LETTER

Seasonal sea-ice variability and its trend in the Weddell Sea sector of West Antarctica

Avinash Kumar*1, Juhi Yadav*2 and Rahul Mohan*3

National Centre for Polar and Ocean Research, Ministry of Earth Sciences, Govt. of India, Vasco-da-Gama, Goa 403804, India
E-mail: avinash@ncpor.res.in

Keywords: sea-ice extent, sea surface temperature, net heat flux, climate variability, Weddell Gyre

Supplementary material for this article is available online

Abstract

The Weddell Sea is susceptible to the ongoing climate change and experiences a reduction in an overall increase in the sea-ice extent (SIE). The nature of sea-ice in the Weddell Sea is largely associated with its geographical setup that determines the seasonal and decadal sea-ice variability. The study analysed long-term sea ice-ocean-atmosphere variability and trends (1979–2019) based on satellite and reanalysis measurements. The result shows the expansion of yearly SIE is 2.5 ± 3.5 × 10^3 km^2 yr^−1 with a significant increase in the austral summer (12.4 ± 4.6 × 10^3 km^2 yr^−1), whereas a decrease in the spring SIE (−4.8 ± 5.0 × 10^3 km^2 yr^−1) over the last four decades. Seasonal sea-ice concentration (SIC) variations in the Weddell Sea are associated with latitudinal thermal differences and westerlies intensification, culminating in the weakening or strengthening of the Weddell Gyre. The SIC recorded significant positive trends in the western and eastern parts of the Weddell Sea during the austral summer and autumn, respectively. These changes are consistent with the prevailing wind patterns and Weddell Gyre intensification in the respective seasons. During the austral winter and spring, significant negative SIC trends (north of 65° S) were recorded due to the easterlies intensification and weakening of the Weddell Gyre. While, the significant positive trends observed along the coast are linked with the easterlies intensification and sea-ice advection. Composite analysis reveals that the SIC variability is related to the sea surface temperature (SST) during austral summer and spring, whereas SST and net heat flux both regulate the SIC in the Weddell Sea during the austral winter and autumn. The positive Southern Annular Mode is associated with an increase in sea-ice during austral summer, while sea-ice decreases during the winter in the Weddell Sea. The present study reveals a strong relationship between the sea-ice variability and ocean-atmospheric forcings, but these relationships are not constant over time; therefore, continuous monitoring is required.

1. Introduction

Sea ice plays a fundamental role in the Antarctic climate system. It interacts strongly with the boundary layers of the atmosphere and ocean, thereby modifying the vertical heat and moisture exchange between the ocean and the atmosphere (Hoebert 1991, Raphae et al 2011). Antarctic sea-ice is responsive to climate change and gives early signals of climate change linked to changes in solar energy absorption (Comiso and Nishio 2008). This in turn affects the regional and global climate variability through the ice-albedo feedback (Colman 2013). Earlier studies have reported sea-ice melting and the resultant freshening of surface water and an increased salinity stratification in the Antarctic seas that suppresses the deep convective mixing with the warmer water (Bintanja et al 2015).

In the southern and western area of Weddell Sea, the offshore ice shelves play a crucial role in driving the global ocean conveyor belt as a large Antarctic Bottom Water formation site (Orsi et al 2002) where saline and oxygen-enriched shelf waters are formed due to the substantial sea-ice formation and by the brine rejection in coastal regions (Massom and Stammerjohn 2010). A recent study suggested that the Antarctic Bottom Water salinity is primarily affected by the western Weddell Sea Bottom Water (Gordon et al 2020). In their observation since 1999,
the salinity variation in the Weddell Sea Bottom Water has shown the lowest salinity records from 2014 to 2017. In the Weddell Sea, the dense water formation is induced by the large-scale cyclonic circulation of the Weddell Gyres, which is dominated by westerlies along the northern and easterlies in the southern coasts (Vernet et al. 2019). With the onset of the warm season (Oct–Mar), the Weddell Sea receives more incoming solar radiation contributing to a consequent rise in surface air temperature; hence the sea-ice melting process is enhanced by a reduction in the surface albedo. The enhanced air temperature in the Atlantic sector of the Southern Ocean is favourable for decreasing the storm track activity and sustaining anticyclonic conditions (Morioka et al. 2019).

Over the last four decades, the sea-ice variability in the Weddell Sea has been significantly influenced by ocean-atmospheric forcings in the Atlantic sector (Morioka et al. 2017), therefore there is no analogous trend over the seasons or longitudes (Parkinson and Cavalieri 2012). The ocean is relatively warm compared to the atmosphere because, in winter, sea-ice serves as an excellent insulator, but the temperature difference between the ocean and atmosphere is comparatively less due to favourable ice-albedo feedback in the summer (Parkinson 2004, Vihma et al. 2009). Consequently, the sea-ice trend increased in the Weddell Sea sector during the austral summer and autumn but declined throughout austral winter and spring. The sea-ice growth and its redistribution are manifested by the thermodynamic processes, thus limiting the geographical distribution of open water exposure in leads and polynyas (Venegas and Drinkwater 2001).

Several studies are reported on the sea-ice variabilities and trends in the Weddell Sea is closely linked to the ocean influence and atmospheric response (Zwally 2002, Zhang 2007, Parkinson and Cavalieri 2012, Turner et al. 2020). The inhomogeneous sea-ice extent (SIE) trend in the Weddell Sea has been linked with the positive Southern Annular Mode (SAM), El Niño-Southern Oscillation (ENSO) teleconnections (Yuan 2004, Stammerjohn et al. 2006, Mckee et al. 2011, Murphy et al. 2014, Morioka et al. 2017, Vernet et al. 2019, Jun et al. 2020) and surface heat flux (Holland and Kwok 2012). There is a positive relation between SAM and temperature over the Antarctic Peninsula, while in most eastern Antarctica and parts of western Antarctica, there is a negative relation (Lefebvre et al. 2004, Marshall et al. 2011). It has been reported that the effect of the SAM/ENSO phases on SIE of the Weddell Sea sector is noticeable, especially in the austral summer (Kwok and Comiso 2002). Therefore, during the austral summer, the SIE is strongly correlated with positive SAM and La Niña phase, whereas the relationship is smaller and negative during the rest of the seasons (Pezza et al. 2011). During the austral summer and fall, increasing SAM index are consistent with cooling across the ice sheet and warming over the Antarctic Peninsula.

### Table 1.
The annual and seasonal trends of sea ice extent and standard errors were computed for the Weddell Sea over the period 1979–2019 (1979–2015). Based on a null hypothesis of zero trends with degrees of freedom 39 (n = 41 – 2), and 35 (n = 37 – 2), the R values are highlighted at a significant level of 95% (bold) and 99% (bold italic).

| Year          | SIE (10$^3$ km$^2$ yr$^{-1}$) | R       |
|--------------|-------------------------------|---------|
| 1979–2019    | 2.5 ± 3.5 (8.2 ± 3.7)         | 0.72 (2.1) |
| Summer (JFM) | 12.4 ± 4.6 (19.8 ± 5.1)       | 2.69 (3.9) |
| Autumn (AM)  | 5.8 ± 4.9 (13.9 ± 5.2)        | 1.19 (2.6) |
| Winter (JAS) | −2.8 ± 4.1 (−1.9 ± 4.8)       | −0.68 (−0.4) |
| Spring (OND) | −4.8 ± 5.0 (16.5 ± 5.7)       | −0.95 (0.3) |

The autumn is associated with cooling over the ice sheet and warming across the Antarctic Peninsula due to stratospheric ozone loss and elevated carbon dioxide (Marshall 2007, Polvani et al. 2011, Holland et al. 2014, Jun et al. 2020). However, during winter, the positive SAM accelerates sea-ice growth in the marginal region and sea-ice depletion in the coastal region due to northward sea ice transport, and vice versa (Cerrone et al. 2017b, Fusco et al. 2018).

Over the last four decades, the SIE trend during the austral summer has increased, while in austral winter SIE trend recorded a statistically insignificant decrease in the Weddell Sea (table 1). However, the SIE trend in Weddell sea was recorded 8.2 ± 3.7 × 10$^3$ km$^2$ yr$^{-1}$ during 1979–2015, which has significantly reduced to 2.5 ± 3.5 × 10$^3$ km$^2$ yr$^{-1}$ during 1979–2019 (table 1). In the last 4 years, the major sea-ice loss in the total Antarctic is more evident (Meehl et al. 2019, Turner et al. 2020) and is linked with the super El Niño year (2016) (Wang et al. 2019c). During the El Niño year, the development of northeast cyclonic atmospheric anomaly results in the advection of cold wind anomalies towards the lower latitudes, leading to sea-ice expansion towards the north (Stammerjohn et al. 2008).

The study is aimed to identify where and how the sea-ice had changed in the Weddell Sea (60° W to 20° E) over the period—interannual, seasonal and decadal-scale—and to examine the linkages between sea-ice variability and ocean-atmospheric forcings such as sea surface temperature (SST), wind parameters, net heat flux (NHF), SAM, ENSO, Atlantic Meridional Mode (AMM) and Indian Ocean dipole mode (IOD). The influence of recent changes in SIE (for the last 4 years, i.e. 2016–2019) in the Weddell Sea sector has been studied to identify the influence of ocean-atmospheric forcings. Statistical analyses—significant trend and composite analyses—using satellite observation and reanalysis data were performed for this purpose. The study demonstrated the effect of long-term sea-ice variability during all four seasons—austral summer (JFM), autumn (AMJ), austral winter (JAS), and spring (OND)—and the associated atmospheric variability over the Weddell Sea sector of West Antarctica.
2. Data materials and method

2.1. Data products
The long-term SIE for monthly and seasonal scales (1979–2019) for the Weddell Sea sector (60° W to 20° E) were estimated from passive microwave satellite data analysed using the ‘NASA Team’ algorithm (Zwally 2002, Parkinson and Cavalieri 2012). SIE computation is based on the threshold value of at least 15% of sea-ice concentration (SIC) data from the National Snow and Ice Data Center (www.nsidc.org). The SIC datasets for the last 41 years were obtained from the Met Office Hadley Centre sea ice and SST (HadISST; www.metoffice.gov.uk/hadobs/hadisst2/) (Titchner and Rayner 2014).

Ocean-atmospheric parameters such as SST, wind speed, zonal wind and meridional winds (U and V components) at 10 m were analysed using the European Centre for Medium-Range Weather Forecasts ERA5 reanalysis datasets (0.25 × 0.25° grid) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview). The available ERA5 data are based on the integrated forecasting system that provides a relevant wind and temperature datasets for the southern hemisphere (Tetzner et al 2019). The temperature data obtained from ERA have been tested earlier with the local temperature datasets in Antarctic sectors that signifies the good performance of the ERA data (Wang et al 2016, Hersbach et al 2020, Hillebrand et al 2020).

The NHF of the surface is a metric to understand the effect of atmospheric forcing on ocean fluctuations and vice versa. The heat flux components such as latent heat (LH) flux, sensible heat (SH) flux, and net longwave (LW) and shortwave (SW), downward near-infrared radiation (NIR) radiations have been obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html) reanalysis dataset from 1979 to 2019. The NCEP/NCAR reanalysis datasets are based on global data assimilation system that supports climate monitoring with higher accuracy (Kalnay et al 1996). To understand the influence of telecommunications over the sea-ice in the Weddell Sea, monthly climate indices—SAM, ENSO AMM and IOD—were obtained from the Physical Research Laboratory (https://psl.noaa.gov/).

2.2. Computation of air-sea heat flux
The NHF over the Weddell Sea was computed using well-established numerical analysis methodologies (Budillon et al 2000). The NHF is determined by the composition of surface radiation heat fluxes (net LW emission and net SW radiation) and surfaces turbulent heat fluxes (LH and SH). The NHF (Qnet) at the ocean surface has been expressed as follows:

\[ Q_{\text{net}} = Q_{\text{LH}} + Q_{\text{SH}} + Q_{\text{ LW}} + Q_{\text{SW}} \]

where Qnet is NHF, QLH is LH flux, QSH is SH flux, QLW is net LW radiation, and QSW is SW radiation. Qnet is referred to as NHF throughout the present study.

2.3. Statistical approach
The SIE variability has been studied based on monthly, seasonal, annual, and decadal timescales. The SIE trends for 1979–2019 (41 years) and 1979–2015 (37 years) were calculated based on the linear regression method (table 1). The standard deviations and significance level of the trends were calculated using the trend ratio R to its standard deviation (Taylor 1997). The significance level of trend is determined at 95% and 99% confidence level if the value of R exceeds 1.68 (1.69) and 2.42 (2.43), respectively. This statistically significant level is derived from the Student’s t-test by assuming degrees of freedom as 39 (n = 41–2) and 35 (n = 37–2) with the zero trend as the null hypothesis. Similarly, the decadal trend calculation has been performed on the gridded datasets of SIC, SST, WS, Zonal and Meridional winds along with its significance level at 95%. The anomalies were calculated for the SIE, SIC, and aforementioned ocean-atmospheric forcing variables on an annual and seasonal scale were calculated by subtracting the mean extent value of the climatology year (1981–2010) from the mean values of a total of 41 years (1979–2019). Further, the impact of the ocean-atmosphere forcing and the climate modes on SIE in the Weddell Sea were examined by computing the correlation analysis (Yuan and Li 2008, Stuecker et al 2017). The statistical significance level of the correlation coefficient is based on the two-tailed Student’s t-test by taking the degrees of freedom as 39 (n = 41–2).

The principal component (PC) analysis was performed on the seasonal SIC anomalies that provides an annular structure of the total variance. First, based on the PC1 of SIC anomalies the extreme years were selected as high and low sea-ice years which is having standard deviation greater than 1 or smaller than −1, respectively (table S1 (available online at stacks.iop.org/ERL/16/024046/mmedia)) (Watanabe et al 2006). Second, after the selection of high and low sea-ice years in the Weddell Sea, they were averaged and further, the composite difference was calculated by subtracting the low sea-ice year from the high sea-ice year (Morioka et al 2019).

The composite analyses were performed to illustrate the impact of the sea-ice variability on the composite NHF, SST and SIC anomalies during all the four seasons. In the previous study phases of NAO and its relationship with the sea-ice in the Barents-Kara Sea region have been studied (Luo et al 2017, 2019). Similarly, to understand the role...
of ocean-atmospheric circulation better, we have examined SAM phases to decipher their influence on the seasonal SIC, downward NIR, LHF, SHF, and NHF. Based on the detrended SAM, positive (greater than 1) and negative (smaller than −1) SAM event years are determined (table S3) (Doddridge and Marshall 2017).

3. Results and discussion

The result shows the expansion of SIE is 2.5±3.5 × 10^3 km^2 yr^-1 in the Weddell Sea sector over the last four decades (1979–2019). However, a rapid sea-ice decline was observed after 2015. To understand this decline, the comparison between the annual and seasonal trends of SIE for 41 year (1979–2019) and 37 year (1979–2015) was performed (table 1). The result shows that the last 41 years’ SIE trend has decreased by about 69% compared to the trend obtained for the 37 years (8.2 ± 3.7 × 10^3 km^2 yr^-1). Over the 41 years, the SIE trends during austral summer have increased significantly by 12.4 ± 4.6 × 10^3 km^2 yr^-1 followed by autumn 5.8 ± 4.9 × 10^3 km^2 yr^-1 while SIE trends have decreased during spring (−4.8 ± 5.0 × 10^3 km^2 yr^-1) and winter (−2.8 ± 4.1 × 10^3 km^2 yr^-1) (table 1). The largest negative trend recorded during spring (−4.8 ± 5.0 × 10^3 km^2 yr^-1) is four times lower than the computed trend of the 37 year (1.6 ± 5.7 × 10^3 km^2 yr^-1). However, over the 41 years, SIE trends of remaining season have shifted rapidly towards the negative magnitude—in autumn by 58% followed by 49% in winter and 37% in summer—compared to the 37 years (1979–2015) (table 1). The dramatic changes in the Weddell Sea sector are ideally the consequence of the sea-ice instabilities that have occurred during 2016–2019 and may be caused by changes in atmospheric circulation associated with intraseasonal and interannual climate variability (Parkinson 2019).

3.1. Seasonal sea-ice variability

3.1.1. Changes during austral summer

Earlier studies have reported the linkages of summer sea-ice in the western Weddell Sea is associated with the Antarctic Peninsula that serves as a topographic barrier to the warmer air-mass present towards the western Antarctic Peninsula (Turner et al 1998, Comiso and Nishio 2008). During the austral summer (JFM), the SIC has significantly increased below the 60° S latitude, especially in the southwestern region and in some regions along the coast of the Weddell Sea sector (figure 1(a)). The southwestern region of the Weddell Sea experiences the net sea-ice increase, whereas the northwestern part is associated with the sea-ice retreat (Kimura and Wakatsuchi 2011). Over the last four decades, the results show highly significant (p < 0.05) declining sea-ice trends towards the west of the Antarctic Peninsula and increasing sea-ice trends towards the east of the Antarctic Peninsula (figure 1(a)). The significant decrease (increase) of SST is observed in the Weddell Sea, showing a strong inverse relationship with the sea-ice expansion (retreat) and western Antarctic Peninsula (figures 1(a) and (b)). The higher SST (low pressure) in the western Antarctic Peninsula results in variations in thermodynamic and pressure between the lower (north of 60° S) and higher latitudes (south of 60° S) that induce the westerlies intensification (De Santis et al 2017, Lee et al 2017). The pronounced increase in the zonal wind and wind speed, particularly towards the lower latitudes (55° S to 50° S) indicates the intensification of the westerlies (figures 1(c) and (d)). This intensification accelerates the Ekman transport of the cooler SST towards the north and the formation of Weddell Gyre approximately from 75° S to 60° S (Liu et al 2004, Vernet et al 2019). The Weddell Gyre is largely associated with the cooling of the surface layers within the gyre and warming towards the north (Wang et al 2017). The atmospheric circulation and Weddell Gyre play a significant role in the process of sea-ice advection, as it results in the eastward advection of sea-ice in the northern limb of gyre, westward in the southern part and towards the north in eastern Antarctic Peninsula (Turner et al 2020). This process creates an optimal environment for sea-ice growth, where the coastal area encounters the displacement of sea-ice northward (sea-ice expands) and disrupts the ocean-atmosphere heat exchange. Therefore, during the austral summer, when the insolation is comparatively high, the sea-ice melting from the surface is not influenced. This is possibly due to the water column’s lower temperature difference below the sea-ice, where no vertical mixing of the warm deep water takes place (Lee et al 2017). Atmospheric forcing has been reported to contribute relatively more than oceanic forcing in the sea-ice loss (Ferreira et al 2015).

3.1.2. Changes during autumn

The declining trend of SIC in the Weddell Sea sector can be linked with the onset of the autumn season when the significant loss is prevalent along the western Antarctic Peninsula in the Amundsen Sea. However, significantly higher SIC trends (between 60° S to 65° S) were observed in the eastern part of the Weddell Sea (figure 2(a)). Similarly, the SST trends show the opposite relation with the trend of SIC. Over the 41 years, SST shows a positive trend in the eastern part of the Antarctic Peninsula, while a significant positive trend was recorded in its northern end and along the western part. However, the overall SST trend in the Weddell Sea is negative which is significant in its eastern part (between 10° W and 20° E) during the autumn (figure 2(b)). The negative trend of SST is associated with the presence of more sea-ice that results in the cooler surface in the eastern
Figure 1. Spatial plot showing the 41 years (1979–2019) trends of austral summer (JFM) for (a) sea-ice concentration (% decades$^{-1}$), (b) sea surface temperature ($^\circ$C decades$^{-1}$), (c) zonal wind (m s$^{-1}$ decades$^{-1}$) and (d) wind speed (m s$^{-1}$ decades$^{-1}$) overlaid by wind vector (u and v components) trends. Black dots symbol represents the region where trends are significant at 95% confidence level.

Weddell Sea (Comiso et al 2017). It has been observed that latitudinal (N-S) differences in the SST are relatively less (figure 2(b)), which leads to the weakening of the westerlies wind. Therefore, zonal wind recorded the shift towards the northeast direction (to the west of 20$^\circ$ W longitude) (figure 2(c)). In the autumn (compared to the summer), the westerlies weakening and anomalous decrease in the zonal wind were observed while the meridional wind strengthens during this period (figures 2(c) and (d)). The intensification of meridional wind is directly associated with the Ekman transport of the warmer ocean water (Årthun et al 2012). Therefore, the movement of warmer surface water towards the western Weddell Sea accelerates the process of sea-ice melting. The SIC trends are positive towards the eastern Weddell Sea, i.e. associated mainly with the intensification of the easterlies (figures 2(a)–(d)) (Holland 2014). As discussed earlier, the Weddell Gyre also determines the direction of sea-ice advection and here the sea-ice is moving towards the eastern Weddell Sea (figure 2(a)). Since 1979, the wind speed has weakened remarkably in the central part of the Weddell Sea, and the lowest negative trend is recorded towards the eastern coast of Antarctica south of 60$^\circ$ S that resulted in higher SIC (figure 2(d)). In this sector, the eastern Antarctic coast shows sea-ice growth due to the gravity-driven flow of sea-ice supported by the significant increase in the easterlies (De Santis et al 2017). Moreover, a change in the wind patterns and its weakened intensity results in a weakening of the Weddell Gyre, which leads to the warm water upwelling (Gordon et al 2007).

3.1.3. Changes during the austral winter

The negative SIC trend recorded at the northern end of the Antarctic Peninsula in autumn has further resulted in no virtual increase in winter SIC trend (figures 2(a) and 3(a)). During the austral winter, this sector experiences significant sea-ice loss towards the south of 65$^\circ$ S, whereas a significant increase is observed in the coastal region (figure 3(a)). The sea-ice formation observed in the eastern Weddell Sea and some parts of the western Antarctic Peninsula are the possible results of the easterlies and northwesterly winds, respectively (Liu et al 2004, Morioka et al 2017). Earlier reports suggest that the easterlies are weak during austral summer and strengthens during the winter (Hazel and Stewart 2019). The winter SST shows a negative (positive) trend towards the south (north) of 60$^\circ$ S as well as in the western Antarctic Peninsula (figure 3(b)). Although, the SST increasing and decreasing trends are not significant in major parts of the Weddell Sea region but they facilitate in the latitudinal temperature difference from north to south. The strength of the Weddell Gyre changes due to the weakening of the wind pattern (Meredith et al 2014, Hazel and Stewart 2019). The zonal wind trend is strengthening from the eastern Antarctic Peninsula towards the northeastern region while weakening occurs over the eastern Antarctic mainland, possibly enhancing the easterlies (figure 3(c)). In winter, the wind speed in the Weddell Sea is relatively low, and the westerlies are weakened considerably towards the south of 65$^\circ$ S (figure 3(d)). Also, the weakening of the westerlies is associated with an increase in the Ekman transport of the warm Atlantic water from
higher latitude to lower latitude (Lee et al. 2017). During winter, the Weddell Gyre is relatively weak due to meridional temperature difference (Lee et al. 2017), resulting in oceanic heat divergence and sea-ice retreat towards the north of 65° S (figure 3(a)). Overall, the sea-ice formation is dominated along the coastal region of the Antarctic mainland, primarily due to the gravity and wind-driven forces that are exacerbated by the intensification of the easterlies.

3.1.4. Changes during spring
The Weddell Sea sector experiences increase in SIC along the coastal shelf-region during the spring season, especially between 40° W and 20° W, while the anomalous decrease was observed in the western part of the Antarctic Peninsula and north of 65° S latitude (figure 5(a)). In these 41 years, the SST trend shows surface warming from the centre of the eastern Weddell Sea, roughly from the 50° E latitude and considerable surface cooling in the eastern Antarctic Peninsula (figure 4(b)). A significant gain in the SST has been observed in the western end of the Antarctic Peninsula. The zonal wind in the spring develops a dipole structure by the intensification of both westerlies (north of 65° S) and easterlies (south of 65° S) (figure 4(c)). The intensification of westerlies (in the north) and easterlies (in the south) leads to a strong Weddell Gyre formation (Jullion et al. 2014). Due to the wind stress above the gyre, the Ekman transport of cooler surface water occurs towards the north of the Antarctic mainland. The Weddell gyre is associated with the warming in the north and cooling towards the south leading to thermodynamically driven sea-ice retreat and expansion in the Weddell Sea, respectively (Mckee et al. 2011).

3.2. Long-term sea-ice variability (1979–2019)
Since 1979, the Weddell Sea sector recorded a maximum (4.78 million km²) and minimum (3.77 million km²) SIE during 2015 and 1999, respectively, while SIE in 2018 was recorded the second-lowest value (3.82 million km²) over the last 41 years (figure S1). The long-term seasonal SIE average in this sector shows the highest SIE record in winter (6.34 million km²) followed by spring (5.48 million km²), autumn (3.66 million km²), and summer (1.59 million km²) (figure S1). Overall seasonal trend analysis reveals that this sector is experiencing sea-ice retreat and expansion during the winter and summer, respectively (table 1). The statistical analysis (1979–2019) indicates that the SIE is having significant negative relation with SST throughout the year, highest in the winter ($r = -0.85$, $p < 0.01$) followed by autumn and spring ($r = -0.84$, $p < 0.01$) and summer ($r = -0.72$, $p < 0.01$) (table S2). The sea-ice growth and retreat are majorly influenced due to SST change (Maheshwari et al. 2013). The earlier study reported that SIE positive trend corresponds well with the SST negative trend (Parkinson 2019). It has been observed that the maximum SIE record in 2015 had recorded the lowest SST (−1.12 °C) while in 2018, when SIE was observed second lowest, the SST was recorded second highest (−0.74 °C) (figure 5). However, in the last 41 years, the average SST is observed to be maximum during summer (−0.03 °C) followed by autumn (−0.94 °C) and the minimum in winter (−1.48 °C) and spring (−1.3 °C). Sea-ice acts as an insulator that restrict the heat exchange between the ocean and atmosphere, thus, influencing the sensible heat flux and prevents the LH loss from the surface (Budillon et al. 2000, Kwok et al. 2017).
Therefore, it is important to understand the energy budget as the incoming radiation increases the sensible heat, whereas evaporation and release of energy from the surface induce the LH that together drives the ocean-atmospheric circulation (Li et al 2011). The atmospheric NHF is showing a relatively positive correlation with SIE in austral summer and spring ($r = 0.29$, $p < 0.1$) in the Weddell Sea sector, whereas there is a strong negative correlation in the autumn ($r = -0.72$, $p < 0.01$) and austral winter ($r = -0.56$, $p < 0.01$) (table S2). The interannual variations are shown in timeseries plot (figure 5), the lowest NHF was observed in the year 1998 (366.43 W m$^{-2}$), which is close to the NHF record in 2015 (367.8 W m$^{-2}$) and highest in the year 1984 (372.36 W m$^{-2}$) followed by 1985 (371.76 W m$^{-2}$), 1988 (371.66 W m$^{-2}$) and 2018 (371.6 W m$^{-2}$). Seasonal NHF analysis shows that maximum NHF is recorded in spring (567 W m$^{-2}$) followed by summer (489.4 W m$^{-2}$) and autumn (214.4 W m$^{-2}$) whereas lowest during winter (207 W m$^{-2}$).

Over the last four decades, the Weddell Sea sector has recorded considerable changes in the sea-ice cover associated with ongoing ocean-atmospheric processes. To understand the far-reaching influence of the tropical processes, the present study has
attempted to link the local climatic conditions and the different climate variability modes which include ENSO, AMM, SAM, and IOD (figure 5; table S2). The SAM is a large-scale pattern associated with the mid-latitude westerlies (Thompson and Solomon 2002, Simmonds 2015) that largely influences the SST patterns in the Weddell Sea (Fusco et al 2018). The positive phase of SAM is related to an increase of SST, leading into the warmer water at the ocean surface, attributed to strong upwelling during the winter in the Weddell Sea (Lefebvre et al 2004). Hence, the correlation between the SAM and SST is negative in this region, indicating that sea-ice retreats (advances) with an increase (decrease) in SST. The present study shows that annual SIE does not have a significant correlation with SAM. However, the seasonal correlation matrix computed between SIE and SAM shows significant positive correlation during the austral summer ($r = 0.26, p < 0.1$) and significant negative correlation in austral winter ($r = -0.32, p < 0.05$) and spring ($r = -0.27, p < 0.1$) while autumn does not show any significant relation (table S2). This is possibly attributed to the SAM relation with SIE that intensifies with the onset of spring and the next summer, which is anomalous to the intensification of westerly winds (Clem et al 2016). The positive SAM results in an intensification of the westerlies over the $55^\circ$ S latitude in the Weddell Sea, largely due to the pressure difference over Antarctica (low pressure) and subtropical latitudes (high pressure), thus leading to surface freshening and sea-ice expansion (Lee et al 2017, Turner et al 2017, Screen et al 2018). The observation reveals that the Atlantic SST does not influence the SIE in this sector, as the SIE recorded does not significantly correlate with the AMM throughout the year (table S2). The AMM is the dominant mode of non-ENSO coupled ocean-atmospheric variability in the Atlantic basin leading to the meridional

---

**Figure 5.** Seasonal anomalies of (a) austral summer; (b) autumn; (c) austral winter and (d) spring showing interannual variation (1979–2019) of sea-ice extent (million km$^2$), sea surface temperature ($^\circ$C), net heat flux (W m$^{-2}$), ENSO, AMM, and SAM during the (1979–2019) over the Weddell Sea (averaged from 60$^\circ$ W to 20$^\circ$ E and 55$^\circ$ S to 75$^\circ$ S). The anomalies are computed based on the climatology year (1981–2010).
displacement of the intertropical convergence zone towards the warmer hemisphere (Vimont and Kossin 2007). The SIE has a weak, insignificant correlation with IOD throughout the year, except in austral winter ($r = -0.30, p < 0.05$), which has been reported in an earlier study (Nuncio and Yuan 2015). The IOD mode is associated with a difference in the changes in SST and subsurface ocean temperature in the eastern and western Indian Ocean (Feng et al 2019) where positive (negative) IOD is associated with warming (cooling) in the western Indian Ocean. However, the ENSO mode is the primary driver influencing SST of the Pacific Ocean through the Rossby wave trains which are influenced by the tropical Walker circulation (Wang et al 2019a).

3.3. Composite analysis—high minus low sea-ice

To understand the sea-ice variability due to the ocean-atmospheric heat exchange during high sea-ice years, we have examined the composite difference anomaly (high minus low ice years) of NHF and SST (figure 6).

The computed composite analysis shows the western Weddell Sea experiences positive SIC anomaly while the western Antarctic Peninsula shows negative SIC anomaly during the austral summer (figure 6(a)). In the same period, the NHF recorded the negative anomaly in the western region of the Weddell Sea (60° W to 45° W) when the majority of the sector experiences a positive NHF anomaly (figure 6(b)). However, a negative SST anomaly was recorded in the Weddell Sea, and the positive anomaly was dominant in the western Antarctic Peninsula (figure 6(c)). It can also be inferred that warming is experienced in the western Antarctic Peninsula region due to recorded positive NHF and SST anomalies. From figure 6(a), it has been observed that the SIC gain is comparatively higher in the western Weddell Sea when compared to its northeastern regions. As a result, the region having higher SIC is largely associated with the higher negative SST anomaly ($r = -0.65, p < 0.01$) that accelerates the formation of sea-ice (figures 6(a)–(c) and table S2).

In autumn, the negative SIC anomaly is observed in the central part of the western Weddell Sea region (figure 6(d)). In these high sea-ice years (table S1), the anomaly of NHF shows negative and positive heat flux towards the south (roughly between 50° W and 0°) and north of 60° S, respectively (figure 6(e)). This could be attributed to the heat gained during the summer months, which is released back to the atmosphere in the later season, especially in autumn and winter (England et al 2018). The SST shows strong positive anomalies towards the north of 60° S with a relatively lower negative anomaly in a small region of the eastern Antarctic mainland during autumn, where the loss of heat from the ocean to the atmosphere is highest (figure 6(f)). The loss of SIC is resultant of both NHF ($r = -0.74, p < 0.01$) and SST ($r = -0.78, p < 0.01$) (figures 6(e) and (f), table S2). The warming signal of the ocean is persistent over the north of 60° S, and significant positive relation between NHF and SST ($r = 0.70, p < 0.01$), which is possibly linked to the atmospheric heat.

Similarly, in the high sea-ice years during the austral winter, the SIE anomaly shows a considerable SIC increase and decrease in western and eastern Weddell Sea, respectively, particularly towards the north of 60° S (figure 6(g)). The sea-ice increase can be deciphered with a negative NHF anomaly over the northern Antarctic Peninsula and into the northwestern region (roughly below the 60° S), while a comparatively positive anomaly is predominant over 60° S (figure 6(h)). The SST shows positive anomaly only towards the northeastern while the majority of the Weddell Sea experiences negative anomaly (figure 6(i)). The positive SIC anomaly nearly northward of 63° S in the austral winter correlates well with the negative NHF ($r = -0.59, p < 0.01$) and SST ($r = -0.59, p < 0.01$) anomalies (table S2, figures 6(g)–(i)).

The SIC anomaly indicates negative SIC anomaly persists in a major part of the Weddell Sea in the spring season (figure 6(j)). The negative NHF anomaly dominates the Weddell Sea sector, but positive anomalies exist towards the south of 60° S, mostly in its eastern part (figure 6(k)). The positive SST anomaly is observed towards the east of 0° (figure 6(l)). There is a significant negative correlation between NHF and SST ($r = -0.32, p < 0.05$) in the Weddell Sea during spring (table S2). The analysis reveals that there is an inverse relationship between the pattern of NHF and SST (figures 6(k) and (l)). From figures 6(j)–(l), the sea-ice loss in the western Antarctic Peninsula is linked to the positive and negative anomalies of SST and NHF. However, the positive SIC anomaly in the Weddell Sea is resultant of the strong positive and negative correlation between NHF ($r = 0.39, p < 0.05$) and SST ($r = -0.73, p < 0.01$), respectively (table S2).

The positive NHF anomaly corresponds to the heat loss from the atmosphere to the ocean and vice versa, while the amount of energy transferred to the atmosphere increases in the area having low sea-ice cover (England et al 2018). The heat loss from the ocean through the upward heat transport is the outcome of ocean advection, diffusion, and convective overturning (Zhang 2007). It has been reported that deep convection occurs in the region of retracted SIE, which accelerates the upper and lower level diabetic heating and cooling, respectively (White et al 2004). A study on the coupled phenomenon of atmosphere-ocean-sea ice revealed that the Antarctic Circumpolar Wave is postulated as an eastward propagation of the covarying interannual sea level pressure, SST, and SIE anomalies (White and Simmonds 2006). In the positive Antarctic Circumpolar Wave, there is an upward transfer of heat and positive SST anomaly, which is later balanced by deep convection (Simmonds...
Figure 6. Composite difference analysis map of the Weddell Sea showing the high (years >1 standard deviation) minus low (years >−1 standard deviation) sea-ice years, based on the normalised timeseries of SIC anomalies (table S1). The composite anomalies for SIC, NHF, and SST are shown as (a)–(c) austral summer, (d)–(f) autumn, (g)–(i) austral winter, and (j)–(l) spring.

2003). Further, the energy transfer from the ocean to the atmosphere results in cool SST, whereas from the atmosphere to the ocean results in warmer SST (Christoph et al 1998). The computed correlation between NHF and SST indicates that their correlation is positive in austral summer and winter (r = 0.32, p < 0.05), although a strong significant strong relation was observed in autumn (r = 0.70, p < 0.01) and a significant negative correlation was observed in spring (r = −0.32, p < 0.05) (table S2). It has been speculated that the heat fluxes widely impact the oceanic components through the atmosphere. The mechanism of convective overturning and vertical advection is merely a result of heat transport into the mixed layer (Zhang et al 1998). Seasonally, the SST is higher in autumn and spring and lower in austral summer and winter. The absence of solar radiation in winter thereby results in enhanced upward radiation from the open-seas (Yuan and Martinson 2000) in the following season. However, there is an interannual variability in the Antarctic Circumpolar Wave as it can only be a coupled mode at some point and uncoupled mode at other points (Cerrone et al 2017a).

3.4. Composite analysis—positive minus negative SAM

The composite analysis was performed using the SAM index to understand its influence on the SIC, downward NIR, LHF, SHE, and NHF in the Weddell Sea (figure 7) for different seasons. As discussed earlier (section 3.2), the SAM shows a significant correlation with SIC during the austral summer (positive correlation) and winter (negative correlation) (table S4). Therefore, the positive phase of the SAM is associated with sea-ice growth in austral summer, while loss during the austral winter has been observed in the Weddell Sea (figure 7). The SIC increase is observed mainly towards the east of 40° W, whereas the region lying towards the Antarctic Peninsula experiences a decrease in SIC during austral summer. The wind patterns also play a significant role in determining the sea-ice during different SAM phases (Doddridge and Marshall 2017). The Antarctic sea-ice has a two-dimensional response towards the different phases of SAM. The positive SAM is associated with the intensification of westerlies and sea ice growth in the austral summer, as reported in the earlier studies, while the easterlies intensify, resulting in the retreat of sea ice southward in the austral winter (Lefebvre et al 2004, Pezza et al 2011). Similar observations of an increase in sea-ice (figure 1(a)) due to intensification of westerlies during austral summer (figure 1(d)) are recorded that accelerates the sea-ice towards the north. The Weddell Sea mostly shows a negative anomaly in the austral winter, particularly at northern tip of the Antarctic Peninsula during positive SAM. The spatial patterns of positive and negative anomalies are seen in autumn and spring, respectively (figure 7).

The composite difference analysis for the downward NIR shows a remarkable seasonal variation in the Weddell Sea sector. During positive SAM years in the austral summer, the region lying towards the west and east of 20° W of Weddell Sea experiences positive and negative anomalies, respectively (figure 7). However, downward NIR in the Antarctic Peninsula region shows a higher negative anomaly. In autumn and austral winter, downward NIR shows a negative anomaly, but it is not significant. In spring, it shows the highest negative anomaly over a major part of the Weddell Sea, except a part of the eastern region experiencing a positive anomaly. The downward NIR decrease is primarily associated with a decrease in cloud cover (Wang et al 2019b). The study shows
an inverse relationship between SAM and downward NIR anomaly which is significant in autumn ($r = -0.26, p < 0.1$) and spring ($r = -0.30, p < 0.05$). Therefore, it can be derived that positive SAM is associated with the lower downward NIR anomaly in the Weddell Sea. In addition, downward NIR shows significant positive relation with SIC throughout the year, except in the austral summer (table S4). Hence, it can be inferred that summer sea-ice increase is not attributed to the increase in downward NIR in the Weddell Sea. In comparison, when the downward NIR decreases, the SIC is also decreased during the subsequent seasons. The increasing downward NIR is possibly due to the sea-ice reflectance resulting in positive downward NIR in the regions having positive SIC anomaly and vice versa (Xia et al 2020). The increase or decrease in downward NIR is likely to be influenced by the LHF, SHF, and NHF in one or the other season (table S4).

The positive LHF is associated with surface cooling due to heat loss from the ocean to the atmosphere. The Weddell Sea sector experiences a positive anomaly during the positive SAM years in the austral summer, winter, and spring and a negative anomaly in the autumn ($r = -0.40, p < 0.01$) (table S4). Also, SAM has a negative correlation with SHF and NHF anomalies throughout the year with a significant relationship in austral summer and autumn. During the positive SAM years, the austral summer and autumn show negative SHF and NHF anomalies in most of the Weddell Sea sectors (figure 7). However, positive NHF is dominant in the austral winter and spring.

**4. Summary and conclusions**

The long-term 41 years annual record shows, the SIE has increased about 21% between the record minimum (1999) and the maximum (2015), whereas it has dramatically declined by about 20% between 2015 and 2018. However, the average seasonal record shows that SIE increase is prominent in autumn (~56.5%) when, compared to winter (~42%) relative to their preceding seasons austral summer and autumn, respectively. Further, the SIE decrease is higher in the austral summer (~71%) than in spring (~14%) with respect to spring and austral winter, respectively. Hence, net sea-ice in the Weddell Sea sector remained only about 14% throughout the year, which is a resultant of sea-ice growth (~98%) and loss (~84%) over the last 41 years.

The study reveals that SIE of the Weddell Sea sector has increased at the rate of $2.5 \pm 3.5$
The study reveals that the SIC variability during austral summer and spring are influenced mainly by the SST. However, during austral winter, the SIC is largely associated with both the NHF and SST in the Weddell Sea. The study demonstrated that during the austral summer and spring, the oceanic heating is the primary force resulting in sea-ice variability, while both ocean-atmospheric forcings influence the instability during austral and winter.

**Data availability statement**

All data that support the findings of this study are included within the article (and any supplementary files).

**Acknowledgments**

We gratefully acknowledge Ministry of Earth Sciences (MoES), New Delhi, for continuous support. Thanks are due to Dr. M. Ravichandran, Director, National Centre for Polar and Ocean Research (NCPOR), Goa, for insightful comments and suggestions on the previous draft, which improved the quality of the paper. This authors sincerely acknowledge various organisations such as National Snow and Ice Data Center (NSIDC), National Oceanic and Atmospheric Administration (NOAA), Copernicus Marine Environment Monitoring Service, National Centre for Atmospheric Research (NCAR), European Centre for Medium-Range Weather Forecasts (ERA5), Technische Universitat Dresden, and the Polar Science Center, Applied Physics Laboratory for providing various datasets available in their portals. Authors thank anonymous reviewers and Editors—ERL, for their insightful comments and suggestions on the previous draft, which improved the quality of the paper. This is NCPOR contribution no J-93/2020–21.

**ORCID iDs**

Avinash Kumar  
https://orcid.org/0000-0002-6511-8435

Juhi Yadav  
https://orcid.org/0000-0002-4575-7942

Rahul Mohan  
https://orcid.org/0000-0001-8758-2215
