Temporal and spatial evolution of the Antarctic sea ice prior to the September 2012 record maximum extent

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[1] On 24 September 2012 the Antarctic sea ice extent (SIE) reached a new annual daily maximum (ADM) for the satellite era of 19.72×10^6 km^2. The largest positive SIE anomalies compared to the mean of all ADMs were found over the northern Amundsen Sea, off the coast of Wilkes Land, with smaller positive anomalies off the Dronning Maud Land coast (30°W to 30°E). The SIE at the ADM is significantly correlated with the extents for the previous 80 days, but the ice growth during the winter of 2012 was close to the climatological rate, and 1 month before the ADM, the SIE was near the recent mean. Deep depressions in the circumpolar trough since late August 2012 resulted in strong southerly flow and marked northward sea ice advection. The linear trend in SIE suggests that it contributed ~40% to the 2012 anomaly, with depression activity adding ~60%.
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1. Introduction

[2] During September 2012 both polar regions experienced new record extents of sea ice for the satellite era (since 1979). On 16 September the Arctic sea ice extent (SIE) reached a new minimum level of 3.41×10^6 km^2 [*Parkinson and Comiso*, 2013], beating the previous record minimum that occurred in 2007. However, in the Antarctic there was a new record *maximum* SIE of 19.72×10^6 km^2 on 24 September, exceeding the previous record of 19.59×10^6 km^2 , which occurred on 24 September 2006.

[3] Both events are consistent with the contrasting and continuing trends in SIE that have been observed in the two polar regions over recent decades [*Turner and Overland*, 2009]. Arctic sea ice has been declining in extent throughout the year [*Serreze et al*., 2007], but with the maximum loss of almost 14% declination (dec^{-1}) being found in September (http://nsidc.org/arcticseaicenews/2013/10/a-better-year-for-the-cryosphere/). The Arctic SIE has a large natural variability, indicated by the fact that the previous minimum extent before 2012 occurred some years before in 2007. *Stroeve et al*. [2012] estimated that anthropogenic forcing had contributed 50–60% of the long-term decline of Arctic SIE.

[4] The positive trend in Antarctic SIE has been noted in several studies [*Comiso and Nishio*, 2008; *Parkinson and Cavalieri*, 2012; *Zwally et al*., 2002], and while the change is much smaller in absolute magnitude compared to the loss in the Arctic, the trend in annual mean SIE is still statistically significant at $p < 0.01$. However, the overall increase masks large regional variations [*Holland and Kwok*, 2012; *Stammerjohn et al*., 2012], and in particular, contrasting trends between the Bellingshausen Sea and the Ross Sea (areas of the Antarctic continent and Southern Ocean referred to in the text are shown on Figure 1), with a large loss of ice over the former [*Stammerjohn et al*., 2008] and a positive trend across the latter [*Comiso et al*., 2011].

[5] The mechanism or mechanisms responsible for the overall increase in Antarctic SIE are still not fully understood, but the loss of stratospheric ozone [*Turner et al*., 2009], freshwater injection from the ice sheet [*Bintanja et al*., 2013], ocean-ice feedback processes [*Zhang*, 2007], and ocean change [*Jacobs and Comiso*, 1997] have all been put forward as possibly playing a part. However, analysis of sea ice motion vectors in conjunction with near-surface wind data has suggested that off West Antarctica, the sea ice anomalies are predominantly a result of wind-driven changes in ice advection, while elsewhere wind-driven thermodynamic changes play a greater part [*Holland and Kwok*, 2012].

[6] In this paper we examine the conditions that led to the record sea ice maximum in September 2012 and consider how the 2012 record extent relates to the long-term trend and the ice advance in previous years.

2. Data

[7] Daily fields (every 2 days before 1989) of mean sea ice concentration computed using the Bootstrap version 2 algorithm were obtained from the U.S. National Snow and Ice Data Center (www.nsidc.org) and regridded onto a 0.25° longitude by 0.25° latitude grid. Daily mean SIE for the whole Antarctic were computed, with values for every other day prior to 1989 being estimated by linear interpolation. SIE was computed as the total area of all 0.25° × 0.25° grid cells where the sea ice concentration exceeded 15%. We also examined the SIE values computed using the NASA Team algorithm. There are small differences compared to the values used here, but both data sets give a record Antarctic SIE in September 2012. In this study we particularly focus on the maximum SIE in each year, which we refer to as the Annual Daily Maximum (ADM).

[8] Atmospheric circulation variability was examined using the 6-hourly European Centre for Medium-Range Weather

Additional supporting information may be found in the online version of this article.

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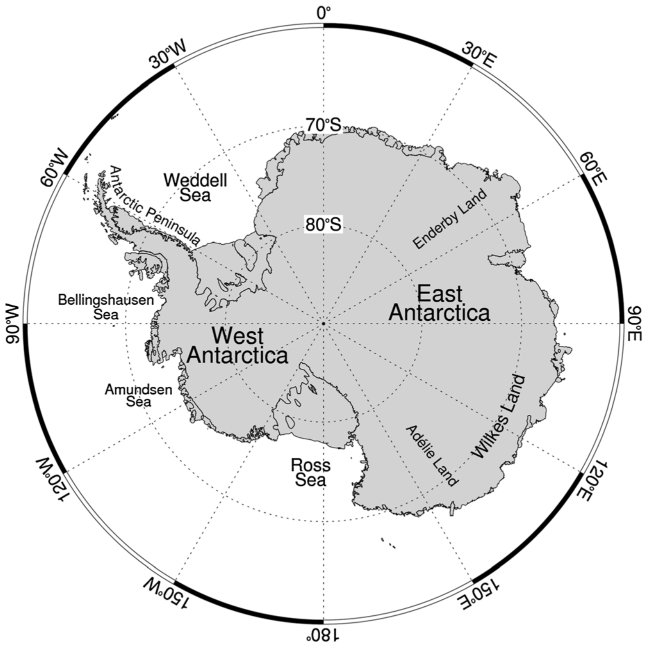

Figure 1. Map of the Antarctic and Southern Ocean indicating the areas referred to in the text.

Forecasts Interim reanalysis (ERA-Interim) fields, at a horizontal grid spacing of ~120 km.

3. Results

[9] The mean ADM SIE for 1979–2012 is 18.81×10^6 km^2 and occurs on 21 September (Figure 2a). Over the 34 year period the ADM SIE has varied from 18.21×10^6 km^2 (1986) to 19.72×10^6 km^2 (2012). The 2012 ADM was more than 4.8% above (and more than 2 standard deviation (SD) beyond) the 1979–2012 mean. The day of ADM SIE has varied by more than a month, from 19 August (1984) to 3 October (1988); however, there is no significant relationship between the day of the ADM SIE and the extent of the ice on that day. The trend in the ADM SIE has been 0.18×10^6 km^2 dec^{-1} (0.95% dec^{-1}) (Figure 2b), which is significant at $p < 0.01$. Since 1979 the day of the ADM SIE has shifted later at a rate of 2.2 days dec^{-1}; however, this is not significant.

[10] The correlation of the ADM SIE for each year decreases almost linearly with the daily SIE values over the 2 months preceding the ADM (Figure 2c). The correlation is significant at $p < 0.05$ until 80 days before the day of the ADM. Therefore, the ice extents earlier in the year play relatively little part in determining the ADM SIE in any year.

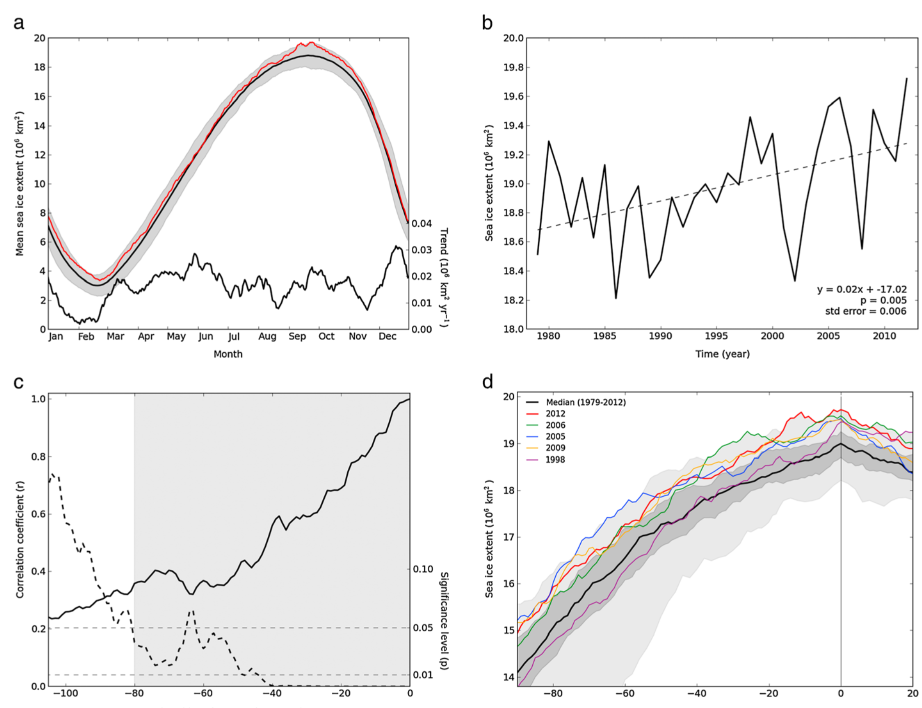

Figure 2. (a) The 1979–2012 mean daily Antarctic sea ice extent (upper solid black line) and trend (lower solid black line). The two standard deviation variability about the mean is indicated by the shading. The red line shows the 2012 daily SIE. (b) The annual daily maximum Antarctic SIE for 1979–2012 (solid line) and the linear trend (dashed line). (c) The correlation of the detrended SIE on the annual daily maximum with the extent on previous days (solid line). The broken line shows the significance, with the significance ($p < 0.05$) also indicated by the shading. (d) The total Antarctic SIE on the 100 days prior to and 20 days after the maximum for the mean of all years and the 5 years with the largest maximum SIE. The dark shading indicates the 1 standard deviation from the mean. The light shading shows the maximum and minimum extends in the 34 year record.

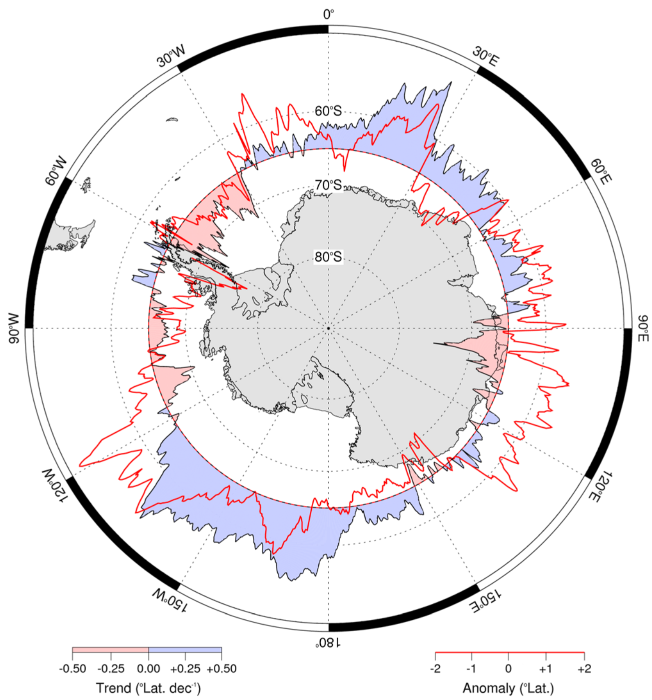

Figure 3. The 1979–2012 trends in sea ice edge on the day of maximum extent. Blue (red) indicates greater (less) ice. The red line indicates the SIE anomalies on the 2012 day of the annual daily maximum.

[11] The Antarctic winter sea ice advance is highly variable on a day-to-day basis, as can been seen from the mean daily extents for the 100 days before the ADM for the 5 years of greatest SIE (Figure 2d). There are fluctuations of total SIE on a range of timescales from days to weeks as synoptic-scale weather systems change in intensity and move around the continent, altering the near-surface meridional wind field. Eighty days before the ADM in 2012 (6 July), the SIE was only the sixth largest in the record. At 30 days before the ADM (25 August), it still only had the sixth largest SIE (only 1 SD above the long-term mean) since the ice advance between these dates was close to the average rate. These observations indicate that the 30 days preceding the ADM had the critical changes in sea ice advection or growth that led to the record maximum SIE.

[12] At the 2012 ADM the largest SIE anomalies were over the northern Amundsen Sea, off the coast of Wilkes Land and to a lesser extent between 30°W and 30°E (Figure 3). Negative ice anomalies were found over the northern Bellingshausen and Weddell Seas, between 30°E and 50°E (northwest of Enderby Land) and between 140°E and 170°E (north of the Wilkes Land coast). Climatologically, the most northerly extensions of ice are found to the west of the centers of low mean sea level anomalies (MSLP) (Figure 4a), which are regions of predominantly southerly flow, with net northward transport of ice and extensive sea ice creation close to the coast. Areas to the immediate east of the low centers, such as the Bellingshausen Sea and off Adélie Land have a smaller northward extension of sea ice.

[13] There is a high correlation between the areas of positive and negative September 2012 ADM ice anomalies (Figure 3) and the areas of anomalous meridional near-surface flow resulting from anomalies in the mean MSLP field over the

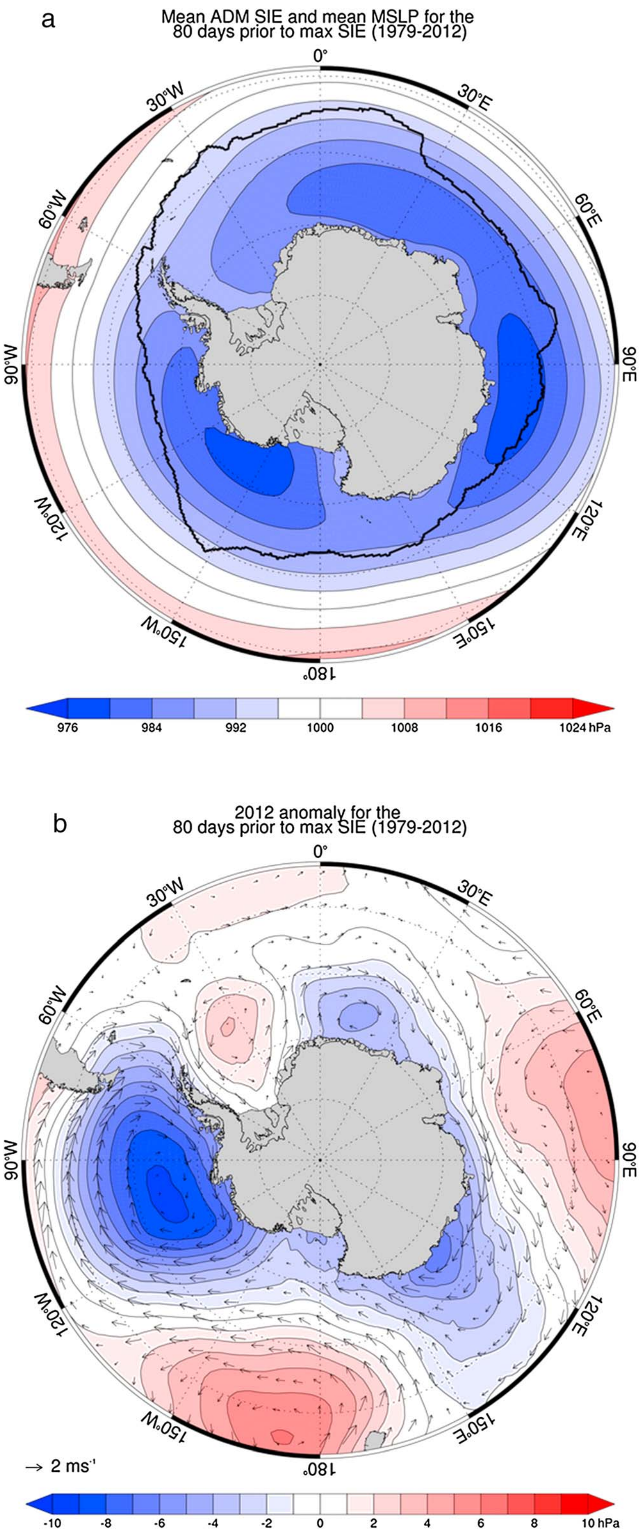

Figure 4. (a) Mean MSLP for the 80 days before the annual daily maximum and the mean SIE at the annual daily maximum. (b) The MSLP and 10 m vector wind anomalies for the 80 days before 24 September 2012 compared to the mean of the 80 days before all the annual daily maxima of 1979–2012.

80 days prior to the ice maximum (Figure 4b). The largest pressure anomalies were a couplet of low (<-9 hPa)/high (>6 hPa) anomalies between the Antarctic Peninsula and 180° that gave a southerly meridional near-surface wind anomaly of >1.5 m s^{-1} across 110°W–150°W and 1.5 m air temperature anomalies of >-2.5°C. As we noted earlier, the atmospheric conditions over the 30 days prior to the ADM were critical in establishing the record SIE and MSLP anomalies were particularly pronounced during August 2012. During the month there was a >22 hPa difference between the MSLP at the center of the Amundsen Sea low (ASL) (the climatological center of low pressure off West Antarctica) and the high pressure center near 180°, which resulted in a 10 m meridional wind component anomaly of >3.5 m s^{-1} and 1.5 m air temperature anomalies of >-5°C.

[14] Other synoptic features that contributed to the establishment of the record 2012 SIE anomalies were a high/low couplet between 30°W and 15°E that gave strong southerly flow over the eastern Weddell Sea, and a trough/ridge system between 80°E and 130°E giving southerly flow off Wilkes Land, which contributed to the large, positive ice anomaly in this area.

[15] On 25 August 2012 the SIE was close to the recent mean, but growth of 1.20×10^6 km^2 over the following 30 days was the largest in the 34 year record for this period and was critical in establishing the 2012 SIE record. The ice advance was greatest during the periods 5–13 and 18–24 September, separated by a brief retreat during14–17 September (Figure 2d) (see the supporting information for the synoptic analyses for these periods). The first period of growth led to a SIE of 19.66×10^6 km^2 on 13 September, which on its own would have been a new record ice extent. This advance occurred because of a very deep depression that moved from the Bellingshausen Sea to the eastern Weddell Sea advecting sea ice equatorward on its western flank. In addition, quasi-stationary, deep lows in the Ross Sea and close to 90°E established positive sea ice anomalies to the west of these locations. The ice advance was particularly marked over 7–11 September when the ASL had a central pressure of <964 hPa giving southerly flow over the Ross Sea of >14 m s^{-1}.

[16] During the retreat phase the SIE decreased by 0.22×10^6 km^2 as there was less cyclonic activity in the Bellingshausen Sea and the establishment of the climatological northerly flow resulted in southward movement of the ice edge. The flow over the Ross Sea also became more northerly, leading to sea ice retreat in this sector.

[17] The second advance phase occurred over 18–24 September and took the SIE to its record of 19.72×10^6 km^2. This period was characterized by an amplification of the climatological wave number 3 pattern (Figure 4a), with deep lows close to 0°E, 90°E, and 135°W. This synoptic pattern resulted in ice advance over the Ross Sea, the eastern Weddell Sea, and between 70°E and 100°E. Of particular note was the depression just to the north of the Ross Ice Shelf on 18 September that had a central pressure of <936 hPa, and which gave a 10 m wind speed of >20 m s^{-1} over the Ross Sea (see supporting information), resulting in a large northward advance of the ice edge.

[18] Following the SIE maximum on 24 September, the extent remained almost unchanged until 26 September and then decreased rapidly as strong northerly flow near the Greenwich Meridian, across the Bellingshausen Sea and close to 150°W pushed the ice edge south. During October 2012 the SIE fell below that of other years with extensive ice (Figure 2d) as a series of deep depressions brought warm air southward on their eastern flank, especially over the northern Amundsen Sea and off Wilkes Land.

4. Discussion

[19] Alterations in the synoptic environment can result in rapid changes in SIE on the weekly to monthly timescales (Figure 2d). This was particularly the case just prior to the ADM in 1998 when the SIE increased by 0.90×10^6 km^2 from the long-term mean to the fifth largest extent in just 14 days. Such an advance at this time year from a larger baseline extent at the start of September would have resulted in a record SIE. In addition, it should be noted that the mean SIE shows a rise over approximately the 10 days before the ADM, suggesting that a synoptic events on this timescale cause the final ice advance to the annual maximum.

[20] The SIE anomalies at the ADM in 2012 were aligned spatially with the long-term SIE trends in some sectors of the continent, but not in others (Figure 3). The long-term increase (decrease) of ice in the Ross (Bellingshausen) Sea is consistent with a long-term deepening of the ASL [*Turner et al.*, 2012]. During winter/early spring of 2012 there were deep depressions between the Antarctic Peninsula and the Ross Sea, but they were generally further east than usual, resulting in the 2012 ice anomaly being to the east of the long-term trend in this sector. The 2012 ice anomaly peak centered on 20°E was very close to the location of the long-term trend, and a result of deeper depressions near 0°, although frequent deep lows over the northeast Weddell Sea also gave a large anomaly across 10°W–30°W. The 2012 anomaly across 90°E–130°E occurred in an area where there had been no long-term ice trend and was a result of the high-low pressure couplet between 90°E and 135°E.

[21] Strong meridional flow, and therefore greater sea ice transport northward, is associated with amplified planetary waves around the Antarctic continent [*Raphael*, 2007]. In particular, a large amplitude of wave number 3 results in three, marked climatological surface low MSLP centers, such as shown on Figure 4a. Over the 80 days before the 2012 ADM SIE the atmospheric flow had an amplified wave 3 pattern, with the ASL being particularly marked. A Fourier analysis of the 500 hPa geopotential heights at 60°S indicates that the wave number 3 amplitude has increased during August by almost a factor of 3 since 1979 ($p < 0.05$), with the 2012 amplitude being the largest since 1979 and more than 2 SD above the mean. The amplitude of the wave in September 2012 was also 26% above the 1979–2012 mean, although the trend is not significant. The strong wave number 3 structure to the atmospheric flow around the Antarctic has been linked to the shape of the continent and the flow over the Southern Ocean [*Baines and Fraedrich*, 1989]. During August the midtropospheric flow just north of the Antarctic coast around East Antarctica has increased at a statistically significant rate, which may have contributed to the growth in amplitude of wave number 3. However, it is presently unclear whether this increase is a result of natural variability or some anthropogenic influence.

[22] Over the 34 years of the satellite record the SIE has increased in all months of the year (Figure 2a), with the ADM SIE increasing at 0.18×10^6 km^2 dec^{-1} (0.95% dec^{-1}) (Figure 2b), which is significant at $p < 0.01$. The ADM has a

large interannual variability (Figure 2b), but the four largest ADM have occurred in the last 8 years. The SIE in 2012 reached a new record because of the long-term underlying upward trend, coupled with a marked sea ice advance between 25 August and 24 September as a result of deep depressions within the circumpolar trough. The reasons for the long-term upward trend in Antarctic SIE are still not fully understood, and modeling studies suggest that recent changes may still be within the bounds of intrinsic variability [*Polvani and Smith*, 2013]. As we still do not understand the mechanisms behind the trend in SIE, it is not possible to accurately attribute the 2012 anomalies to the mechanisms behind the trend and particular conditions in that year. However, the linear trend in the SIE at the ADM suggests that ~40% of the 2012 anomaly came from the long-term trend, with ~60% attributable to the deep depression activity.

[23] The large interannual variability of the ice advance through the winter was highlighted by the conditions in 2013. An early assessment of the 2013 SIE shows that, unlike in 2012, a large, positive SIE of ~1 SD was established early in the winter, which increased to more than 2 SD by August. By the end of September the SIE had exceeded the record extent of 2012, although through September the SIE remained fairly constant without the two peaks seen in 2012. Spatially, the SIE anomalies in 2013 were dominated by large positive values from the Antarctic Peninsula westward to 140°W, with negative anomalies over the western Ross Sea. Off the coast of East Antarctica there were no large SIE anomalies, although large negative anomalies were present over the eastern Weddell Sea.

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