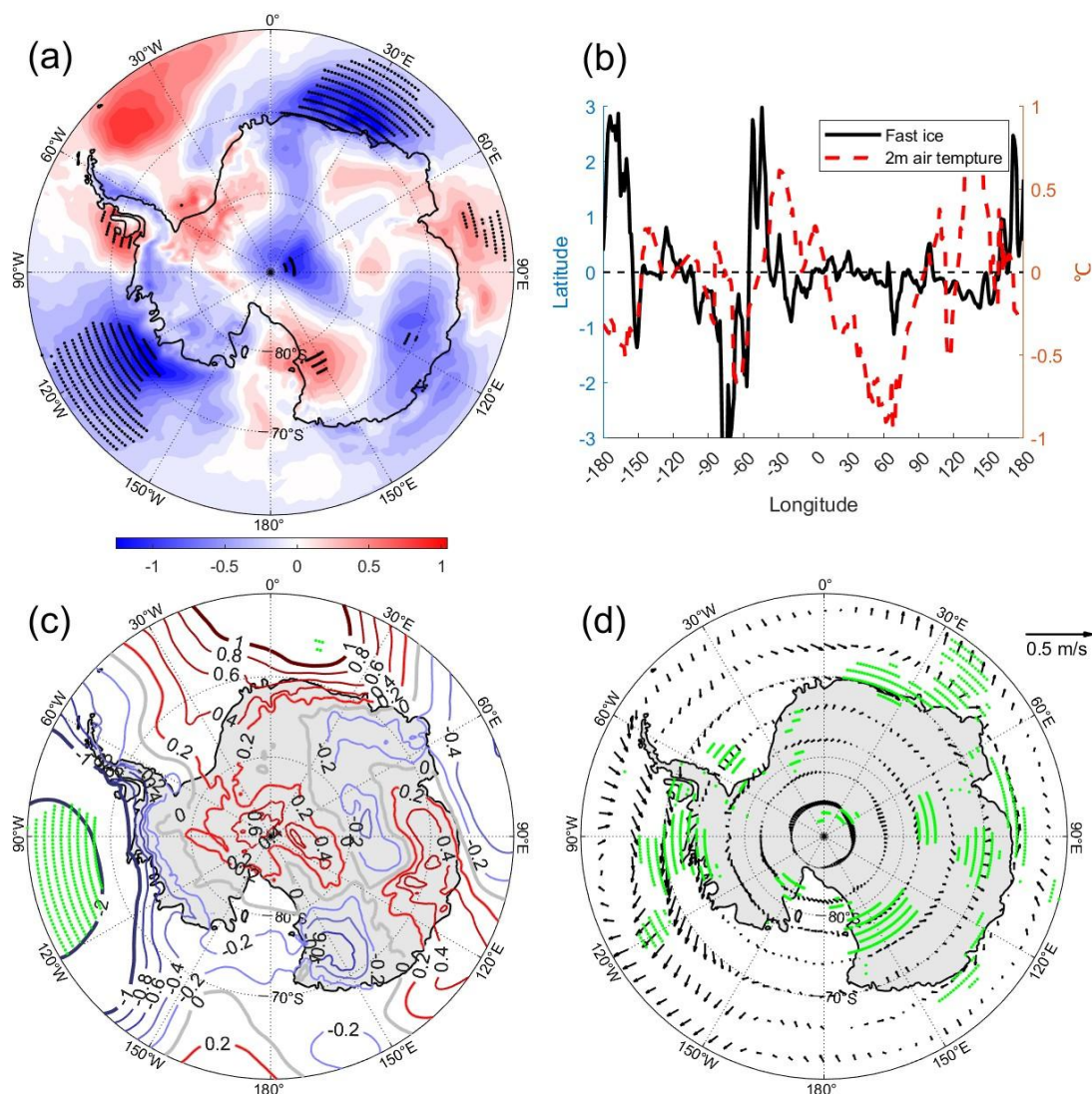
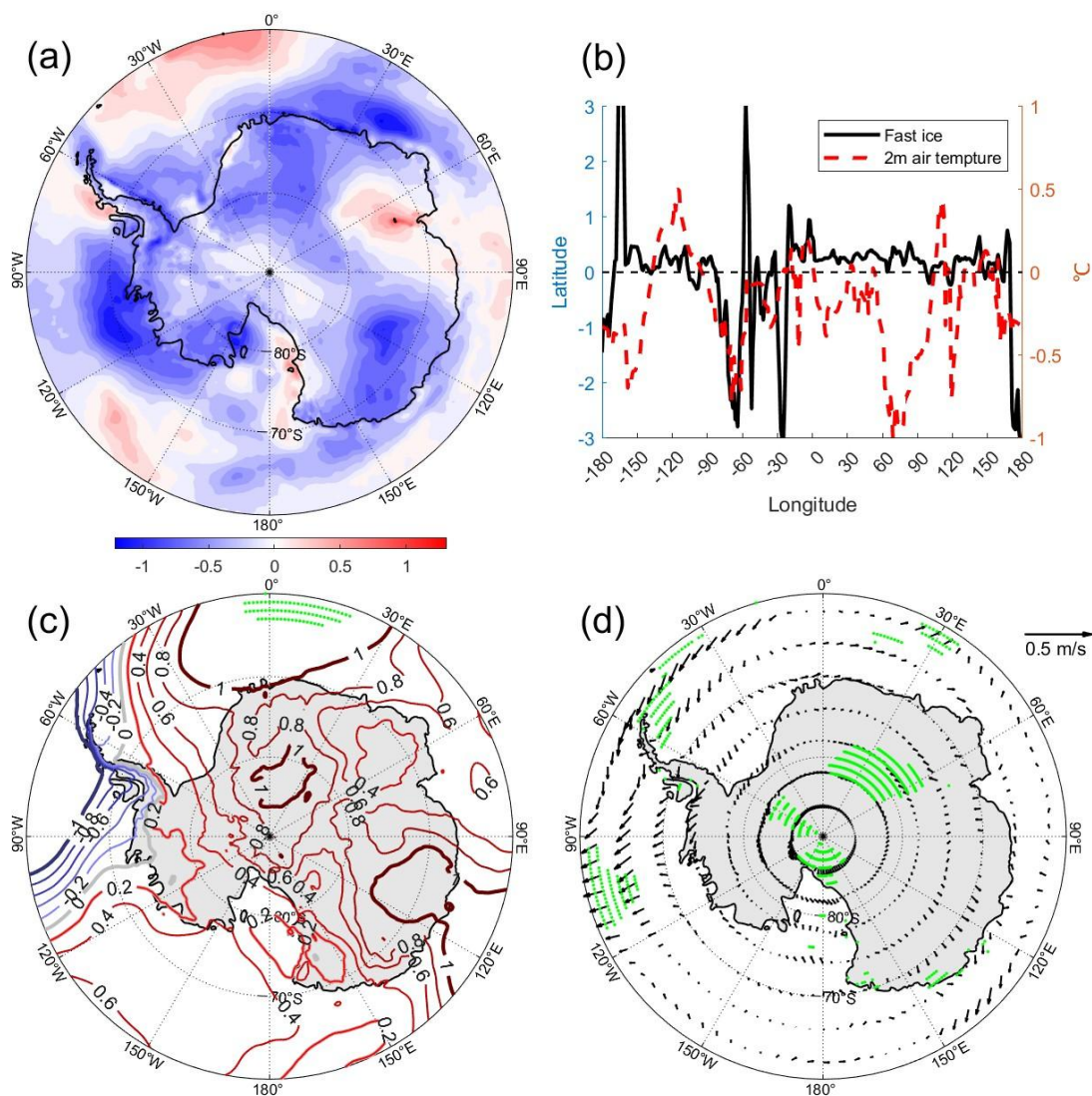


Figure 7: Regression of atmospheric variables onto the PC1 during austral autumn (MAM) (a) 2-m air temperature (in °C), (b) 2-m air temperature (dashed) in fast ice region and fast ice coverage (solid), (c) MSLP (in hPa), (d) 10-m wind field. Green and black dots indicate above 95% confidence level.



260 **Figure 8. The same as Figure 7, but for austral winter (JJA).**

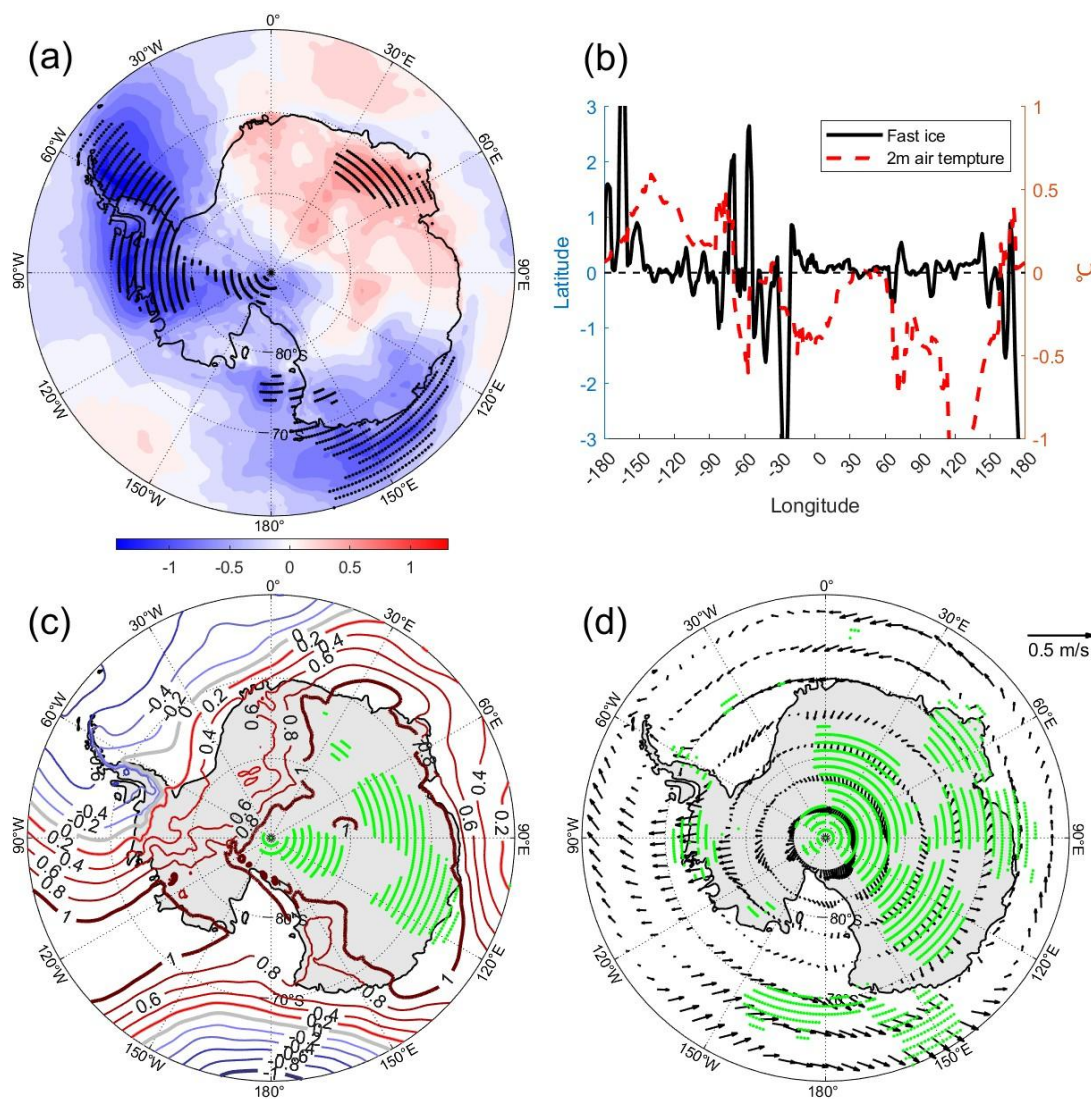


Figure 9. The same as Figure 7, but for austral spring (SON).

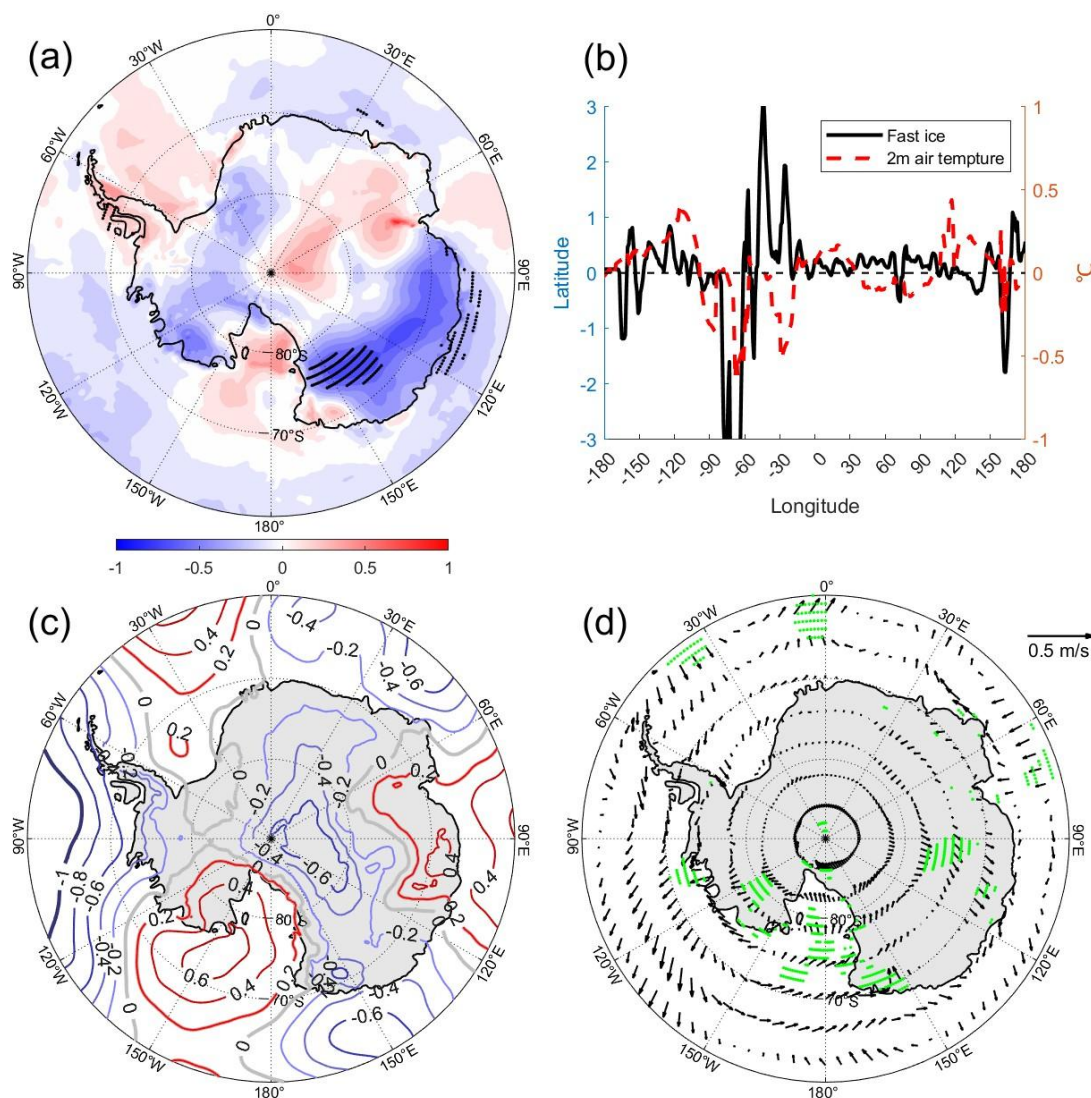


Figure 10. The same as Figure 7, but for austral summer (DJF).



4 Discussion and Conclusions

In this study, we employed EOF analysis method to examine the main modes of the variation of seasonal Antarctic fast ice extent for the 2000-2018 period. These main modes show distinct temporal and spatial variability depending on seasons. Temporally, the PC1s exhibit a gradually increasing trend with fluctuations during the austral winter and austral spring. In contrast, during the austral summer and austral autumn, the PCs show a interannual and decadal variability. Spatially, the anomalies in fast ice extent are more pronounced in West Antarctica, particularly in the Ross Sea, the Antarctic Peninsula, the Bellingshausen and Weddell Seas. This finding is consistent with the changes in the width of fast ice zone (Li et al. 2020). This spatial variability is attributed to the complex, the complex coastline of West Antarctica and the presence of numerous peripheral islands, where changes in island-associated fast ice significantly contribute to regional anomalies. Li et al. (2020) also suggests that icebergs play a critical role in the formation and maintenance of fast ice along this coastline. In contrast, the Indian Ocean sector of East Antarctica, characterized by a smoother coastline, exhibits relatively minor variations.

The analysis further elucidates the physical mechanisms by which remote SST anomalies influence Antarctic fast ice. During austral autumn, tropical SST anomalies trigger convective activity, leading to upper-level outgoing longwave radiation OLR anomalies. These anomalies excite planetary-scale atmospheric waves, manifested as alternating positive and negative geopotential height anomalies at 200 hPa. As these waves propagate poleward, they perturb near-coastal MSLP and wind fields due to barotropic structure, which directly modulate fast-ice formation or disintegration. Southerly winds, onshore zonal winds, and wind convergence in both direction and speed contribute to the expansion of fast ice extent, whereas northerly winds, offshore zonal winds, and wind divergence lead to reductions in fast ice coverage. Rapid, large-scale reductions in Antarctic fast-ice cover are typically triggered when offshore winds (often in combination with ocean swell and thermodynamic weakening) fracture or detach the ice, leading to its disintegration and opening of coastal polynyas. Additionally, wind anomalies indirectly affect fast ice by altering air temperatures, thereby influencing thermodynamic processes. During austral winter and spring, the dominant driver shifts to the subtropical SST dipole mode in the Southern Hemisphere. This dipole pattern similarly influences Antarctic fast ice through the aforementioned chain of processes, though its spatial configuration shifts southward during spring. In austral summer, the weakening of the SST dipole reduces the wavelength of atmospheric planetary waves, altering wind speed and direction patterns around Antarctica and resulting in distinct seasonal differences in fast ice variability compared to preceding seasons.

Aoki (2017) established a correlation between the latitude of fast ice edges and sea surface temperatures (SST) in the eastern equatorial Pacific, further describing a teleconnection mechanism whereby anomalously warm SSTs in the tropical eastern Pacific during austral summer trigger Rossby waves that propagate toward East Antarctica's Queen Maud Land. Separately, Murphy et al. (2014) demonstrated linkages between Weddell Sea fast ice extent and climate modes (ENSO/SAM), noting that fast ice break-up is modulated by SAM-associated westerly/northwesterly winds. Our results align with their studies, extending previous studies into the entire Antarctic fast-ice zone.



Our study also reveals seasonal differences in the dominant factors controlling fast ice. During austral autumn and winter, thermodynamic processes, particularly air temperature, predominantly govern ice extent across most regions. Higher
300 temperatures are associated with less fast ice, while lower temperatures promote its expansion. However, in austral spring and summer, when formation of new fast ice is limited, the correlation between air temperature and ice extent weakens, with over half of the regions showing no inverse relationship. Instead, wind direction and speed emerge as the primary dynamical drivers, explaining most of the variability in fast-ice extent. This suggests that dynamic forcing (e.g., wind-driven ice advection, compaction, and disintegration) dominates fast-ice anomalies during these seasons. Wei & Qin (2016) and Voermans et al.
305 (2021) similarly concluded that during the austral spring, strong onshore winds and gale-driven ocean waves erode coastal fast ice margins.

Although we focused on the novel aspect of remote forcing of tropical and subtropical SSTs on Antarctic fast ice, we recognize that the direct oceanic forcing is local and includes both dynamic and thermodynamic factors. The former are related to currents, tidal effects, and swell (Inall et al. (2022), while basal melt is the primary thermodynamic factor (Kusahara et al., 2021).
310 The 18-year study period (2000–2018) was insufficient to capture the interdecadal-scale oscillations that may influence Antarctic fast ice dynamics. Long-term observations are required to disentangle these complex interactions between tropical SST anomalies and Antarctic fast ice and validate the proposed mechanisms. The impacts of global warming on Antarctic fast-ice extent should also be investigated in future studies. Further, to achieve more robust process-level attribution of the statistical results obtained, coupled climate model experiments with prescribed tropical SST anomalies are needed. Process-level
315 understanding of the interannual and decadal variability of Antarctic fast-ice extent across seasons enhances our knowledge of the processes governing the variability and future evolution of Antarctic sea ice and ice shelves.



Code and data availability

The fast-ice dataset analysed here is freely available at <https://doi.org/10.26179/5d267d1ceb60c>. Monthly atmospheric
320 variables are provided by the ERA5 reanalysis dataset (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download>). Monthly sea surface temperature (SST) data are derived from the U.S. National Oceanic and Atmospheric Administration (NOAA)'s Extended Reconstructed SST dataset, version 5 (<https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html>). The OLR data are available from the NOAA Interpolated OLR (https://psl.noaa.gov/data/gridded/data.uninterp_OLR.html). Computer code is available from the corresponding author upon
325 reasonable request.

Author contributions

LY designed the study; CJ performed the EOF and regression analyses; CJ and LY wrote the manuscript draft with
330 contributions from JZ and TV.

Competing interests

The authors declare no conflict of interest.

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