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Key Points:
- Summer sea ice in the Weddell Sea, Antarctica decreased to a near-record low extent in 2016/2017 and has subsequently remained low
- Westerly winds of record strength and the reappearance of the Maud Rise polynya were significant factors in the change in ice conditions
- The Weddell Sea summer ice extent is now 1,000,000 km^2 less than in 2013/2014

Supporting Information:
- Supporting Information S1

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Recent Decrease of Summer Sea Ice in the Weddell Sea, Antarctica

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Abstract In Austral summer 2016/2017, the sea ice extent (SIE) in the Weddell Sea dropped to a near-record value in the satellite era (1.88×10^6 km^2), a large negative seasonal anomaly that persisted in an unprecedented fashion for the following three summers. Various atmospheric and oceanic factors played a part in the change. Ice loss started in September 2016 when the northern Weddell Sea experienced westerly winds of record strength, advecting multiyear sea ice from the region. In late 2016, a polynya over Maud Rise contributed to low SIE over the eastern Weddell Sea. With extensive areas of open water early in the summer, upper ocean temperatures increased by ~0.5°C, with the anomalies persisting in subsequent years. The reappearance of the Maud Rise polynya in 2017, high ocean temperatures, and storms of record depth kept the summer SIE low.

Plain Language Summary Sea ice is an extremely important part of the Antarctic environment, providing an essential habitat for seals, seabirds, and Antarctic krill. It also caps the ocean, strongly influencing the transfer of heat from the relatively warm ocean into the frigid Antarctic atmosphere. In addition, it affects the ocean circulation through the release of salt when ice grows. In 2016/2017, the extent of summer sea ice in the Weddell Sea, Antarctica, dropped to a near-record level in the satellite era, which starts in late 1978. The ice loss was in part caused by the reappearance of the Maud Rise polynya, an area of open water within the main area of pack ice. The ice-free conditions allowed more energy from the Sun to be absorbed by the ocean, with the higher ocean temperatures persisting in subsequent years and slowing the formation of new ice. In parallel, westerly winds of record strength carried sea ice out of the region, so that the summer sea ice extent in the Weddell Sea is now 1,000,000 km^2 less than in 2013/2014.

1. Introduction

Variability and change in the Weddell Sea sea ice cover is important for many atmospheric (Turner et al., 2017), oceanographic (Ohshima et al., 2013), biological (Meyer et al., 2017), and chemical processes (Zemmelink et al., 2008), as well as logistical activities (Turner et al., 2002). The Weddell Sea is a unique region containing the largest amount of Antarctic multiyear sea (Parkinson & Cavalieri, 2012; see their Figure 1). Southern Ocean biota are strongly influenced by the presence, seasonality, and properties of sea ice. Sea ice provides an essential habitat for many species, including seabirds, seals (Trathan et al., 2020), and krill (Meyer et al., 2017).

Sea ice can survive the summer (December–February) melt over the western Weddell Sea east of the Antarctic Peninsula (Comiso & Nishio, 2008) since it is a frigid region remote from relatively warm air-masses found west of the peninsula and in other sectors of the Southern Ocean. The climatological cyclonic atmospheric circulation and the ocean gyre in the Weddell Sea result in westward ice advection along the southern part of the region, northward advection of ice along the eastern peninsula, and eastward advection of ice across the northern limb of the cyclonic circulation. The north-western Weddell Sea is an area of net ice melt, compared to the southwestern Weddell Sea, which is an area of net production (Kimura & Wakatsuchi, 2011).

During summer, the interannual variability of mean sea level pressure (MSLP) over the Weddell Sea is larger than over any other region of high southern latitudes besides the Amundsen-Bellingshausen Sea where the

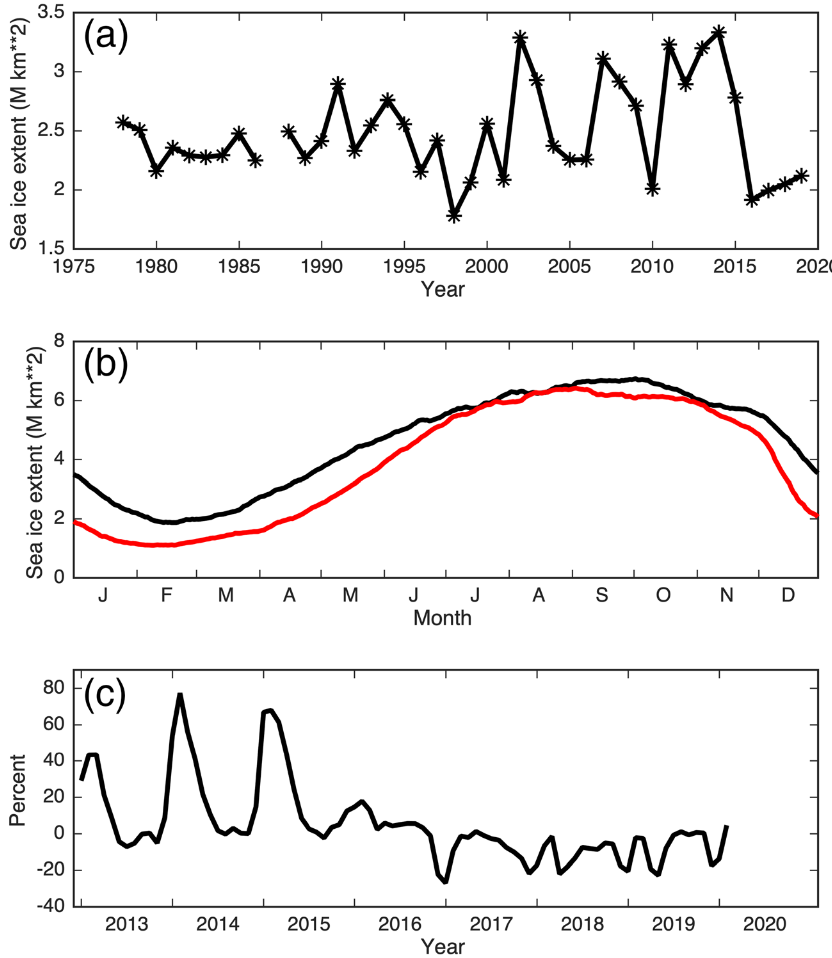

Figure 1. (a) The 1978/1979–2019/2020 mean summer SIEs for the Weddell Sea. The *x* axis values refer to the year in which the December of each summer occurred. (b) Mean annual cycles of Weddell Sea SIE based on daily data for 2013–2015 (black) and 2017–2019 (red). The month indicators mark the midpoint of each month. (c) The monthly percentage SIE anomalies (from the monthly mean climatological SIEs for 1979–2008) since 2013. The year indicators mark the midpoint of each year.

"pole of variability" is located (Connolley, 1997). Variability in MSLP in the Weddell Sea will influence the strength of the southerly barrier wind and be a contributing factor to the large interannual variability in the sea ice extent (SIE) in the Weddell Sea. Since the start of the satellite-based sea ice data in 1978, there has been a small (0.05×10^6 km^2 dec^{-1}) but statistically insignificant increase of summer SIE in the Weddell Sea (Figure 1a). There have been summers with both large negative and positive SIE anomalies, but these have been followed by reversals or reductions in the sign of the anomaly. However, between 2015/2016 and 2016/2017, there was the largest decrease in summer SIE in the 40-year record (0.89×10^6 km^2). This came after the major Antarctic-wide decrease of sea ice in spring 2016 (Meehl et al., 2019; Purich & England, 2019; Turner et al., 2017; Wang et al., 2019; Wang et al., 2019), in which the Weddell Sea sector made the largest contribution (34%) to the total Southern Ocean sea ice decrease. While large SIE anomalies recovered quickly in previous years, the 2016/2017 anomaly has persisted until summer 2019/2020, indicating an unprecedented change in Weddell Sea sea ice.

The largest decrease in percentage SIE anomaly has been during the summer, but SIE has also decreased during the fall (March–May) (Figure 1b), although by midwinter, there has been little change in extent. The major change in sea ice in the Weddell Sea in 2016 can also be appreciated via the monthly percentage SIE anomalies for 2013–2019 (Figure 1c). The largest significant summer sea ice concentration (SIC) decrease over 2013/2015–2016/2018 has been over the southeast Weddell Sea and along the eastern edge of the region of multiyear sea ice in the western Weddell Sea (Figure 2a).

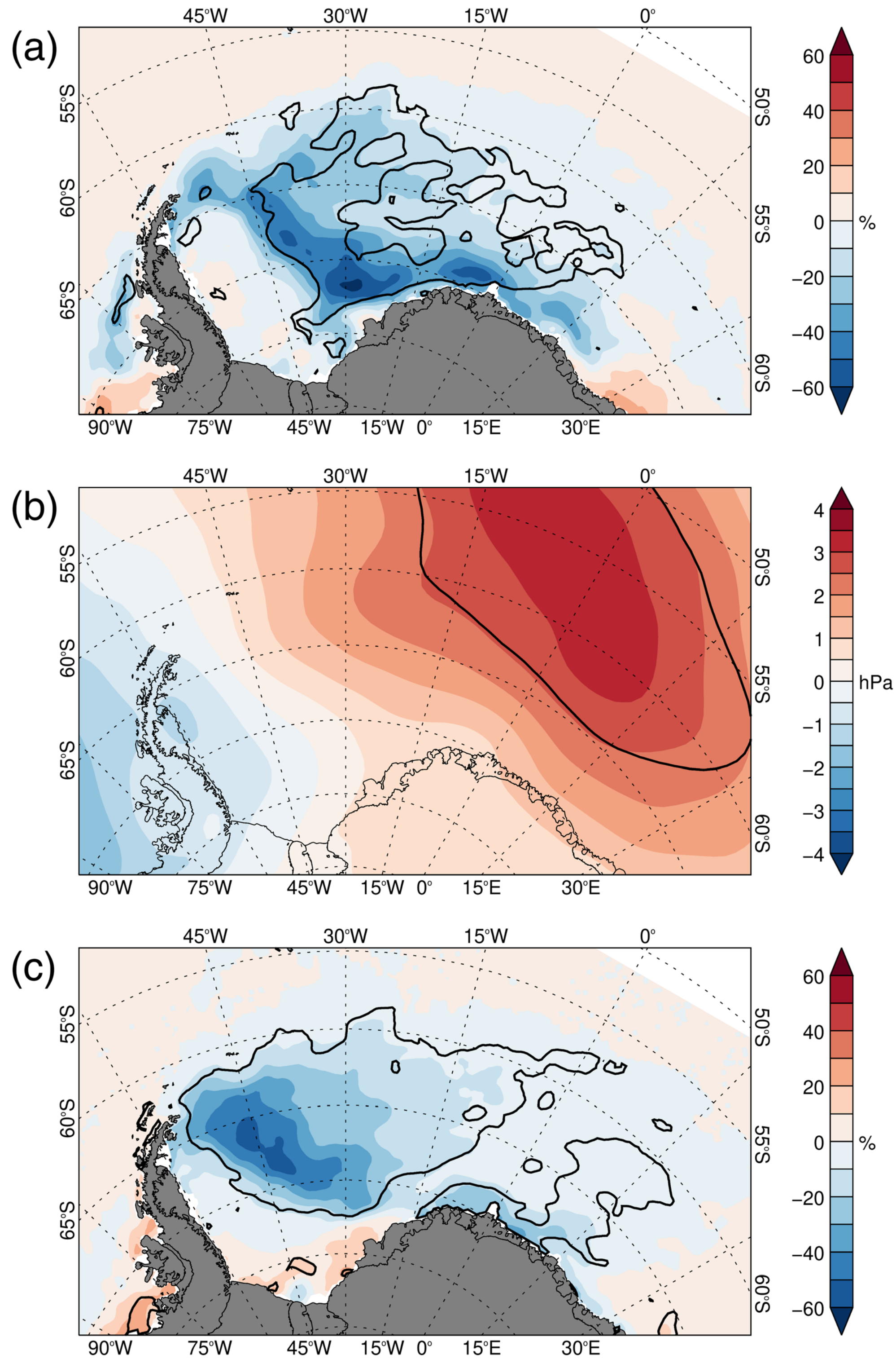

Figure 2. (a) The difference of summer SIC between 2013/2015 and 2016/2018, (b) difference in summer MSLP between the years in the lower and upper quartile of SIE in the Weddell Sea prior to 2016, and (c) the same as panel (b) but for SIC. In all the figures, the areas where the difference is significant at $p < 0.05$ are enclosed by a bold line.

Here we examine the conditions that led to the low summer Weddell Sea SIE in 2016/2017 and consider how the anomalies could persist for the following three summers.

2. Data and Methods

Daily, monthly, and seasonal SIE for the Weddell Sea sector (60°W to 20°E) were computed from SIC data from the U.S. National Snow and Ice Data Center (www.nsidc.org). SIE was computed as the total area of all satellite pixels where the SIC equaled or exceeded 15%. We have used the National Aeronautics and Space Administration (NASA) Team algorithm 1.1 SIC values (Cavalieri et al., 1984) as these are available as a consistent time series from late 1978 to 2018. For 2019, we used the NASA Team Real Time data. Anomalies were computed from a 30-year base period of 1979–2008. Ice drift motion data were obtained from the Eumetsat Ocean and Sea Ice Satellite Applications Facility (http://osisaf.met.no/p/ice/index.html#lrdrift).

Atmospheric conditions were examined using the ECMWF Interim (ERA-Interim) reanalysis fields. These are reliable across high southern latitudes from 1979 and are considered the best reanalysis data for depicting Antarctic climate (Bracegirdle & Marshall, 2012).

To investigate oceanic conditions within the Weddell Sea, ARGO float data were employed. Quality-controlled monthly potential temperature and salinity data available at a $0.25° \times 0.25°$ grid spacing were obtained for 1979–2018 from ECMWF's advanced operational ocean reanalysis system (ORAS5) (Zuo et al., 2018). Optimum interpolated sea surface temperature (SST) (OI SST v2) data were acquired from National Oceanic and Atmospheric Administration (NOAA), with the data constructed from merging the available satellite and in situ observations (Reynolds et al., 2002). SSTs in the sea ice zone were estimated by Reynolds et al. (2002) from passive microwave brightness temperatures using the method of Parker et al. (1999). We have averaged the ocean variables over the whole Weddell Sea region from 60°W to 20°E and 55°S to the Antarctica coast. The mixed layer depth was computed as the uppermost level of uniform potential density ($\sigma\theta$) at the depth where the density in the upper level varies by 0.01 kg m^{-3} with reference to the surface (Kaufman et al., 2014). Kaufman et al. (2014) compared various methods of determining mixed layer depth and found no significant difference among all the methods.

We used the University of Melbourne cyclone tracking scheme (Murray & Simmonds, 1991) to compute depression statistics, such as storm frequency and maximum depth (Phillips, 2020). The scheme used ERA Interim reanalysis MSLP fields at N80 resolution (for details, see Murray & Simmonds, 1991). Here we used central pressure P (hPa) and DP (hPa) of each depression. DP represents the pressure difference between the edge and the center of a given system (Simmonds et al., 2003), providing an indication of the strength of the low.

3. Variability of Summer Sea Ice in the Weddell Sea

Over the summers 1978/1979–2015/2016, the Weddell Sea experienced large variations in SIE, from 1.78×10^6 km^2 (1998/1999) to 3.33×10^6 km^2 (2014/2015) (Figure 1a). The difference in summer MSLP between the years in the lower and upper quartiles of SIE in the Weddell Sea prior to 2016/2017 (Figure 2b) was characterized by a statistically significant ($p < 0.05$) positive MSLP anomaly in the South Atlantic and a small nonsignificant negative anomaly to the west of the Antarctic Peninsula. Such anomalies suggest a greater frequency of warm northwesterly flow across the northwestern Weddell Sea, reducing the northeastward export of sea ice from the southwestern Weddell Sea, resulting in a negative SIC anomaly to the east of the tip of the Peninsula (Figure 2c). The greater northwesterly flow also gives a positive SIC anomaly over the southern Weddell Sea as a result of less ice export. A similar scenario occurred in summer 2001/2002 when extensive sea ice along the coast of Coates Land prevented the resupply of Halley station for the first time in 50 years (Turner et al., 2002).

Sea ice retreat in the Weddell Sea is greatest during December (mean -2.47×10^6 km^2), being larger than that of November (-0.73×10^6 km^2) or January (-1.22×10^6 km^2) (Figure 1b). Not surprisingly, Decembers with large SIE retreat tend to be followed by a January with reduced retreat as there is less sea ice remaining that can be melted.

Loss of sea ice in December is critical in influencing the mean summer SIE, as once large negative sea ice anomalies are established in that month, they persist well into the summer leading to warming of the

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ocean surface and additional ice melt. This can be appreciated from the September–February daily SIE and 3-day SIE changes for 2010/2011 (Figure S1 in the supporting information), which was a summer with one of the smallest mean SIE prior to 2016/2017. However, it should be noted that the timing and spatial pattern of the sea ice anomalies in 2010/2011 was rather different from that in recent summers. During December 2010, there were three large 3-day decreases of SIE, which reduced the total Weddell SIE. These were all associated with high MSLP near 0°E and depressions between the Antarctic Peninsula and 0°E, which advected warm South Atlantic air over the eastern Weddell Sea.

Summer 1998/1999 had the lowest mean SIE of all (Figure 1a) with the largest 3-day sea ice retreat taking place at the very start of December. As with other summers of low SIE, this rapid retreat took place with a deep cyclone (<948 hPa central pressure in this case) moving into the southern Weddell Sea.

Climatologically, December is a month of sea ice decrease over the eastern Weddell Sea, with the largest ice loss east of 15°W. Warm air advection into this area early in the melt season has a lasting impact through the summer.

4. Establishment of the 2016/2017 Record Negative Sea Ice Anomaly

The reanalysis data show that during April–August 2016, southerly winds across the western Weddell Sea (60–20°W) were very close to the strongest in the record. This contributed to the establishment of a positive SIC anomaly along the northern sea ice edge on the eastern side of the Weddell Sea, leading to a positive SIE anomaly for the whole Weddell Sea, which reached a maximum of 0.71×10^6 km^2 on 29 August (Figure S2a). However, September 2016 had extensive cyclonic activity over the southern Weddell Sea, with the MSLP anomaly for the month being less than −12 hPa on the Ronne Ice Shelf (Figure S3a). During September, the deepest storm ever recorded in the southern Weddell Sea developed, reaching a central pressure of 931 hPa on 9 September (see Figure 3a). MSLP was very low across the whole of the Antarctic, with record low monthly mean MSLP anomalies observed at six staffed and automated weather stations, consistent with the strong positive Southern Annular Mode (SAM) index of 2.46, which tied for the fourth most positive value in the record (Scambos & Stammerjohn, 2018).

Low pressure over the southern Weddell Sea and high pressure over the South Atlantic (Figure S3a) gave record September westerly winds over the northwest Weddell Sea. The strong winds advected sea ice to the east and northeast (Figure S4), creating a large area of negative SIC anomaly in the northwest Weddell Sea by 1 October (Figure S2b) and contributing to the overall ice loss.

Another factor in the reduction of Weddell Sea sea ice in late 2016 was the reappearance of the Maud Rise polynya. This feature was present in the winters of 1974–1976 and has been studied extensively via satellite data and modeling investigations (Carsey, 1980; Martinson et al., 1981). The 2016 polynya grew from an area of lower ice concentration close to the Maud Rise seamount (10°E, 68°S), with its initial appearance in the middle of July attributed to ocean preconditioning by salinity anomalies (Campbell et al., 2019; Jena et al., 2019). The polynya subsequently closed, but reopened and was clearly apparent in the SIC anomaly field on 1 November 2016 (Figure S2c). In some earlier years, there have been small negative SIC anomalies in the Maud Rise area at the start of November, for example, 2010 and 1995; however, the negative anomaly was larger on 1 November 2016 than observed previously on that day of the year (Figure S5). During November 2016, the negative anomaly expanded toward the west and then north as a result of ice melt as warm air arrived in a northwesterly flow associated with a deep depression over the western Weddell Sea (Figure 3c). The SAM index for November 2016 was −3.12, the fifth lowest November value on record, with new record high November MSLP values set at five continental staffed and automated weather stations. This pattern marked a dramatic switch from the strong positive SAM index in September to the strong negative SAM index in November, favoring warm, northerly flow toward much of the continent resulting in an ~3°C positive surface air temperature (SAT) anomaly (2 standard deviations) over the Weddell Sea, new record high November mean SATs at four coastal East Antarctic staffed stations, and the overall Antarctic-wide SIE dropped to more than 5 standard deviations below the November climatological average (Scambos & Stammerjohn, 2018).

The mean December 2016 SIE was the lowest on record (3.12×10^6 km^2). In December 2015, there had been a positive SIE anomaly at the start of the month (Figure 4a), but in 2016, the SIE was close to the long-term

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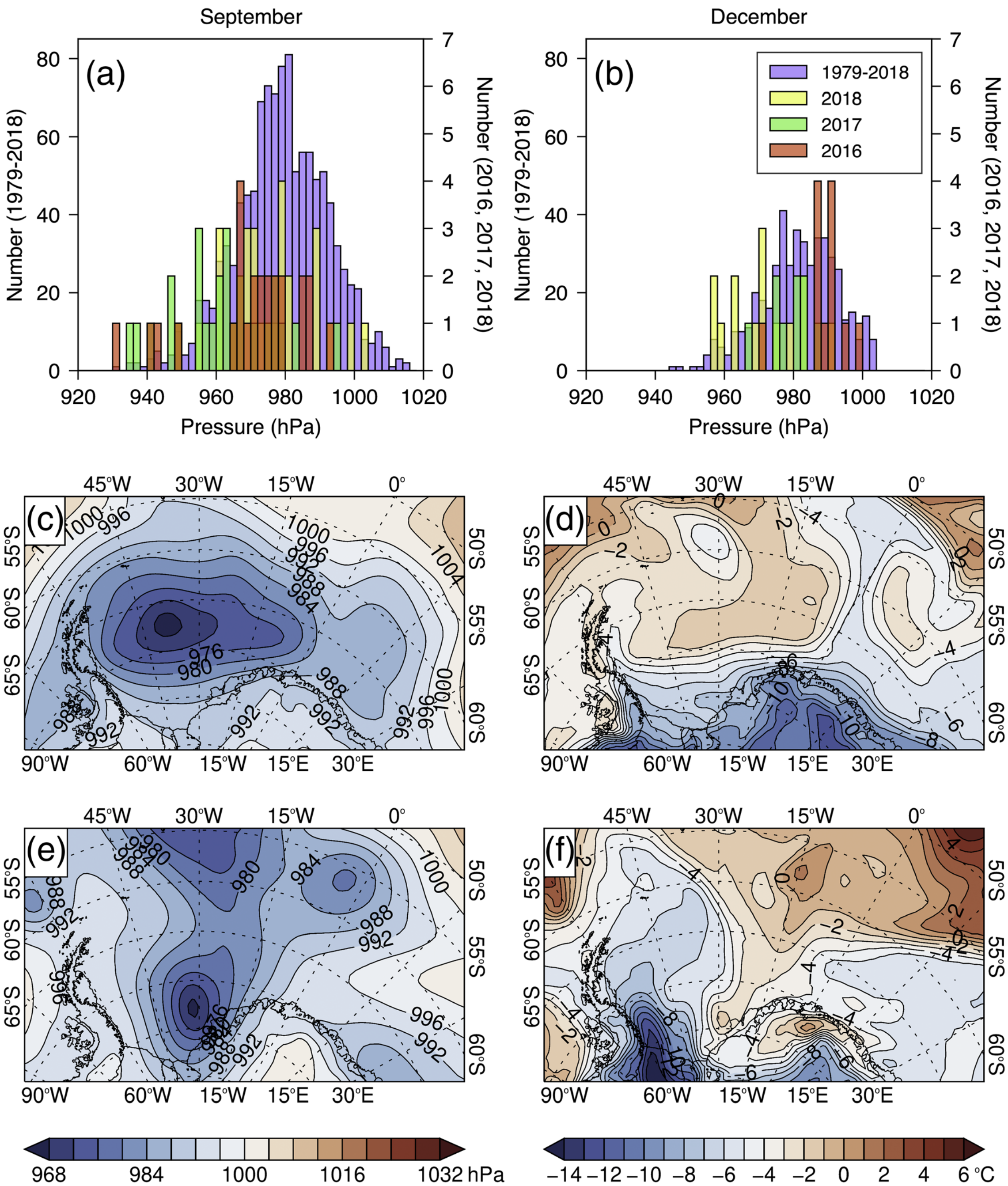

Figure 3. Depressions in the Weddell Sea. Histograms of the minimum depth of all depressions within 70–80°S, 60–0°W for 1979–2018 (blue), 2016 (red), 2017 (green), and 2018 (yellow). Data are shown for September (a) and December (b). Fields for 00 UTC 26 November 2016, (c) MSLP, and (d) 950 hPa temperature. Fields for 6 UTC 12 December 2016 (e) MSLP and (f) 950 hPa temperature.

mean (Figure 4b). Over the first 10 days of December 2016, the SIE decreased most to the east of 0°E in strong mean flow from the south, with the sea ice being carried to more northerly latitudes and relatively warm ocean conditions that accelerated the ice melt. However, the most rapid sea ice loss occurred over 11–15 December 2016 (Figure 4b), with the largest daily ice loss of 0.25×10^6 km^2 over 12 and 13 December. In addition, the retreat of -0.64×10^6 km^2 over the 3 days ending 13 December was the fourth largest 3-day retreat in the record. The period culminated in the largest negative SIE anomaly of -1.30×10^6 km^2 occurring on 15 December.

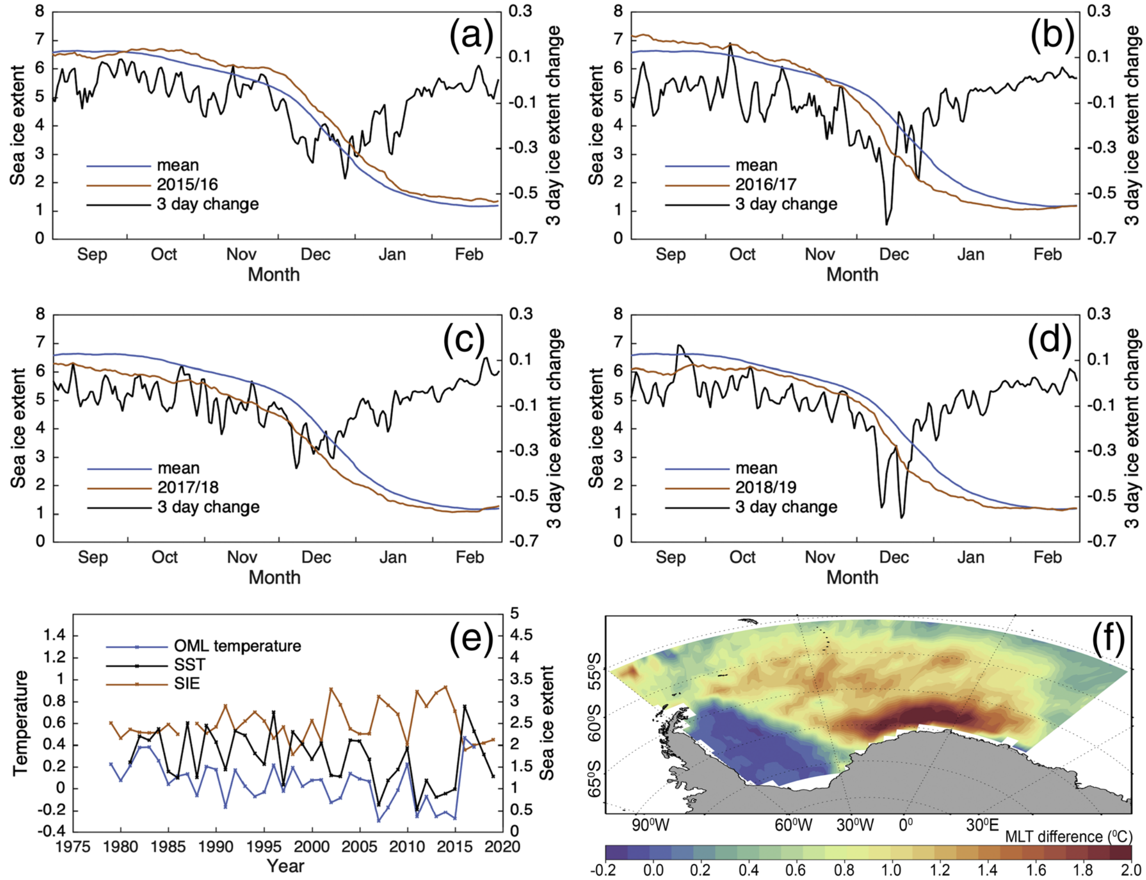

Figure 4. The September to February daily SIEs for the Weddell Sea, along with the 3-day SIE retreats and the long-term mean daily extents (all $10^6 \times km^2$), (a) 2015/2016, (b) 2016/2017, (c) 2017/2018, and (d) 2018/2019. (e) The summer OML temperature, SST, and SIE for 1979/1980–2018/2019, spatially averaged over the Weddell Sea (60°W to 20°E, and 55°S to the Antarctic coast). (f) The difference of summer OML temperature between 2013/2014/2015 and 2016/2017 based on ECMWF ORAS5 data. Data were available until December 2018. The OML was computed as the uppermost level of uniform potential density (σθ) at the depth where the density in the upper level varied by 0.01 kg m^{-3} with reference to the surface (Kaufman et al., 2014).

The 5-day period of 11–15 December was characterized by a deep depression that developed over the central Weddell and tracked down the coast of Coates Land before dissipating on the Ronne Ice Shelf. The occurrence of depressions is at a minimum during the summer (Jones & Simmonds, 1993), and a deep low in the Weddell Sea close to 30°W, such as occurred on 12 December 2016 (Figures 3e and 3f show the MSLP and 950 hPa temperature for 6 GMT 12 December 2016), is a relatively rare event, although not unique (see Figure 3b). Nevertheless, the 12 December 2016 storm was one of the deepest storms in the record that reached south of 75°S, having a central MSLP of <968 hPa. More specifically, this storm was one of the seven storms in the entire record with a DP in the range 8–11 hPa that propagated so far south. These seven storms constitute only 3% of the total number of December storms found south of 75°S in the record. It should be noted that some other deep December storms in the southern Weddell Sea had much less of an effect on the total Weddell Sea area SIE because their strong winds were located over areas that already had little ice or their impact was negated by SIE increases in other parts of the large Weddell Sea sea ice area.

On 12 December, the cyclone reached its maximum depth when it was located just off the Ronne Ice Shelf (72.62°S, 31.67°W); it then dissipated between 13 and 14 December moving as far as 78°S. The rarity of this event is confirmed by the strong winds recorded over the period. The surface observing program at Halley Station on the Brunt Ice Shelf recorded a wind speed of 33 kts at 3 GMT 12 December, which is within the top 1% of observed wind speeds at the station in December. As the low developed from a trough extending down the Weddell Sea, warm air was advected southwards down the coast of Coates Land with 950 hPa temperatures above −2°C at 75°S at 6 GMT 12 December 2016 according to the ERA data (Figure 3f). The second half of December was characterized by higher atmospheric pressure and much slower sea ice retreat.

January and February 2017 had anomalously northeasterly atmospheric flow that advected sea ice toward the western and southern parts of the Weddell Sea and the region of multiyear sea ice, resulting in an ~1.5°C positive SAT anomaly (>3 standard deviations) close to the Greenwich Meridian (Scambos & Stammerjohn, 2018). The minimum SIE for the summer was 1.04×10^6 km^2, which occurred on 6 February. This was lower than the sea ice minimum of 2016 and was a continuation of the decrease in the amount of sea ice that survived the summer melt season, which had been ongoing since the maximum of multiyear ice of 1.99×10^6 km^2 on 19 February 2014.

With so much open water in the Weddell Sea after December 2016, there was greater absorption of shortwave radiation. This resulted in anomalous upper ocean warming, with the summer SSTs reaching a record high of 0.75°C, compared to the climatological mean of 0.32°C (Figure 4e). The mean February 2017 SST for the whole Weddell Sea was 1.45°C, which was the highest monthly mean SST in the record and 0.56°C above the climatological mean. Analysis of ARGO data from the Weddell Sea indicates that upper ocean warming started in the summer of 2016/2017 and extended to a depth of 50 m (Figure S6). Ocean mixed layer (OML) temperatures as high as 2.5°C were observed over Maud Rise during summer 2016/2017 (Figure S6b). The mean summer OML temperature for the whole Weddell Sea was ~0.5°C, the highest in the ORAS5 record (Figure 4e).

5. Persistence of the Sea Ice Anomaly Over the Following Summers

During summers 2017/2018, 2018/2019, and 2019/2020, the SIE across the Weddell Sea remained at near-record low levels (Figure 1a), with the summers having the third, fifth, and eighth lowest SIEs in the 40-year record.

The winter 2017 Weddell Sea SIE was close to the long-term mean, only developing a negative anomaly toward the time of the climatological SIE maximum in September (Figures 4c and S7). Over September–December 2017, the northerly wind component over 55–70°S, 15°W to 20°E was the third largest in the 40-year record (Figure S8), contributing to a +2°C (3 standard deviations) SAT anomaly over the sea ice zone (Scambos & Stammerjohn, 2018), which played an important part in the maintenance of the negative ice anomaly.

The rapid decline in SIE started during 9–12 September when MSLP was low over the Ronne Ice Shelf, giving very strong northwesterly warm air advection onto the ice edge and into the sea ice zone over the eastern Weddell Sea. MSLP was low in the southern Weddell Sea as a result of a deep storm that developed in the southern Bellingshausen Sea, crossed the base of the Antarctic Peninsula, and deepened over the Weddell Sea, reaching a minimum central pressure of 947 hPa. In September, six individual storms were present in the Weddell Sea between 70°S and 80°S, with all the lows having central pressures within 0.5% of the deepest September depressions in this area. Such cyclonic conditions resulted in the September 2017 MSLP anomaly on the edge of the Ronne Ice Shelf being less than −18 hPa (more than 3 standard deviations below the climatological mean), with the monthly mean MSLP of 974 hPa being the lowest in the record (Figure S9a). During September–November 2017, the tropical Pacific Ocean was in a weak La Niña state and the large-scale circulation pattern in September 2017 showed a pronounced La Niña/Pacific South American Association pattern, with a low pressure anomaly in the Weddell Sea. MSLP was low in September 2016 and September 2017 during a period when the SAM was particularly positive (Figure S10).

October 2017 had anomalously strong easterly flow across the Weddell Sea (Figure S9b), which did not promote the development of a larger negative SIE anomaly. However, November and December were more cyclonic (Figures S9c and S9d), associated with a strong positive SAM (the November/December mean was 2.21, the fourth highest since 1957), and the negative SIE anomaly became larger (Figures S7c and S7d). A deep storm in the circumpolar trough near 0°E contributed to the large 3-day ice retreat of 0.38×10^6 km^2 ending on 8 December (Figure 4c), giving the largest daily SIE anomaly of the 2017/2018 summer (-1.008×10^6 km^2) on that day.

The Maud Rise polynya reappeared in the middle of September 2017 (Swart et al., 2018) (Figure S7b), and its thermal signature was also clear during September and November–December 2017 in the data from ARGO float 5904468 (Figure S6b).

The ice-free area expanded until by 1 December it had developed into an extensive area of open water within the pack ice (Figure S7d). On 1 December 2017, the large negative SIC anomalies east of 15°W were a result of less sea ice in two main areas—the ice-free region that developed from the polynya and an area of negative anomaly along the ice edge east of 15°W, the latter being a result of the strong northerly winds in the enhanced cyclonic flow in the Weddell Sea.

The large positive OML temperature anomaly established in summer 2016/2017 (Figure 4e) played an important part in the maintenance of the SIE anomaly over the following months and years, contributing to a later formation of sea ice and earlier melt (Figure 1b). During the 3-month period January–March 2017, the monthly mean OML temperatures were the highest in the 40-year record covering 1979–2018, with the anomaly ranging from 0.34°C to 0.55°C. During the summer of 2017/2018, there was a persistence of the 0.4°C warming of the OML (Figure 4e).

Following the 2017/2018 summer, SIE anomalies were negative in the winter of 2018 but became less so in October and November (Figures 4d, S11b, and S11c), and by the beginning of December, the SIC was close to the long-term mean (Figure 4d). The December negative SIE anomaly (the eighth largest for December) was primarily established during two periods, with large 3-day retreats ending on the 12 and 19 December (Figure 4d). These events were a result of three deep depressions in the southern Weddell Sea, which were all within the deepest 5% of December storms between 70°S and 80°S in the Weddell Sea (Figure 3b). The overall December 2018 MSLP anomaly was negative (Figure S12d), which also contributed to the warmest December on record at South Pole as the anomalous cyclones advected warm South Atlantic air deep into the interior of the continent. After the two rapid retreat periods, the magnitude of the SIE anomaly gradually reduced, and the SIE was close to the long-term mean by February (Figure 4d). While 2017 and 2018 had early SIE minima on 6 and 9 February, the 2019 minimum was on 22 February, which is close to the average day of minimum on 18 February.

6. Discussion and Conclusions

A number of atmospheric and oceanic factors were responsible for the sudden decrease of summer SIE in the Weddell Sea between 2015/2016 and 2016/2017. We have focused on the role of the Maud Rise polynya and intense storms in the Weddell Sea, although other oceanic changes will also have played a part, for example, subsurface heat anomalies (Lecomte et al., 2017; Meehl et al., 2019). However, it should be noted that with the data available, it is very difficult to quantify the relative roles of individual factors.

Polynyas near Maud Rise are rare events, with the polynya of 2016 being the most significant since that of the 1970s. It provided an ice-free region that could absorb shortwave radiation early in the summer and increase ocean temperatures. In 2016 and 2017, the ice-free area of the Maud Rise polynya in November expanded westwards and northwards as radiation was absorbed. The expansion was enhanced because of the warmer than usual ocean temperatures.

The deep storms in 2016 and 2017 also played an import part in the SIC decrease. In the month of September alone, 2016 and 2017 had the two deepest storms that occurred within 70–80°S, 60–0°W among the total of 1,130 depressions identified by the depression tracking scheme in all Septembers over 1979–2018. The storms occurred when the September SAM index was at a near-record positive level, with several record low pressure values observed at weather stations over the Antarctic continent. The record westerly winds near the tip of the Antarctic Peninsula in September 2016 advected sea ice out of the northwestern Weddell Sea, creating a large negative SIC anomaly. Thus, the sudden decrease of Weddell Sea sea ice occurred because of both local and broadscale factors, with the establishment of the Maud Rise polynya a result of oceanographic and atmospheric factors. Then a near-record negative SAM index in November 2016 resulted in anomalous warm northeasterly flow into the Weddell Sea that helped to maintain/reinforce the negative September sea ice anomalies.

The loss of sea ice early in the summer allowed more solar radiation to be absorbed by the ocean, creating a positive OML temperature anomaly that persisted from 2016 until 2019. The result will have contributed to the reduction in length of the sea ice season, with later (earlier) sea ice formation (melt).

The Weddell Sea daily SIE values for summer 2019/2020 closely followed those for 2016/2017–2018/2019 (Figure S13), giving an unprecedented four summers of very low SIEs. The marked drop in Weddell Sea summer SIE since 2016/2017 suggests a large change in the highly coupled regional atmosphere/ocean/sea ice system. The sudden decrease may be a result of a oceanic change, but further work is needed to confirm this.

With such a short observational record, it is not possible to say whether the summer SIE in the Weddell Sea will return to its pre-2016 values or whether this marks the start of the longer-term decline in Southern Ocean sea ice that is predicted by coupled climate models. However, it has highlighted the large variability in the extent of sea ice in the Weddell Sea and the importance of very deep depressions and the Maud Rise polynya.

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

We are grateful to ECMWF for the provision of the ERA-Interim meteorological fields (available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim), to EUMETSAT for the OSISAF ice drift data, and to the U.S. National Snow and Ice Data Center for providing sea ice data (available at http://nsidc.org/data). The ARGO data were obtained from http://www.argo.ucsd.edu/Argo_data_and.html. The depression tracking data can be obtained from https://doi.org/10.5285/d3b5d87d-c882-4fed-9d47-14c73be43bca.

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