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Drivers of Spatially Heterogeneous Changes in Summertime Sea Ice Variability in the Weddell Sea

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Abstract Interannual variability of Antarctic sea ice has undergone substantial changes in recent decades, particularly in the Weddell Sea. Previous study examined the change in interannual variability of sea ice extent (SIE) in the Weddell Sea. However, the spatial characteristics and driving mechanisms of changes in sea-ice concentration (SIC) interannual variability within the Weddell Sea remain insufficiently understood. Here, we investigate changes in austral summer (January–March) interannual SIC variability in the Weddell Sea during 1979–2024. The results reveal a distinct dipole pattern, characterized by increasing interannual variability in the northern Weddell Sea and decreasing variability in the southern Weddell Sea. Enhanced convective activity over eastern Australia and the southern Indian Ocean excites separate Rossby wave trains that propagate into the Southern Ocean and generate opposite zonal pressure gradients over the Weddell Sea. The resulting anomalous northerly (southerly) winds promote sea ice convergence and increased sea-ice concentration in the southern (northern) Weddell Sea, thereby contributing to reduced (enhanced) interannual sea-ice variability.

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1. Introduction

The Weddell Sea, located east of the Antarctic Peninsula, is one of the climatically most important regions of the Southern Ocean. It exhibits strong atmosphere–ice–ocean interactions that exert substantial influences on both the Antarctic and global climate systems (Hobbs et al., 2016; Morioka et al., 2017, 2019). The region plays a central role in Antarctic Bottom Water formation, deep-ocean ventilation, and meridional heat exchange, making variability in Weddell Sea sea ice an important component of the global climate system. Variations in Weddell Sea sea ice conditions influence surface albedo, air–sea heat exchange, ocean stratification, and large-scale atmospheric circulation, thereby affecting climate variability on both regional and global scales.

Although long-term trends in Weddell Sea sea ice extent have remained statistically weak compared with other Antarctic sectors (Parkinson, 2019), sea ice in the Weddell Sea exhibits substantial interannual variability (Murphy et al., 2014; Morioka and Behera, 2021). The occurrence of several recent extremely low sea-ice years has attracted considerable attention (Turner et al., 2020; Jena et al., 2020). In particular, previous studies have identified a pronounced increase in the interannual variance of summertime sea ice extent in the Weddell Sea since the 1990s (Venegas and Drinkwater, 2001; Morioka et al., 2017; Guo et al., 2023). Such enhanced variability suggests increasing instability in the regional sea-ice system and may reflect changing atmosphere–ocean forcing under a warming climate. Understanding the mechanisms governing sea-ice variability in the Weddell Sea is therefore crucial for improving projections of Antarctic climate and its global teleconnections.

Much of the interannual sea-ice variability has been attributed to large-scale modes of climate variability. Previous studies have shown that SIC in the Weddell Sea is significantly associated with the El Niño–Southern Oscillation (ENSO) (Carleton, 1988; Turner, 2004; Yu et al., 2021, 2024). During El Niño events, a weakened Amundsen Sea Low tends to induce anomalous southerly winds over the Weddell Sea, favoring enhanced sea-ice concentration, whereas the opposite conditions generally occur during La Niña events (Yu et al., 2024). In addition, different "flavors" of ENSO events, including eastern-Pacific and central-Pacific El Niño events, can produce distinct seasonal and regional sea ice responses in the Weddell Sea (Ciasto et al., 2015; Zhang et al., 2021).

The Southern Annular Mode (SAM), the leading mode of Southern Hemisphere atmospheric

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circulation variability on interannual timescales, also exerts an important influence on Weddell Sea SIC. Positive (negative) phases of the SAM are generally associated with reduced (enhanced) SIC in the Weddell Sea through modulation of surface winds, atmospheric temperature, and oceanic circulation (Lefebvre et al., 2004). Furthermore, interactions between ENSO and SAM can generate distinct patterns of sea-ice variability in the Weddell Sea (Fogt et al., 2010; Wang et al., 2023), indicating the importance of combined large-scale climate forcing.

In addition to atmospheric circulation variability, sea surface temperature (SST) anomalies in the tropical oceans also contribute significantly to interannual sea ice variability in the Weddell Sea. Previous studies have demonstrated that SST variability in the tropical Indian and Atlantic Oceans can modulate atmospheric teleconnections and influence Antarctic sea ice through Rossby wave propagation and associated circulation anomalies (Nuncio and Yuan, 2015; Ren et al., 2022; Yu et al., 2022, 2023). These studies suggest that tropical forcing from multiple ocean basins plays an important role in determining Antarctic sea-ice variability on interannual timescales.

Despite extensive research on the impacts of interannual climate drivers on sea ice in the Weddell Sea, comparatively little attention has been paid to long-term changes in sea ice interannual variability and their spatial heterogeneity across the Weddell Sea. Previous studies have primarily focused on trends in sea ice extent or basin-averaged variability (Venegas and Drinkwater, 2001; Morioka et al., 2017; Li et al., 2020; Guo et al., 2023), whereas regional differences in trends of sea ice variability within the Weddell Sea remain poorly understood. Such spatially heterogeneous changes are important because they may reflect distinct regional responses to atmospheric circulation, oceanic forcing, and sea-ice feedback processes. Moreover, changes in interannual variability are closely linked to the frequency and magnitude of extreme sea-ice conditions, therefore providing important insights into the stability and predictability of the Antarctic sea-ice system.

In this study, we investigate the spatial patterns and temporal trends of summertime interannual SIC variance across the Weddell Sea using a newly developed variance-trend diagnostic method using wavelet analysis following Torrence and Compo (1998). Particular attention is given to the contrasting trends observed between the northern and southern Weddell Sea. We further examine the associated atmospheric circulation anomalies and tropical SST forcing that may contribute to these regional differences in sea ice interannual variability.

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2. Datasets and Methods

To investigate the spatial and temporal variability of summertime SIC in the Weddell Sea and its associated climate drivers, this study employs multiple observational and reanalysis datasets. These include satellite-derived sea ice observations, atmospheric reanalysis products, sea surface temperature (SST) analyses, outgoing longwave radiation (OLR), and sea ice dynamical and thermodynamical variables. Together, these datasets provide a comprehensive framework for examining atmosphere–ocean–sea ice interactions associated with interannual sea ice variability in the Southern Ocean.

Monthly SIC data for 1979–2024 are obtained from the U.S. National Snow and Ice Data Center (NSIDC) on a polar stereographic grid with a spatial resolution of 25 km (Cavalieri et al., 1996). Monthly atmospheric variables are extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation reanalysis (ERA5) dataset (Hersbach et al., 2020), which has a horizontal resolution of $0.25° \times 0.25°$ and spans the period from 1979 to the present. SST data are obtained from the U.S. National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) dataset (Huang et al., 2017). OLR data, which serve as a proxy for tropical convective activity, are obtained from NOAA's interpolated OLR dataset (Liebmann and Smith, 1996). Sea ice motion and thickness data are taken from the Global Ice–Ocean Modeling and Assimilation System (GIOMAS) datasets (Zhang and Rothrock, 2003).

Our analysis focuses on austral summer (January–March), when Antarctic sea ice extent reaches its seasonal minimum and Weddell Sea sea ice becomes more sensitive to atmospheric and oceanic forcing. The reduced background ice cover during summer enhances air–sea interactions and allows interannual sea ice variability signals to emerge more clearly than during winter. Previous studies have also identified enhanced summertime interannual variability in Weddell Sea sea ice (Venegas and Drinkwater, 2001; Morioka et al., 2017), motivating the focus on this season.

In this study, interannual variability is defined as variability with periods 2-9 years. The resulting variance fields are used to evaluate both temporal trends and spatial patterns of sea ice variability across the Weddell Sea.

Linear regression and correlation analyses are employed to examine the relationships among

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sea ice variability, atmospheric circulation, and tropical SST anomalies. Statistical significance is assessed using a two-tailed Student's t-test. To further investigate the generation and propagation of large-scale atmospheric teleconnection patterns associated with sea ice variability, Rossby wave source diagnostics (Sardeshmukh and Hoskins, 1988) and wave activity flux analyses (Takaya and Nakamura, 2001) are applied to characterize the initiation and propagation pathways of stationary Rossby waves.

3. Results

The trends in the interannual variance of summertime SIC in the Weddell Sea exhibit a distinct dipole structure, with significantly positive trends in the northern Weddell Sea and significantly negative trends in the southern Weddell Sea (Figure 1a). The time series of domain-averaged sea ice anomalies on interannual timescales for the regions with negative variance trends shows a clear reduction in variability after late 1990s (Figure 1d). The standard deviation decreases significantly from 0.0893 prior to 2000 to 0.0568 after 2000 ($p < 0.05$). In contrast, the regions characterized by positive variance trends display a substantial increase in interannual variability (Figure 1e). The standard deviation increases significantly from 0.0655 before 1997 to 0.1523 after 1997 ($p < 0.02$).

To investigate the mechanisms associated with these contrasting trends in SIC interannual variance, regression analyses of SIC, atmospheric circulation, and SST anomalies are performed using the normalized sea ice anomaly time series shown in Figures 1d and 1e. For both the negative- and positive-trend regions, the associated sea ice anomalies display a dipole structure across the Weddell Sea (Figures 1b and 1c) through the regression of sea ice onto the time series in Figure 1d and 1e, suggesting that distinct large-scale circulation patterns modulate sea ice variability in the northern and southern sectors of the basin.

We first examine the mechanisms associated with the regions of negative SIC variance trends. Regression maps of atmospheric variables and SST anomalies are shown in Figures 2 and 3. Enhanced convective activity, seen as negative anomalies in outgoing longwave radiation, over eastern Australia (Figure 2a) induces positive Rossby wave source anomalies and anomalous upper-level divergence at 200 hPa (Figure 2c), thereby exciting a Rossby wave train that propagates southeastward into the Amundsen and Bellingshausen Seas before reaching the

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Weddell Sea. During this process, negative SST anomalies between Australia and New Zealand further strengthen the wave train. The SST anomalies averaged over 32–45°S, 152°E–176°W are significantly correlated with the positive anomalies in the Weddell Sea shown in Figure 1b ($r = -0.45$, $p < 0.02$).

The extratropical wave train exhibits a largely barotropic vertical structure and produces anomalous low (high) sea level pressure over the south-western (north-eastern) Weddell Sea (Figure 3a). This circulation pattern generates anomalous northerly and westerly winds across the Weddell Sea. The anomalous northerly flow drives sea ice southward into the southern Weddell Sea (Figure 3c), leading to sea ice convergence and increased sea ice there (Figure 1b). At the same time, reduced downward longwave radiation contributes to lower snow/ice surface temperatures over the southern Weddell Sea (Figures 3d and 3e), further favoring increased SIC. In addition, enhanced SIC increases surface albedo and reduces net shortwave radiation (Figure 3f), reinforcing surface cooling through the ice–albedo feedback and further promoting sea ice growth.

A similar regression analysis is conducted for the regions exhibiting positive trends in sea ice interannual variance (Figures 4 and 5). In this case, positive sea ice anomalies in the northern Weddell Sea (Figure 1d) are associated with positive SST anomalies in the tropical central Indian Ocean (Figure 4b) and enhanced convective activity over the southern Indian Ocean (Figure 4a). Sea ice anomalies are significantly positively correlated with SST anomalies averaged over 6°N–18°S, 66–82°E ($r = 0.38$, $p < 0.05$) and significantly negatively correlated with OLR anomalies averaged over 12–22°S, 62–70°E ($r = -0.44$, $p < 0.02$). Enhanced convection and anomalous upper-level divergence generate positive Rossby wave source anomalies over the southern Indian Ocean (Figure 4c), which excite a Rossby wave train propagating southeastward into the Ross, Amundsen, Bellingshausen, and Weddell Seas (Figure 4d).

The resulting wave train produces a zonal dipole structure in both 200-hPa geopotential height and sea level pressure anomalies (Figures 4d and 5a), which induces anomalous southerly winds over the Weddell Sea (Figure 5b). These anomalous southerly winds drive sea ice northward, resulting in sea ice divergence and reduced sea ice in the southern Weddell Sea, while simultaneously producing sea ice convergence in the northern Weddell Sea (Figure 5c), which increases SIC there. The associated ice–albedo feedback further amplifies this dipole structure.

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Opposite anomalies in net shortwave radiation between the northern and southern Weddell Sea (Figure 5f) reinforce the sea ice dipole shown in Figure 1c. In addition, reduced downward longwave radiation lowers snow/ice surface temperature over the northern Weddell Sea (Figures 5d and 5e), favoring increased sea ice there.

Changes in the background sea ice state also influence trends in SIC interannual variance (Yu et al., 2026). To evaluate this effect, correlations are calculated between SIC interannual variance and 9-year low-pass filtered SIC and sea ice thickness (Figures S1a and S1b). Regions characterized by positive (negative) variance trends exhibit significantly positive (negative) correlations with SIC and sea ice thickness. In the regions with negative variance trends, both SIC and ice thickness exhibit significant positive trends (Figures S2a and S2b; $p < 0.05$), which act to suppress interannual sea ice variability. In contrast, the regions with positive variance trends do not exhibit statistically significant long-term trends in SIC or ice thickness (Figures S3a and S3b; $p > 0.05$), although interannual variability in both increases noticeably prior to 2016.

These results suggest that the influence of background sea ice conditions on SIC interannual variance is stronger in the regions with negative variance trends than in those with positive variance trends. Increased SIC and ice thickness reduce the available space and mobility of the sea ice pack, thereby limiting sea ice motion and suppressing interannual variability.

4. Conclusions and discussion

Utilizing sea ice and atmospheric data for 1979–2024, this study investigated changes in the interannual variance of austral summertime SIC in the Weddell Sea and identified the dominant mechanisms responsible for these changes.

The interannual variance of summertime SIC exhibits a pronounced dipole pattern across the Weddell Sea, characterized by increasing variance in the northern Weddell Sea and decreasing variance in the southern Weddell Sea. These changes are primarily associated with abrupt regime shifts occurring around 1997 in the north, corresponding to the positive variance trends, and around 2000 in the south, corresponding to the negative variance trends.

The decreasing interannual variance in the southern Weddell Sea is partly associated with a Rossby wave train triggered by enhanced convective activity over eastern Australia. The resulting circulation anomalies strengthen the zonal pressure gradient across the Weddell Sea and generate

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anomalous northerly winds, which promote southward sea ice transport and convergence in the southern Weddell Sea, thereby increasing SIC. In contrast, the increasing interannual variance in the northern Weddell Sea is partly associated with a Rossby wave train triggered by enhanced convection over the southern Indian Ocean. The associated anomalous pressure gradient produces southerly wind anomalies over the Weddell Sea, driving northward sea ice transport and convergence in the northern Weddell Sea, which favors increased sea ice there.

Thermodynamic processes also contribute to the sea ice anomalies associated with both variance trends. Reduced downward longwave radiation lowers snow/ice surface temperature, while changes in net shortwave radiation associated with the ice–albedo feedback further reinforce the observed SIC anomalies. In addition, increasing background SIC and ice thickness in the southern Weddell Sea contribute to the reduction in interannual SIC variance by limiting sea ice mobility and thereby suppressing sea ice motion.

In contrast to previous studies that mainly examined changes in the interannual variance of Weddell Sea ice extent (Venegas and Drinkwater, 2001; Morioka et al., 2017; Guo et al., 2023), the present study focuses on spatially varying changes in interannual variance of SIC. Our results reveal clear regional contrasts between the northern and southern Weddell Sea, highlighting the importance of spatial heterogeneity in Antarctic sea ice variability. Furthermore, our results suggest that both dynamic and thermodynamic processes jointly contribute to the observed SIC variance trends, whereas Guo et al. (2023) emphasized a more dominant role of thermodynamic processes.

The preceding spring Southern Annular Mode (SAM) also exhibits significant correlations with summertime sea ice interannual variability in both regions. From 1999 to 2024, the spring SAM index is positively correlated with sea ice variability in the region of negative variance trends ($r = 0.43$, $p < 0.01$) and negatively correlated with sea ice variability in the region of positive variance trends ($r = -0.62$, $p < 0.01$). The latter relationship is consistent with the findings of Guo et al. (2023). However, while Guo et al. (2023) primarily focused on Antarctic local processes, our study highlights the important role of tropical and subtropical teleconnections in modulating Weddell Sea sea ice variability. Part of the discrepancy between the studies may arise from differences in the definition of austral summer. Guo et al. (2023) defined summer as December–February (DJF), whereas the present study uses January–March (JFM), which includes the climatological minimum of Antarctic sea ice extent.

This study also applies the variance diagnostic method proposed by Yu et al. (2026b), which directly estimates the time series of interannual SIC variance at each grid point. This approach avoids the moving-window analysis commonly used in previous studies (e.g., Guo et al., 2023) and provides a more direct characterization of temporal changes in sea ice variability.

Whether the increasing (decreasing) interannual SIC variance in the northern (southern) Weddell Sea will persist under the recent decline in Antarctic sea ice extent remains an important open question. In particular, the region exhibiting positive variance trends has shown reduced interannual variability since 2016, suggesting the possibility of another regime shift in the Weddell Sea sea-ice system. Continued monitoring and investigation are therefore needed to better understand future changes in Antarctic sea ice variability under a changing climate. Our results also provide a useful framework for improving prediction of interannual sea ice variability in the Weddell Sea.

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Author Contribution

L. Y. designed the research, analyzed the data, and wrote the first draft of the paper. S. Z. and T.V. revised the first draft and provided useful insights during various stages of the work. All authors reviewed the manuscript.

Code/Data availability

The monthly ERA5 atmosphere reanalysis dataset are available from the ECMWF website (Copernicus Climate Change Service, 2023). The monthly SIC data are taken from the NSIDC

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(https://nsidc.org/data/nsidc-0051/versions/2). The monthly sea surface temperature (SST) data are from the NOAA Extended Reconstructed SST V5 (www1.ncdc.noaa.gov/pub/data/cmb/ersst/v5/netcdf/). The monthly OLR dataset is provided by the NOAA (https://www.psl.noaa.gov/data/gridded/data.olrcdr.interp.html). Sea ice motion and thickness data are from Global Sea Ice (GIOMAS) Data Sets (https://psc.apl.uw.edu/data/global-sea-ice-glomas-data-sets/). The code is available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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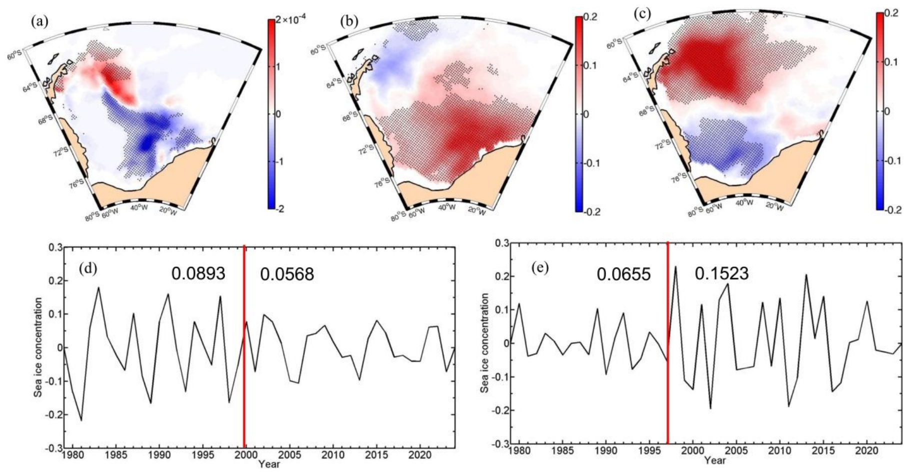

Figure 1. Trends in the interannual variance of summertime sea ice concentration in the Weddell sea (a); sea ice concentration anomalies associated with negative (b) and positive (c) trends in panel (a); the time series of of domain-averaged sea ice concentration anomalies on interannual timescale for negative (d) and (e) positive trends in panel (a). The numbers in panels (d) and (e) indicate the standard deviation prior to and after the year marked by the red lines.

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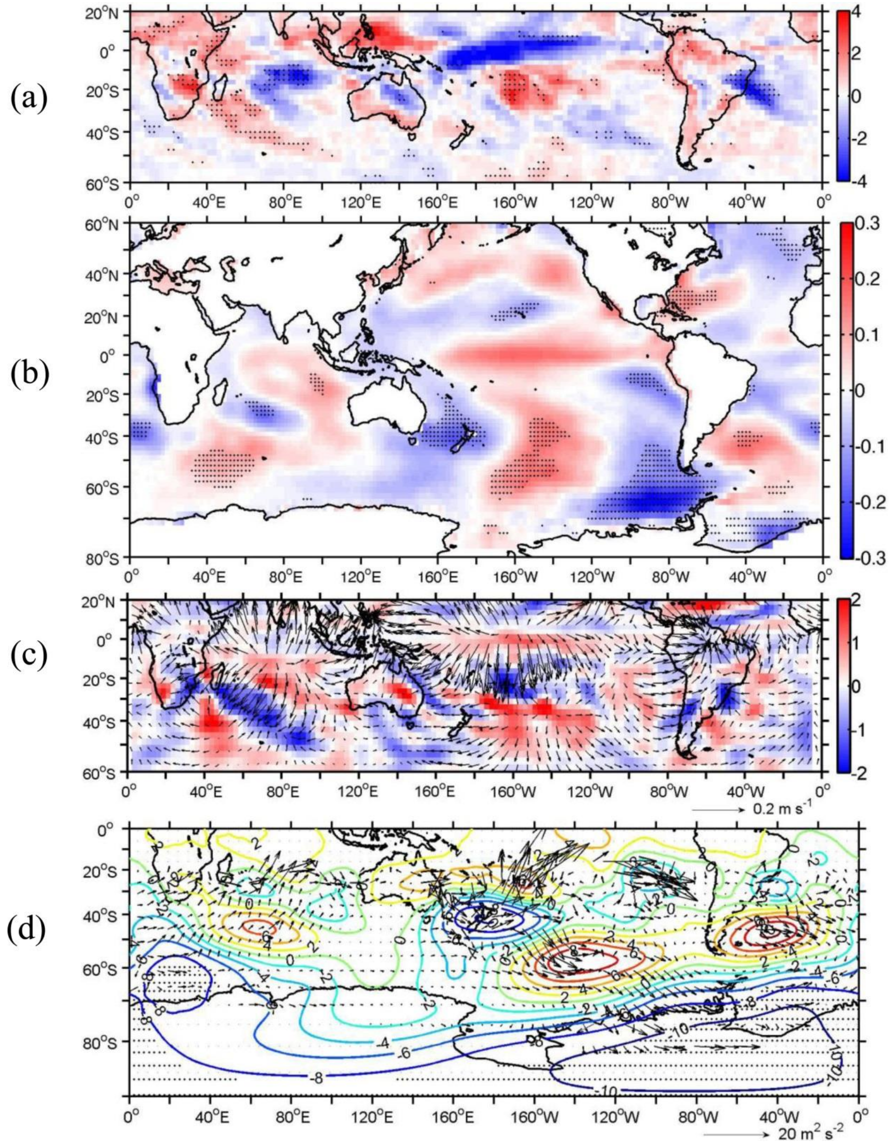

Figure 2. Regression map of anomalous OLR (W m^{-2}) (a), SST (^{o}C) (b), Rossby wave source

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(shaded) (s^{-1}) and 200-hPa divergence wind (vector) (c), and 200-hPa geopotential height (contour, gpm) and wave activity flux (vector) onto the time series of domain-averaged sea ice concentration anomalies on interannual timescale for negative trends (Figure 1d). Dotted regions denote above 95% confidence level.

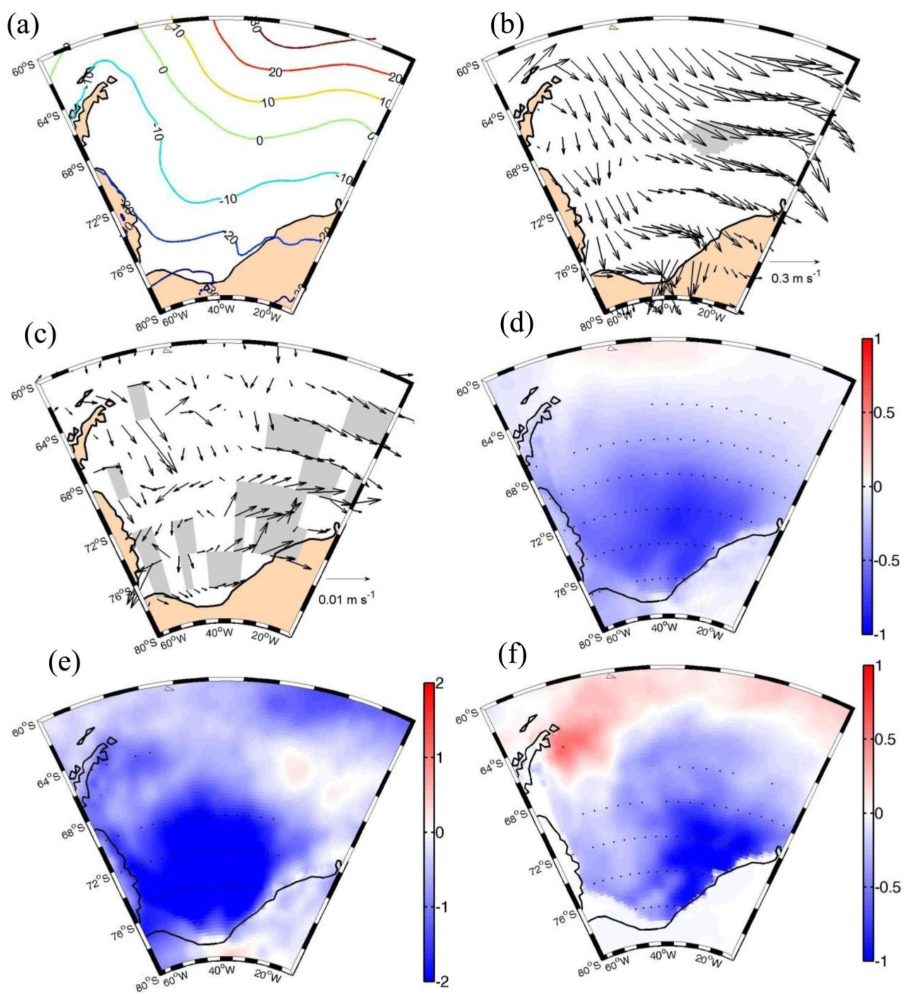

Figure 3. Regression map of anomalous sea level pressure (Pscal) (a), 10-m wind field (b), sea ice motion (c) surface air temperature (°C) (d), accumulated downward long wave radiation (10^5 W m^{-2}) (e), and accumulated net short wave radiation (10^5 W m^{-2}) (f) onto the time series of domain-averaged sea ice concentration anomalies on interannual timescale for negative trends (Figure 1d). Dotted and shaded regions denote above 95% confidence level.

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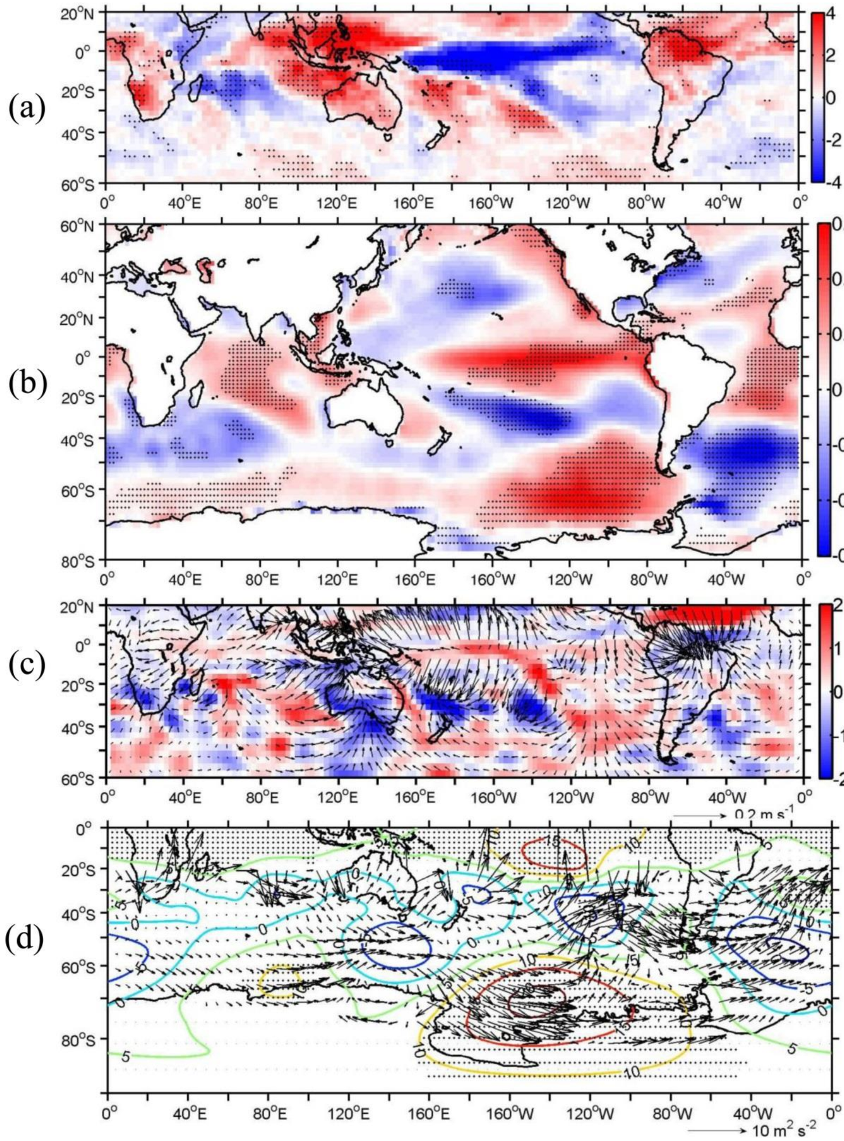

Figure 4. Regression map of anomalous OLR (W m^{-2}) (a), SST (^{o}C) (b), Rossby wave source

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(shaded) (s^{-1}) and 200-hPa divergence wind (vector) (c), and 200-hPa geopotential height (contour, gpm) and wave activity flux (vector) onto the time series of domain-averaged sea ice concentration anomalies on interannual timescale for negative trends (Figure 1d). Dotted regions denote above 95% confidence level.

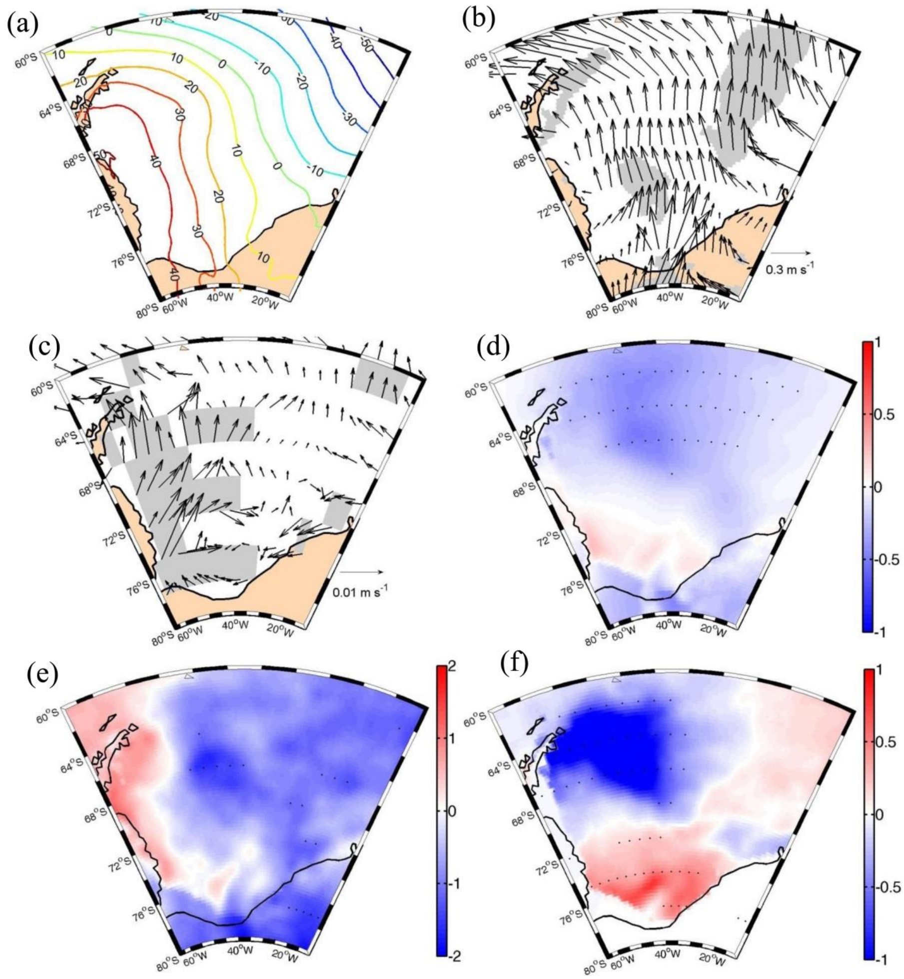

Figure 5. Regression map of anomalous sea level pressure (Pscal) (a), 10-m wind field (b), sea ice motion (c) surface air temperature (°C) (d), accumulated downward long wave radiation (10^5 W m^{-2}) (e), and accumulated net short wave radiation (10^5 W m^{-2}) (f) onto the time series of domain-averaged sea ice concentration anomalies on interannual timescale for positive trends (Figure 1d). Dotted and shaded regions denote above 95% confidence level.

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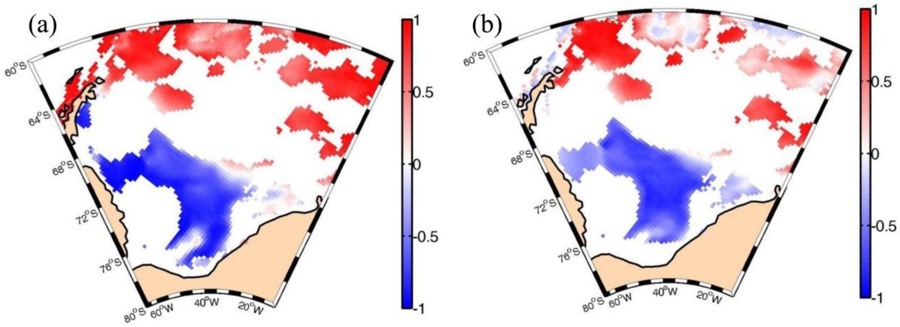

Figure 6. Correlations coefficients of interannual variance of sea ice concentration and (a) sea ice concentration and (b) sea ice thickness, all filtered applying a 9-year low pass filter.

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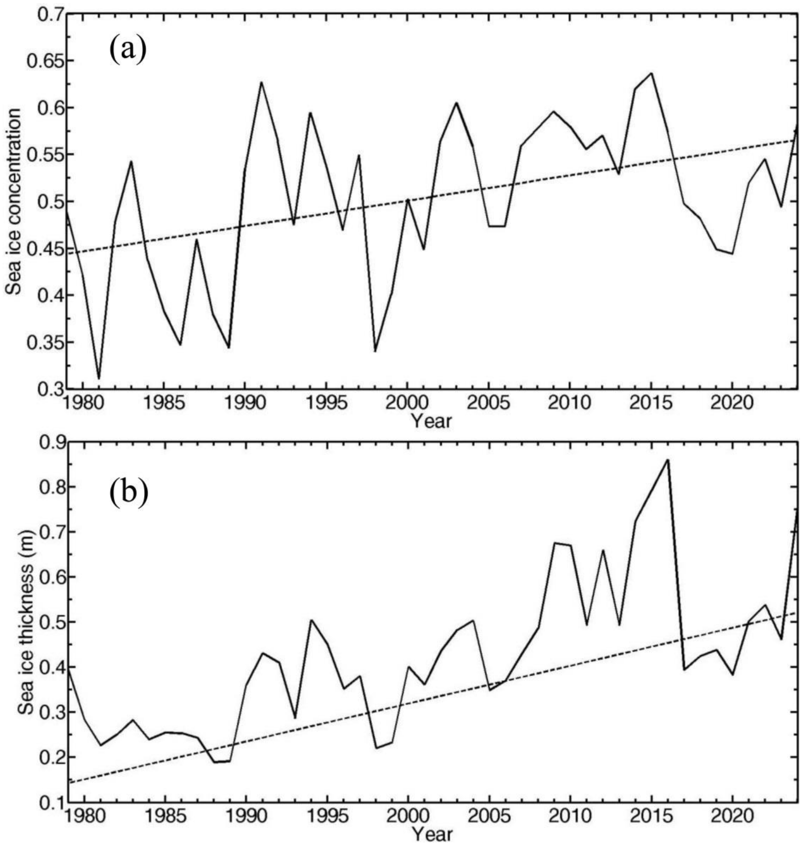

Figure 7. The time series of domain-averaged sea ice concentration (a) and sea ice thickness (b) at the regions of negative variance trends.

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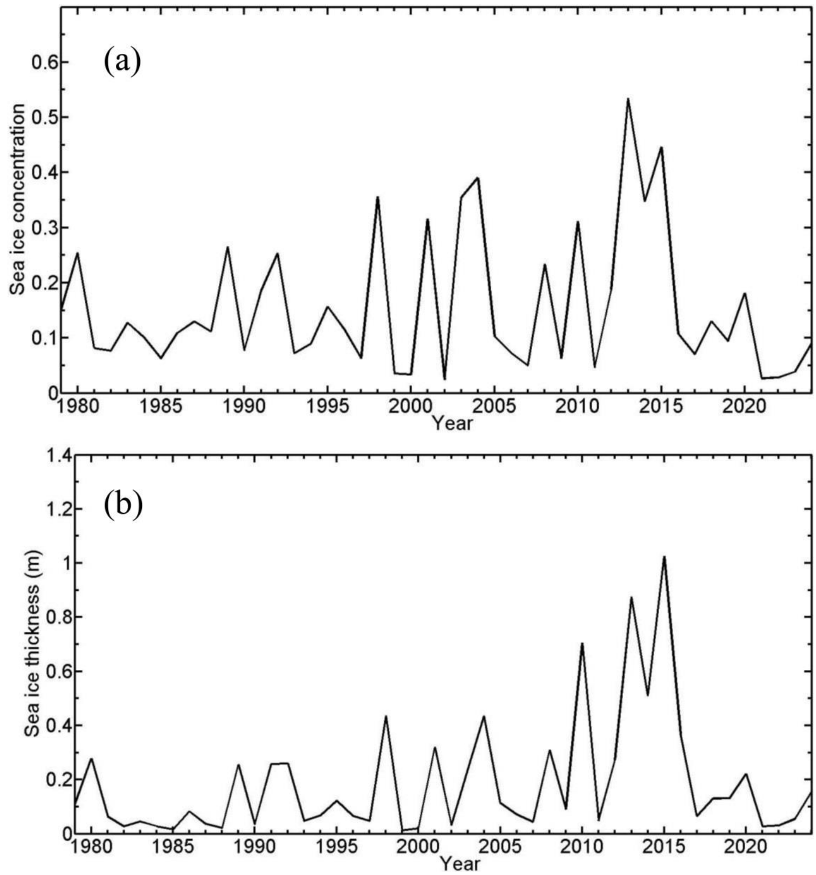

Figure 8. The time series of domain-averaged sea ice concentration (a) and sea ice thickness (b) at the regions of positive variance trends.