Variability in Antarctic sea ice from 1998-2017

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This study was based on the daily sea ice concentration data from the National Snow and Ice Data Center (Cooperative Institute for Research in Environmental Sciences, Boulder, CO, USA) from 1998 to 2017. The Antarctic sea ice was analysed from the total sea ice area (SIA), first year ice area, first year ice melt duration, and multiyear ice area. On a temporal scale, the changes in sea ice parameters were studied over the whole 20 years and for two 10-year periods. The results showed that the total SIA increased by 0.0083×10^6 km^2 yr^{-1} (+2.07% dec^{-1}) between 1998 and 2017. However, the total SIA in the two 10-year periods showed opposite trends, in which the total SIA increased by 0.026×10^6 km^2 yr^{-1} between 1998 and 2007 and decreased by 0.0707×10^6 km^2 yr^{-1} from 2008 to 2017. The first year ice area increased by 0.0059×10^6 km^2 yr^{-1} and the melt duration decreased by 0.0908 days yr^{-1} between 1998 and 2017. The multiyear ice area increased by 0.0154×10^6 km^2 yr^{-1} from 1998 to 2017, and the increase in the last 10 years was about 12.1% more than that in the first 10 years. On a spatial scale, the Entire Antarctica was divided into two areas, namely West Antarctica (WA) and East Antarctica (EA), according to the spatial change rate of sea ice concentration. The results showed that WA had clear warming in recent years; the total sea ice and multiyear ice areas showed a decreasing trend; multiyear ice area sharply decreased and reached the lowest value in 2017, and accounted for only about 10.1% of the 20-year average. However, the total SIA and multiyear ice area all showed an increased trend in EA, in which the multiyear ice area increased by 0.0478×10^6 km^2 yr^{-1}. Therefore, Antarctic sea ice presented an increasing trend, but there were different trends in WA and EA. Different sea ice parameters in WA and EA showed an opposite trend from 1998 to 2007. However, the total SIA, first year ice area, and multiyear ice area all showed a decreasing trend from 2008-2017, especially the total sea ice and first year ice, which changed almost the same in 2014-2017. In summary, although the Antarctic sea ice has increased slightly over time, it has shown a decreasing trend in recent years.

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Variability in Antarctic sea ice from 1998-2017

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Abstract: This study was based on the daily sea ice concentration data from the National Snow and Ice Data Center (Cooperative Institute for Research in Environmental Sciences, Boulder, CO, USA) from 1998 to 2017. The Antarctic sea ice was analysed from the total sea ice area (SIA), first year ice area, first year ice melt duration, and multiyear ice area. On a temporal scale, the changes in sea ice parameters were studied over the whole 20 years and for two 10-year periods. The results showed that the total SIA increased by 0.0083×10^6 km^2 yr^{-1} (+2.07% dec^{-1}) between 1998 and 2017. However, the total SIA in the two 10-year periods showed opposite trends, in which the total SIA increased by 0.026×10^6 km^2 yr^{-1} between 1998 and 2007 and decreased by 0.0707×10^6 km^2 yr^{-1} from 2008 to 2017. The first year ice area increased by 0.0059×10^6 km^2 yr^{-1} and the melt duration decreased by 0.0908 days yr^{-1} between 1998 and 2017. The multiyear ice area increased by 0.0154×10^6 km^2 yr^{-1} from 1998 to 2017, and the increase in the last 10 years was about 12.1% more than that in the first 10 years. On a spatial scale, the Entire Antarctica was divided into two areas, namely West Antarctica (WA) and East Antarctica (EA), according to the spatial change rate of sea ice concentration. The results showed that WA had clear warming in recent years; the total sea ice and multiyear ice areas showed a decreasing trend; multiyear ice area sharply decreased and reached the lowest value in 2017, and accounted for only about 10.1% of the 20-year average. However, the total SIA and multiyear ice area all showed an increased trend in EA, in which the multiyear ice area increased by 0.0478×10^6 km^2 yr^{-1}. Therefore, Antarctic sea ice presented an increasing trend, but there were different trends in WA and EA. Different sea ice parameters in WA and EA showed an opposite trend from 1998 to 2007. However, the total SIA, first year ice area, and multiyear ice area all showed a decreasing

trend from 2008-2017, especially the total sea ice and first year ice, which changed almost the same in 2014-2017. In summary, although the Antarctic sea ice has increased slightly over time, it has shown a decreasing trend in recent years.

Keywords: Antarctic, total sea ice, first year ice, sea ice melt duration, multiyear ice

1 Introduction

The Antarctic is a region that reflects the changes in global sea ice (De la Mare et al., 1997), and its change is one of the main issues of concern to the international community (Comiso, 1998; Cook et al., 2005). Sea ice plays several important roles in the climate system. It serves as a barrier between the ocean and the atmosphere, thereby reducing the exchange of heat, mass, and momentum. It is also a crucial component of the ice-albedo feedback system, wherein it greatly impacts the amount of solar radiation absorbed at the surface through its reflection of most of the incident solar radiation (Grenfell and Maykut, 1977; Massom and Stammerjohn, 2010). Moreover, the distribution of sea ice is very important for the demarcation of ships' routes at sea, and it affects the establishment of offshore facilities (Moreau et al., 2010). Sea ice area (SIA) is one of the parameters that indicate a change in sea ice. Through this parameter, we can further understand the change in sea ice. Therefore, studying the changes in SIA over long periods in the Antarctic is important for understanding the effects of sea ice on global climate change.

Passive microwave remote sensing technology is almost not affected by the weather, and sustainable observation of the earth has become the main means of monitoring SIA. Parkinson et al. (2004) found that the sea ice extent (SIE) of the Antarctic during 1979-1998 increased by 11180±4190 km^2 yr^{-1}. Cavalieri et al. (2008) showed that the Antarctic SIE increased by 1.0±0.4% yr^{-1} from 1979 to 2006. The Antarctic SIE and sea surface temperature propagate from west to east on the El Niño time scale(White et al. 2004; Warren et al. 1996; Simmonds et al. 1995). Cavalieri and Parkinson (2003) showed that the Antarctic SIE decreased significantly from 1973-1977 before gradually increasing from 1977-2002. Over 1979-2013, the annual mean total Antarctic SIE increased at a rate of 195×10^3 km^2 dec^{-1} (1.6% dec^{-1})(Simmonds, I. 2017). The largest regional positive trend in annual mean SIE of 119×10^3 km^2 dec^{-1} (4.0% dec^{-1}) was in the Ross Sea sector from 1979 to 2013(Turner et al., 2016). Trends in satellite-derived Antarctic sea ice concentrations (1979-2002) have shown a pronounced increase (decrease) of 4-10% dec^{-1} in the central Pacific sector (Bellingshausen/western Weddell sector)(Liu et al., 2004). Zwally et al. (2002) reported that from 1979 to 1996 the total Antarctic SIE and SIA increased by 11,180 km^2 yr^{-1} and 10,860 km^2 yr^{-1}, respectively. Regionally, the trends are positive in the Pacific Ocean, Ross Sea, and Weddell Sea, and negative in the Indian Ocean, Bellingshausen Sea, and Amundsen Sea. From 2002 to 2011, the Antarctic SIE and SIA increased by 3.64% and 3.8%, respectively (Shen et al., 2017).

Antarctic SIE has shown a small but significant increase during the last 30 years. However, in 2016, an unusually early onset of the melt season was observed; the maximum Antarctic SIE was reached as early as August rather than at the end of September, and was followed by a rapid decrease. The decrease in the SIA started even earlier in July (Schlosser et al., 2018). The Antarctic Peninsula has experienced a major warming over the last 50 years, with temperatures at Faraday/Vernadsky station having increased at a rate of 0.56 °C dec^{-1} during the year and 1.09 °C dec^{-1} during the winter (Turner et al., 2005). Worthwhile to note here that the Peninsula warming has halted in the last decade or so (Turner et al., 2016).

At present, most of the studies on Antarctic sea ice have been based on a single sea ice parameter, and few studies have used multiple parameters. In addition, there have been few studies on Antarctic sea ice variability in recent years. In this paper, our analysis of sea ice variability was performed primarily based on the total SIA, first year ice area, melt duration, and multiyear ice area. It also focused on the comparison of Antarctic sea ice in the first and second decades, namely 1998-2007 and 2008-2017, respectively. The Entire Antarctica was divided into two areas, namely WA (near the West Antarctic) and EA (near the East Antarctic), according to the spatial change rate of the sea ice concentration in order to compare the changes in sea ice parameters.

2 Materials & Methods

The data used in this study were derived from the National Snow and Ice Data Center (NSIDC). Data were obtained from several microwave radiometers (Table 1), namely the Nimbus-7 Scanning Multichannel Microwave Radiometer; Defense Meteorological Satellite Program (DMSP, Defense); F8, F11, and F13 Special Sensor Microwave/Imagers; and the DMSP-F17 and DMSP-F18 Special Sensor Microwave Imager/Sounders (Cavalieri et al., 2012). The sea ice concentration calculation was performed using the NASA Team algorithm proposed by the Sea Ice Division of NASA's Goddard Space Flight Center Hydrological Sciences Laboratory (Swift et al., 1985). The data were also mapped to a common rectangular grid overlaid on a north polar stereographic projection with a grid cell size of 25×25 km (NSIDC, 1992). The sea ice concentration data set was the source data for the calculations of SIE and SIA. In this study, we used data from 1998 to 2017.

3 Results and Analysis

3.1 Total Sea Ice Area

The SIE is the cumulative area of all polar grid cells that have at least 15% sea ice concentration. The SIA is the sum of the grid cell areas multiplied by the sea ice concentration for all cells with ice concentration of at least 15%. The 15% threshold is used for both SIE and SIA calculations (Parkinson et al., 1999). Heinrichs et al. (2006) found that setting the concentration of 15% as the threshold between seawater and sea ice can better identify the sea ice edge, and can remove ice floes or other factors. Therefore, the SIA calculated in this study was the sum of sea ice pixels with a concentration greater than 0.15. Based on the data provided by the NSIDC of the daily sea ice concentration in the Antarctic from 1998 to 2017, monthly and yearly sea ice concentration results were obtained.

The average sea ice concentration results for the 20-year period are presented in Fig. 1. As illustrated in Fig. 1, the average sea ice concentration in the Antarctic was relatively low, and sea ice with a concentration greater than 0.8 accounted for only about 18.8% of the total SIA. The high-concentration sea ice was mainly distributed near the Antarctic continental margin, of which the Weddell Sea accounted for a large proportion.

In order to more intuitively obtain the trend in the spatial variation in sea ice concentration in the Antarctic region for 20 years, a linear tendency regression analysis on the yearly sea ice concentration in the Antarctic was conducted, and the results are shown in Fig. 2. According to Fig. 2, the variation in sea ice distribution in the Entire Antarctica was very different, and showed two states of increasing and decreasing, of which about 57% of the regions showed an increasing trend and 42% showed a decreasing trend. The area with the clearest increase was the Weddell Sea, and those with the clearest decrease were the Amundsen Sea and Ross Sea. The sea area adjacent to the Indian Ocean also showed a decreasing trend, but the area of sea ice in this region was relatively lower, and the decrease was weaker than that in the Amundsen Sea or Ross Sea. Therefore, the Entire Antarctica area was divided into two areas for research, as shown in Fig. 3 (Near West Antarctica (WA) and Near East Antarctica (EA) (WA:75°W-180°, EA: 180-75°W)). The yearly SIA in the different regions are shown in Table 2.

3.1.1 Entire Antarctica

The yearly average fitting line of the total SIA from 1998 to 2017 is plotted in Fig. 4. The results in Fig. 4 reveal that the total SIA increased by approximately 0.00083×10^{6} km^{2} yr^{-1} from 1998 to 2017. During the period from 1998 to 2011, the SIA showed clearer cyclical changes, with a stable increase every five years. The data presented in Fig. 2 indicate that the total SIA significantly increased from 2011 to 2014 by about 4.53% yr^{-1}, and the maximum total SIA in 2014 was approximately 9.836×10^{6} km^{2} in the past 20 years. However, there was a significant decrease from 2014-2017 by about 6.14% yr^{-1}, and the minimum total SIA in 2017 was approximately 8.025×10^{6} km^{2} between 1998 and 2017. Overall, the total Antarctic SIA showed a growth trend, but in recent years it has decreased significantly. From 1998 to 2007, the total SIA increased by 0.026×10^{6} km^{2} yr^{-1}, and from 2008 to 2017 it decreased at a rate of 0.0707×10^{6} km^{2} yr^{-1}. It showed opposite trends, and the decrease during the later 10 years was clearly greater than the increase during the first 10 years. Therefore, the total Antarctic SIA will show a decreasing trend in the future.

3.1.2 West Antarctica

The total SIA in WA was statistically analysed, and the results are shown in Fig. 5. Fig. 5 reveals that the total SIA decreased from 1998 to 2017 by approximately 0.0079×10^6 km^2 yr^{-1}. The three years of 2006, 2016, and 2017 were the years with high total SIA, with SIA of 2.684×10^6 km^2, 2.660×10^6 km^2, and 2.582×10^6 km^2, respectively.

The SIA in 2017 was the lowest in the past 20 years. Compared with the Entire Antarctica, the total SIA in WA showed an opposite trend in the past 20 years. The total SIA in the periods of 1998-2007 and 2008-2017 was statistically analysed, as shown in Fig. 5. The data shown in Fig. 5 indicate that the total SIA in both periods showed a decreasing trend; the decrease rates were 0.045×10^6 km^2 yr^{-1} and 0.210×10^6 km^2 yr^{-1}, respectively. As a result, the total SIA in WA in the last 10 years was clearly larger than that in the previous 10 years. The contrast of Fig. 4 and Fig. 5 show that the total SIA in WA and the Entire Antarctica increased from 2008 to 2017, but there was a difference in the total SIA trend between WA and the Entire Antarctica from 1998 to 2011. However, between 2011 and 2017 the trends were almost the same. In the period of 2011-2017, the total SIA in WA decreased by 5.4% yr^{-1}, and there was little difference with that in the Entire Antarctica. Therefore, at the 20-year scale, the total SIA in WA and the Entire Antarctica region had opposite trends. However, in the later 10 years, and especially in the past five years, the changes were almost the same and showed a decreasing trend, and the rates of change became closer.

3.1.3 East Antarctica

The total SIA in EA was statistically analysed, and the results are shown in Fig. 6. The total SIA increased by 0.067×10^6 km^2 yr^{-1} from 1998 to 2017, which was slightly larger than that in the Entire Antarctica. The total SIA was about 6.756×10^6 km^2 in 2014, which was the largest SIA in those 20 years in EA; the smallest SIA was about 5.454×10^6 km^2 in 2017. These two extreme values appeared in the same years as those in the Entire Antarctica. Comparing Fig. 2 and Fig. 8, the trends were similar during the 20 years. The total SIA in EA increased by 5.0%

yr^{-1} in the period of 2011-2014, but decreased by 6.5% yr^{-1} from 2014 to 2017. The total SIA increased by 0.0474×10^6 km^2 yr^{-1} from 1998 to 2007 and decreased by 0.0406×10^6 km^2 yr^{-1} from 2008-2017. Comparing Fig. 4 and Fig. 6, it can be seen that the total SIA in EA and the Entire Antarctica had positive growth in the first 10 years, but had negative growth in the last 10 years. Therefore, the change in the total SIA in EA was similar to that in the Entire Antarctica, especially in recent years.

3.2 First Year Ice Area and Melt Duration

First year sea ice is ice that is thicker than young ice but has no more than one year growth. In other words, it is ice that grows in the fall and winter but does not survive the spring and summer months. To a certain extent the variability in first year ice has an indication function for the climate and environment; when the temperature gap is large during the year, first year ice will increase. On the contrary, the quantity will decrease. The yearly first year ice area in different regions is shown in Table 3.

3.2.1 Entire Antarctica

The maximum and minimum SIE for each day were calculated during one year. Thus, the first year SIE is the difference between the minimum and maximum extents of daily SIE. Finally, statistical trends (Fig. 7) in the first year ice area were obtained.

From Fig. 7, we can see that the first year ice area in the Antarctic decreased slightly from 1998-2017, with a rate of decrease of 0.0059×10^6 km^2 yr^{-1}. Among these years, 2014 had the largest first year ice area, with an area of about 8.146×10^6 km^2, but 2017 had the smallest first year ice area, with an area of about 7.111×10^6 km^2. Also, according to Table 3, the average first year ice area in the Entire Antarctica from 1998 to 2007 was 7.629×10^6 km^2, while from 2008 to 2017 the area was 7.652×10^6 km^2, which was a difference of about 0.3%. However, compared to the first 10 years, the changes in the last 10 years were clearer. Compared with the total SIA, the change in first year ice was relatively small; the difference between the maximum and the minimum in these 20 years was only 14.6%, while the difference in total SIA was 22.6%. The first year ice area in the Entire Antarctica gradually decreased from 1998-2007 and 2008-2017, and the decrease rate in the last 10 years was greater than that in the first 10 years. Comparing Fig. 4 and Fig. 7, the trends in total SIA and first year ice area in these 20 years were opposite, but they both decreased from 2008-2017, and the trend was very similar, especially from 2011-2017. The first year ice area of the Antarctic increased by 3.01% yr^{-1} from 2011-2014, but decreased by 4.24% yr^{-1} from 2014 to 2017. Therefore, the trends in first year ice and total SIA had some differences in the past 20 years, but were generally similar from 2011 to 2017.

The first year ice melt duration can directly reflect the situation of seasonal ice within the year. And it was calculated based on the daily sea ice concentration provided by the NSIDC. We pre-processed the daily sea ice concentration data before calculating melt duration.

First, the sea ice pixels were assigned a value of 0 and seawater pixels were assigned a value of 1. Next, the daily SIE was counted and the annual data were accumulated. Finally, if the accumulated value of a pixel was 365 or 366 (leap year), then the pixel was considered seawater all year. If the accumulated value of a pixel was between 1-364 or 1-365 (leap year), then the value was the number of days that the pixel existed with seawater during the year, namely the melt duration. The pixels of this type (pixel value of 365 or 366) were accumulated and divided by the total number of pixels, and the result was the first year ice melt duration. The trend in melt duration is shown in Fig. 8.

From Fig. 8 it can be seen that the melt duration showed a decreasing trend, and decreased by 0.1908 days yr^{-1}. The melt duration in 2003 was the historical maximum in the past 20 years, which was approximately 191.44 days, but 2015 had the minimum melt duration, which was 175.77 days; there was a difference of about 8.19%. From 1998-2007, the average melt duration was 186.56 days, and it was 182.12 days from 2008-2017, which was a difference of about 2.38%. Comparing Fig. 4 and Fig. 8, there was a clear correlation between the first year ice melt duration and the total SIA; when the melting time was longer, the total SIA was smaller.

3.2.2 West Antarctica

The first year ice area in WA was statistically analysed, and the results are shown in Fig. 9. Figure 9 reveals that the first year ice area increased from 1998 to 2017 by approximately 0.0154×10^6 km^2 yr^{-1}. According to Table 3, the average first year ice area in WA from 1998 to 2007 was 2.521×10^6 km^2, while from 2008 to 2017 the average area was 2.786×10^6 km^2, which was a difference of about 10.5% and was much larger than that in the Entire Antarctica. The first year ice areas from 1998-2007 and 2008-2017 were statistically analysed, as shown in Fig. 9. A comparison of the results of the two consecutive periods (1998-2007 and 2008-2017) revealed that although the first year ice area in both periods showed a decreasing trend, the specific trends were different. Comparing Fig. 7 and Fig. 9, the trends in the first year ice area in WA and the Entire Antarctica were different during the past 20 years, but were very similar from 2008 to 2017. Due to the influence of circulation and ocean currents and geographical location, the variation in first year ice area in distinct regions of the Antarctic were different (Pezza et al. 2012). However, in recent years, the change in first year ice area was consistent between WA and the Entire Antarctica, especially from 2014-2017, when both showed a decreasing trend; the decrease rates were 4.86% yr^{-1} and 4.24% yr^{-1}, respectively.

The variation in first year ice area in WA from 1998-2017 is shown in Fig. 10. From Fig. 10 it can be seen that the melt duration showed a decreasing trend, and decreased by 0.3512 days yr^{-1}. The melt duration in 2007 was the historical maximum in the past 20 years, which was approximately 182.47 days, but 2014 had the minimum melt duration, which was 162.34 days; this was a difference of about 11.03%. Comparing Fig. 8 and Fig. 10, the melt durations both showed a decreasing trend, but the decrease rate in WA was greater than that in the Entire Antarctica.

3.2.3 East Antarctica

The results of the first year ice area in EA are shown in Fig. 11. From 1998-2017, the first year ice area was reduced by 0.0213×10^6 km^2 yr^{-1}. In 2006, the first year ice area was the largest at about 5.355×10^6 km^2, and in 2017, it was the smallest at about 4.533×10^6 km^2. The data in Table 3 reveal that from 1998 to 2007, the average first year ice area was 5.118×10^6 km^2, and from 2008 to 2017, the average first year ice area was 5.031×10^6 km^2. The difference between the two 10-year periods was only about 1.7%, which was far below the difference in WA between the two 10-year periods. Comparing Fig. 7 with Fig. 11, it can be seen that the trends in first year ice area in EA and the Entire Antarctica were almost the same. The first year ice area showed a positive growth trend in the first 10 years, but a negative growth trend in the following 10 years. Comparing Fig. 7, Fig. 9, and Fig. 11, the trend in the first year ice area in EA was consistent with that in the Entire Antarctica or WA in recent years. In particular, from 2014-2017, they decreased by 4.86% yr^{-1} (WA), 5.04% yr^{-1} (EA), and 4.24% yr^{-1} (Entire Antarctica).

The results of the first year ice melt duration in EA are shown in Fig. 12. During the period of 1998-2017, the melt duration showed little change, and decreased by 0.049 days yr^{-1}. However, there were large differences between different years. The melt duration in 2015 was 180.47 days, which was the shortest, and the melt duration in 2016 was 197.12 days, which was the longest in 20 years. The difference was about 9.23% between the adjacent two years. Comparing Fig. 8 with Fig. 12, it can be seen that the melt durations showed decreasing trends in 20 years in both EA and the Entire Antarctica, but the decrease in the Entire Antarctica was about four times that of EA. There was also a large difference in the years of the maximum melt duration and minimum melt duration. However, the trends between 2013 and 2017 were almost the same, and both reached the shortest melt duration in 2015 and the longest melt duration in 2016.

3.3 Analysis of Multiyear Ice Area

Multiyear ice is more stable than first year ice. It is important to obtain a more accurate quantification of multiyear ice through the use of data during the minimum SIE, since at this time, the first year sea ice cover has almost all melted, and what is left is called multiyear ice (Comiso, 1990). The multiyear ice area was based on daily SIE provided by the NSIDC. We pre-processed the daily SIE data before calculating the multiyear ice area. First, sea ice pixels were assigned a value of 0, seawater pixels were assigned a value of 1, and land was masked. Next, the daily SIE was counted, and the annual data were accumulated. Finally, if the accumulated value of a pixel was 0, it meant that the pixel was multiyear ice, if the pixel value was not 0 then it was first year ice or seawater. The yearly multiyear ice areas in different regions are shown in Table 4.

3.3.1 Entire Antarctica

The trend in multiyear ice area from 1998 to 2017 is shown in Fig. 13. From Fig. 13, it can be seen that the multiyear ice area in the Antarctic showed an increasing trend from 1998 to 2017, and increased by about 0.0154×10^6 km^2 yr^{-1}. In 2015, the multiyear ice area reached a maximum of about 2.585×10^6 km^2, and in 2017 it reached a minimum of about 1.261×10^6 km^2, with a large difference of about 51.2%. Comparing Fig. 4 and Fig. 13, the total SIA and multiyear ice area in the Entire Antarctica showed increasing trends over the 20 years, but the change extent of the total SIA was significantly larger than that of the multiyear ice area. The trends between 2015 and 2017 were similar, with both decreasing by approximately 25.6% and 7.3% yr^{-1}, respectively, but the decrease in multiyear ice area was clearer than that of total SIA.

Although the multiyear ice area has been increasing during the past 20 years, large differences have existed between the first and last 10 years. Therefore, in order to reflect more detailed changes in multiyear ice, the trends in multiyear ice area in the two 10-year periods were analysed, as shown in Fig. 13. As can be seen from Fig. 13, the multiyear ice area in the Entire Antarctica showed opposite trends in the two 10-year periods. The multiyear ice area increased by 0.0268×10^6 km^2 yr^{-1} from 1998 to 2007, but decreased by 0.0301×10^6 km^2 yr^{-1} from 2008 to 2017. Comparing Fig. 4 and Fig. 13, the total SIA and multiyear ice area showed increasing trends in the first 10 years, but showed decreasing trends in the last 10 years.

3.3.2 West Antarctica

The results of the multiyear ice area in WA are shown in Fig. 14. The multiyear ice area decreased by 0.0324×10^6 km^2 yr^{-1} (5% yr^{-1}); it continuously decreased, and had almost no significant increase from 1998 to 2017. During the 20-year period, 2001 had the maximum multiyear ice area, which was about 0.774×10^6 km^2; it reached the minimum in 2017, and was about 0.041×10^6 km^2. There was a very large difference of about 94.7% between the maximum and minimum values.

In order to more fully compare the similarities and differences of the changes in WA, the trends in multiyear ice area in the two 10-year periods were analysed, as shown in Fig. 14. Among these two periods, the multiyear ice area decreased by 0.0287×10^6 km^2 yr^{-1} from 1998 to 2007 and decreased by 0.0202×10^6 km^2 yr^{-1} from 2008 to 2017. Comparing Fig. 13 with Fig. 14, it can be seen that the multiyear ice area in WA and in the Entire Antarctica showed opposite trends in the first 10 years, but showed a consistent change in the later 10 years.

3.3.3 East Antarctica

The results of the multiyear ice area in EA are shown in Fig. 15. The multiyear ice area increased by 0.0478×10^6 km^2 yr^{-1} from 1998 to 2017, and it showed a clear opposite trend compared with that in WA. During the 20 years, 2015 had the maximum multiyear ice area, which was about 2.266×10^6 km^2; it reached the minimum in 1998, which was about 0.786×10^6 km^2. There was a very large difference of about 65.3% between the maximum and minimum values.

The multiyear ice area from 1998 to 2007 increased by 0.0556×10^6 km^2 yr^{-1}, but decreased by 0.0099×10^6 km^2 yr^{-1} from 2008 to 2017. Comparing Fig. 13 with Fig. 15, it can be seen that the trend in multiyear ice area in EA was consistent with that in the Entire Antarctica. However, the multiyear ice area fluctuated significantly from 2010-2017; the multiyear ice area in 2015 increased by 72.2% compared to that in 2010, but the 2017 multiyear ice area decreased by 46.1% compared to that in 2015.

4 Discussion

Although the long time series of Antarctic sea ice changes have been studied in many aspects, there are still some shortcomings.

(1) We focuses on the changes of Antarctic sea ice in the past 20 years. The main reason is that the variation of sea ice in Antarctica is relatively large in the past 20 years. The change trend in 2008-2017 is opposite to that in 1998-2007. Of course, in order to study the changes in Antarctic sea ice in more detail, we can extend the study from 1979, which will be the focus of our next work.

(2) In this study, the Antarctic sea ice was analyzed by using the daily sea ice concentration data with a spatial resolution of 25 km provided by NSIDC. This data is suitable for large-scale research, but for small-scale sea ice research, the spatial resolution obviously does not meet the requirements, while the data provided by Bremen, has a higher spatial resolution. Therefore, the next step in our work is to combine the two data for a more comprehensive study of Antarctic sea ice.

(3) This study focuses more on the trend and state of sea ice change, and less on the causes of sea ice change. The causes of sea ice change are more complicated. Global average temperature, ocean currents, geographic location and other extreme natural weather can affect sea ice changes. How to explain the causes of Antarctic sea ice changes will be our next step work.

5 Conclusions

In this study, the variability in Antarctic sea ice from 1998 to 2017 was analysed according to four parameters, namely total SIA, area and melt duration of first year ice, and multiyear ice area. At the temporal scale, the changes in sea ice parameters were studied through the analysis of the entire 20-year period and through comparing the changes and trends in sea ice in the Antarctic between the first and last decade. At the spatial scale, the whole Antarctic region was divided into two areas, namely WA and EA, according to the spatial change rate of the sea ice concentration. The specific conclusions are as follows:

(1) In the Entire Antarctica, the total SIA increased by 0.0083×10^6 km^2 yr^{-1}, and in EA, it increased at a rate of 0.0167×10^6 km^2 yr^{-1}, but decreased by 0.0079×10^6 km^2 yr^{-1} in WA from 1998 to 2017. Although the total SIA in the Antarctic increased slightly in these 20 years, the changes in the first and last decades were diametrically opposite. From 1998-2007, the total SIA increased by 0.026×10^6 km^2 yr^{-1}, but in 2008-2017, it decreased by 0.0707×10^6 km^2 yr^{-1} in the Entire Antarctica. The total SIA in EA had the same trend as the Entire Antarctica in the two 10-year periods. However, WA showed a decreasing trend during both periods, and the decrease in total SIA in WA was always greater than that in EA. Therefore, the total SIA in the Entire

Antarctica increased during the 20 years and the temperature decreased slightly; however, there was a decreasing trend from 2008-2017, and due to the geographical location and the influence of ocean currents and circulation, most of the areas in WA experienced warming in recent years, and sea ice ablation has become apparent.

(2) In the Entire Antarctica, the first year ice area decreased by 0.0059×10^6 km^2 yr^{-1} from 1998-2017, and the first year ice area in EA was consistent with the trend in the Entire Antarctica with a decrease of about 0.0213×10^6 km^2 yr^{-1}. However, WA showed the opposite trend, and increased by 0.0154×10^6 km^2 yr^{-1}. During the period of 1998-2017, the melt duration showed a decreasing trend in the Entire Antarctica, as well as in WA and EA. However, the rate of decrease in WA was significantly greater than that in EA. Looking at the temporal scale, the first year ice area in the Entire Antarctica showed a decreasing trend during both decades, but it decreased more severely in the later 10 years. The first year ice area showed a decreasing trend during the first and second periods in WA, but it had an increasing trend over the 20 years. The reason for this may be that the first year ice area in WA fluctuated greatly from year to year. From 1998-2007, the first year ice area was relatively small, but it was large in 2010, 2013, and 2014, and sharply decreased from 2012-2017. In contrast, the change in the first year ice area between the two periods in EA presented the opposite trend, and the trend in the last 10 years was the same as that in WA. Therefore, the first year ice area showed a decreasing trend with respect to the total SIA, which had an increasing trend in the Entire Antarctica. Although the changes in WA and EA were not the same during the 20 years, between 2014 and 2017 the trends were almost the same, and decreased by 4.86% yr^{-1} and 5.04% yr^{-1}, respectively.

(3) The multiyear ice area increased by 0.0154×10^6 km^2 yr^{-1} during 1998-2017 in the Entire Antarctica, and same trend in EA was observed, but the increase was larger than that in the Entire Antarctica, which increased by 0.0478×10^6 km^2 yr^{-1}. The multiyear ice area in WA decreased with more stable conditions over the 20 years, and it decreased at a rate of 0.0324×10^6 km^2 yr^{-1}. At a temporal scale, the multiyear ice area in the Entire Antarctica increased by 0.0268×10^6 km^2 yr^{-1} from 1998 to 2007, but decreased by 0.0301×10^6 km^2 yr^{-1} from 2008-2017;

it showed a decreasing trend in the first and second decades in WA. The multiyear ice area increased by 0.0556×10^6 km^2 yr^{-1} from 1998 to 2007 in EA. However, the fluctuations in multiyear ice area were relatively large from 2008 to 2017, in which 2010, 2015, and 2017 were the three extreme years; the multiyear ice area in 2015 increased by 72.2% compared to that in 2010, but the multiyear ice area in 2017 decreased by 46.1% compared to that in 2015. Therefore, the multiyear ice decreased more clearly than the total sea ice and first year ice. In particular, in the second 10-year period, the multiyear ice area decreased in the two regions. In 2017, the multiyear ice area reached the smallest amount during the 20 years; it was approximately 0.041×10^6 km^2, which was a decrease of 94.7% compared with that in 1998. The multiyear ice area decreased by 5% yr^{-1} in WA. In particular, in the Ross Sea in WA, the multiyear ice area decreased sharply; following this trend, there may be ice-free conditions in the Ross Sea during the summer of 2018.

Acknowledgements

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Table 1(on next page)

Table1 Yearly results of total sea ice area in different regions (10^6 km^2)

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Table 1 Passive microwave sensor platform and the start and stop time of data collection

Sensor	Platform	Start Time	Stop Time
SSM/Is	DMSP-F13	30 September 1995	31 December 2007
SSMIS	DMSP-F17	1 January 2008	31 March 2016
SSMIS	DMSP-F18	1 April 2016	Present

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Table 2 (on next page)

Table 2 Yearly results of total sea ice area in different regions (10^6 km^2)

Table 2 Yearly results of total sea ice area in different regions (10^6 km^2)

First Decade	Entire Antarctic	WA	EA	Last Decade	Entire Antarctic	WA	EA
1998	8.831	3.061	5.769	2008	9.269	2.953	6.316
1999	8.834	3.207	5.627	2009	9.114	3.012	6.102
2000	8.998	3.056	5.942	2010	9.151	3.065	6.085
2001	8.683	2.955	5.727	2011	8.659	2.797	5.861
2002	8.496	2.759	5.737	2012	9.204	2.843	6.360
2003	9.056	2.809	6.247	2013	9.656	3.191	6.465
2004	9.080	2.892	6.187	2014	9.836	3.080	6.756
2005	8.739	2.780	5.959	2015	9.399	3.013	6.385
2006	8.682	2.683	5.998	2016	8.302	2.660	5.642
2007	9.374	2.804	6.131	2017	8.025	2.582	5.453
Average	8.877	2.901	5.932	Average	9.061	2.919	6.142
Max.	9.374	3.207	6.247	Max.	9.836	3.191	6.756
Min.	8.496	2.683	5.627	Min.	8.025	2.582	5.453

Table 3 (on next page)

Table 3 Yearly results of first year ice area in different regions (10^6 km^2)

Table 3 Yearly results of first year ice area in different regions (10^6 km^2)

First Decade	Entire Antarctic	WA	EA	Last Decade	Entire Antarctic	WA	EA
1998	7.840	2.579	5.261	2008	7.588	2.735	4.853
1999	7.685	2.711	4.973	2009	7.789	2.846	4.942
2000	7.924	2.720	5.204	2010	7.929	2.993	4.935
2001	7.484	2.422	5.062	2011	7.494	2.657	4.836
2002	7.486	2.447	5.038	2012	7.694	2.649	5.045
2003	7.268	2.365	4.902	2013	7.927	2.972	4.955
2004	7.583	2.471	5.112	2014	8.145	2.988	5.157
2005	7.613	2.546	5.066	2015	7.564	2.822	4.741
2006	7.705	2.423	5.281	2016	7.275	2.634	4.641
2007	7.701	2.528	5.173	2017	7.110	2.552	4.557
Average	7.628	2.521	5.107	Average	7.651	2.784	4.866
Max.	7.924	2.720	5.281	Max.	8.145	2.993	5.157
Min.	7.268	2.365	4.902	Min.	7.110	2.552	4.557

Table 4(on next page)

Table 4 Yearly results of multiyear ice area in different regions (10^6 km^2)

Table 4 Yearly results of multiyear ice area in different regions (10^6 km^2)

First Decade	Entire Antarctic	WA	EA	Last Decade	Entire Antarctic	WA	EA
1998	1.462	0.676	0.786	2008	2.385	0.316	2.068
1999	1.656	0.708	0.948	2009	1.835	0.256	1.578
2000	1.556	0.513	1.043	2010	1.430	0.115	1.315
2001	1.731	0.774	0.956	2011	1.703	0.275	1.428
2002	1.477	0.475	1.002	2012	2.093	0.331	1.761
2003	2.394	0.592	1.801	2013	2.398	0.325	2.073
2004	2.110	0.628	1.481	2014	2.335	0.150	2.185
2005	1.710	0.430	1.280	2015	2.585	0.319	2.265
2006	1.475	0.448	1.027	2016	1.431	0.044	1.387
2007	1.781	0.441	1.348	2017	1.260	0.040	1.220
Average	1.735	0.568	1.167	Average	1.945	2.171	1.728
Max.	2.394	0.774	1.801	Max.	2.398	0.331	2.265
Min.	1.462	0.430	0.786	Min.	1.260	0.040	1.220

Figure 1

The results of the average sea ice concentration from 1998 to 2017.

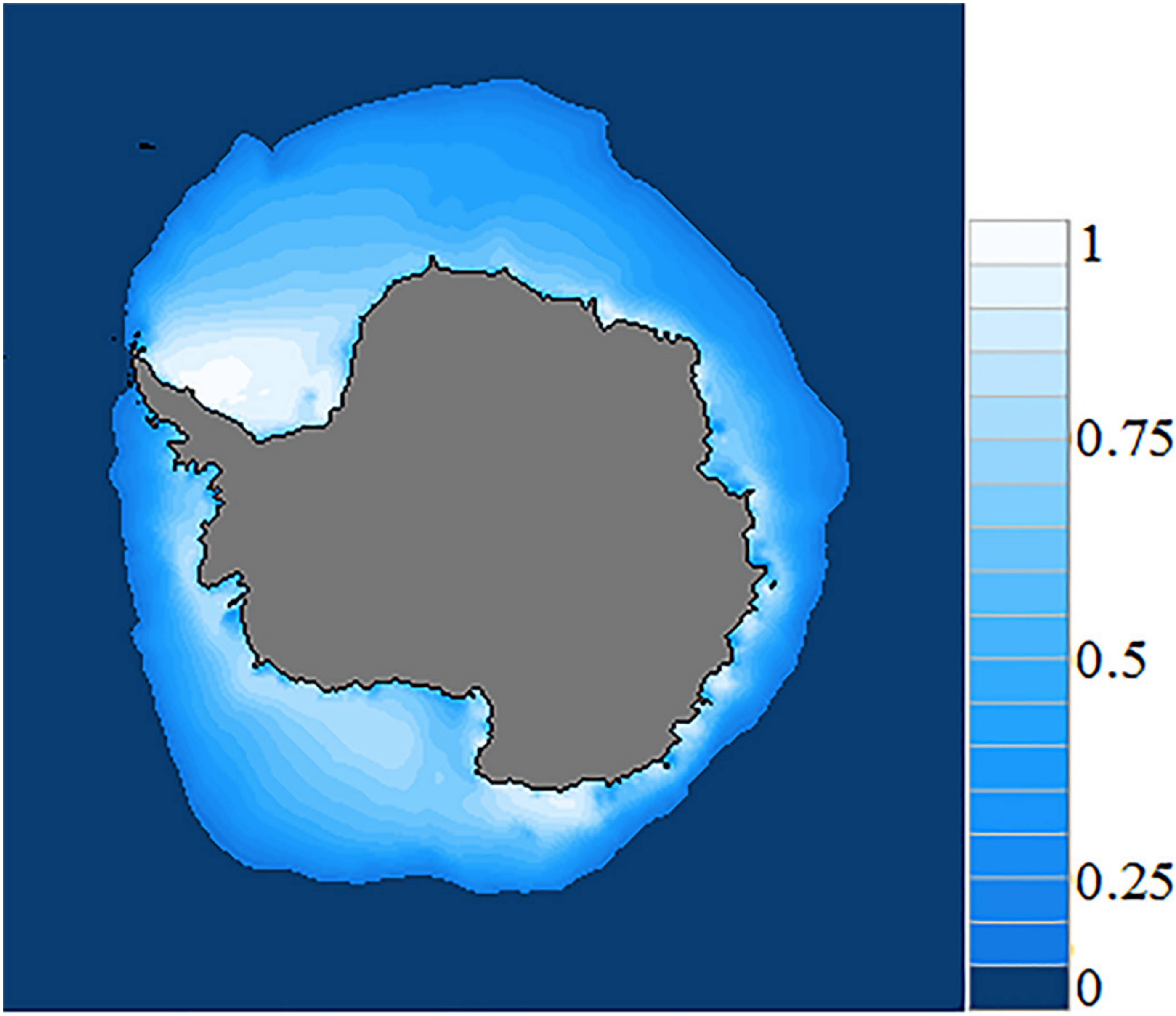

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Figure 2

The variation in Antarctic sea ice concentration distribution from 1998 to 2017

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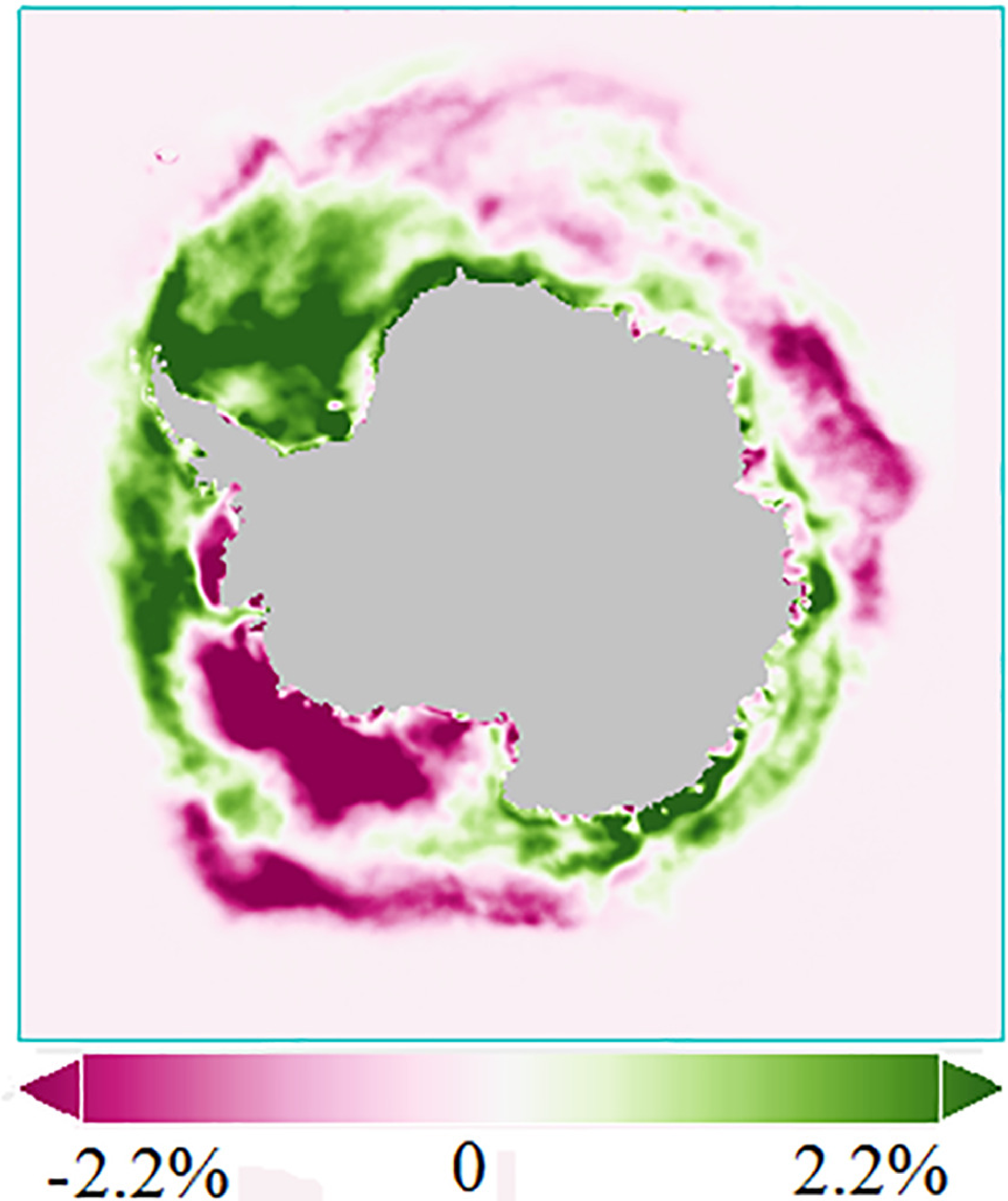

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Figure 3

Map of the Antarctic regional division (WA: 180-75°W, EA: 75°W-180°E)

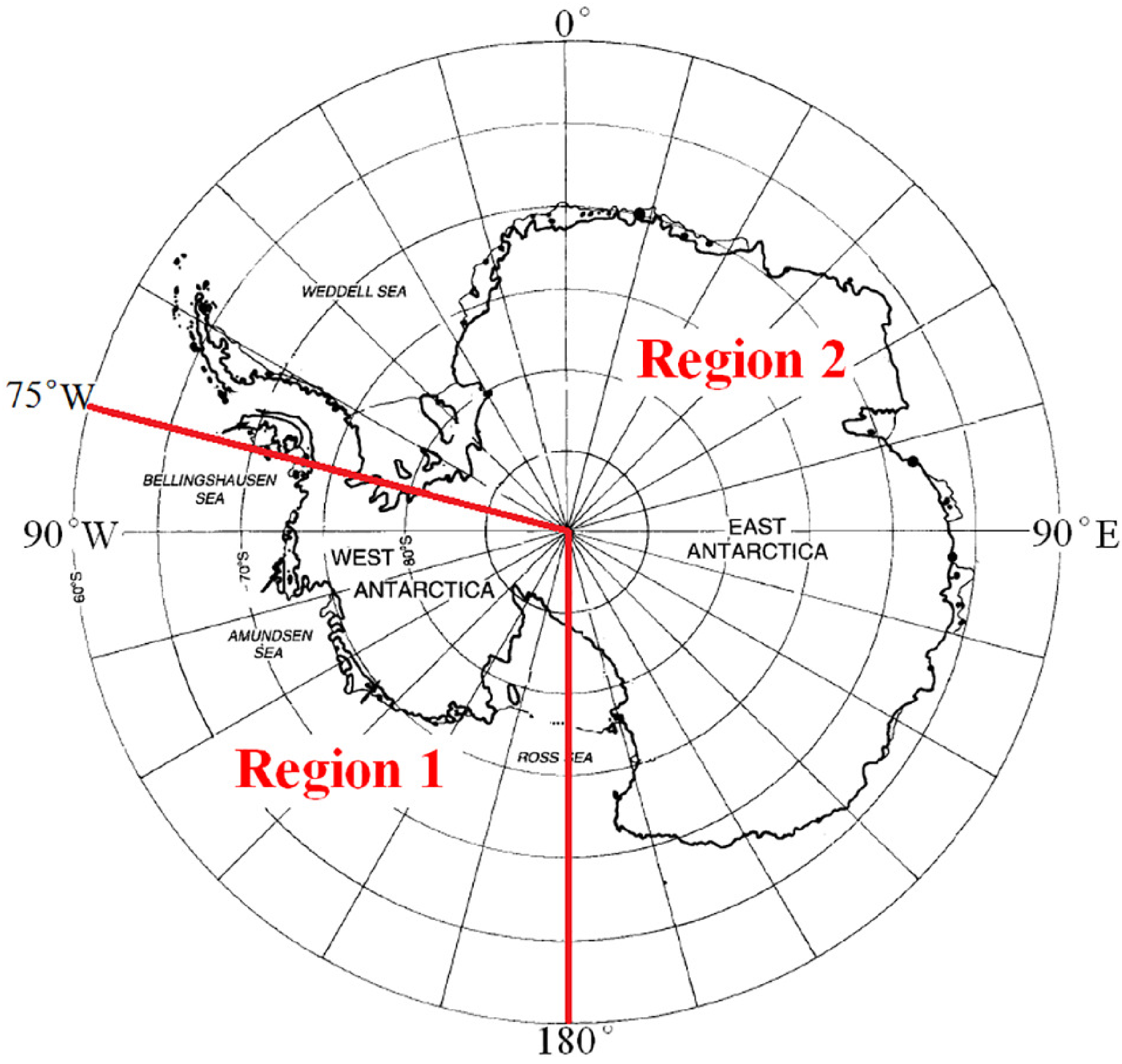

Figure 4

The variation in total SIA in Antarctic from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))

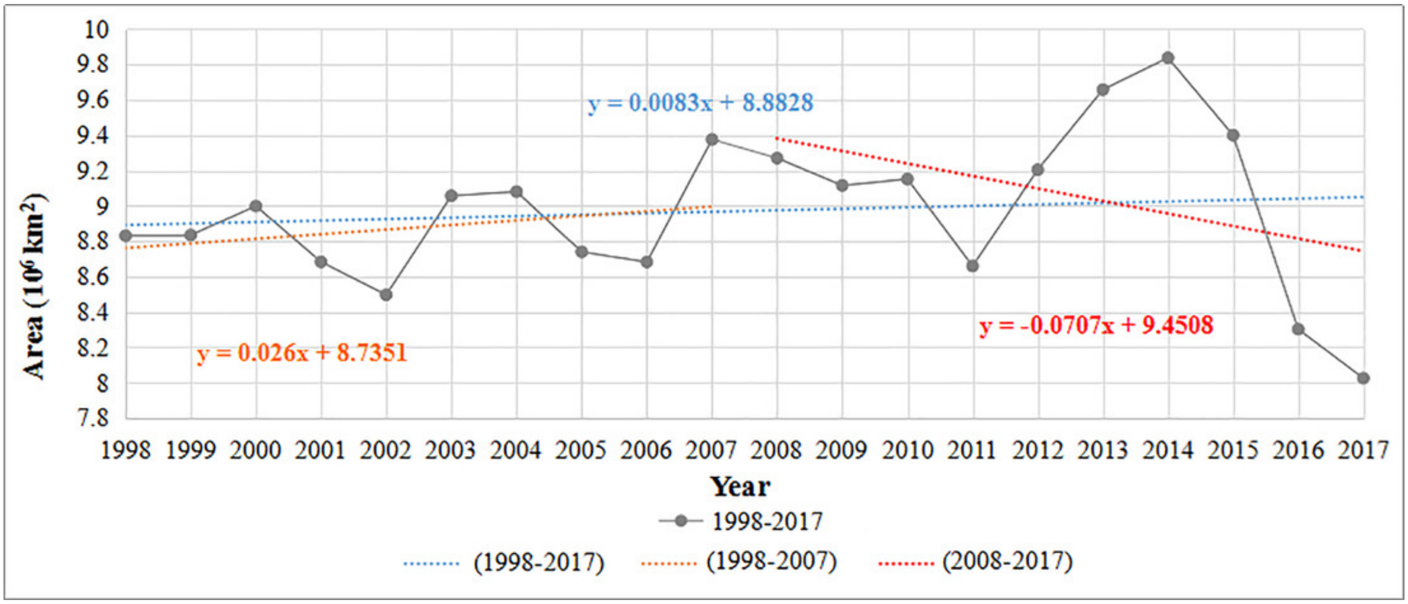

Figure 5

The variation in total SIA in WA from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))

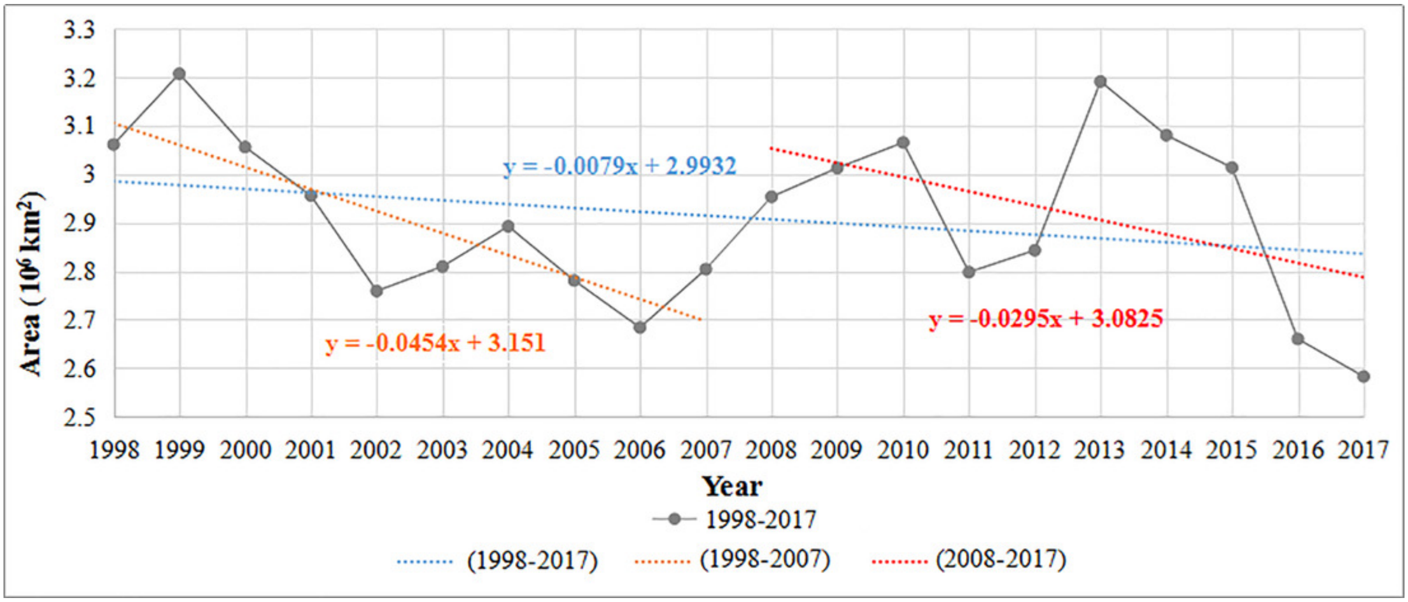

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Figure 6

The variation in total SIA in EA from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))

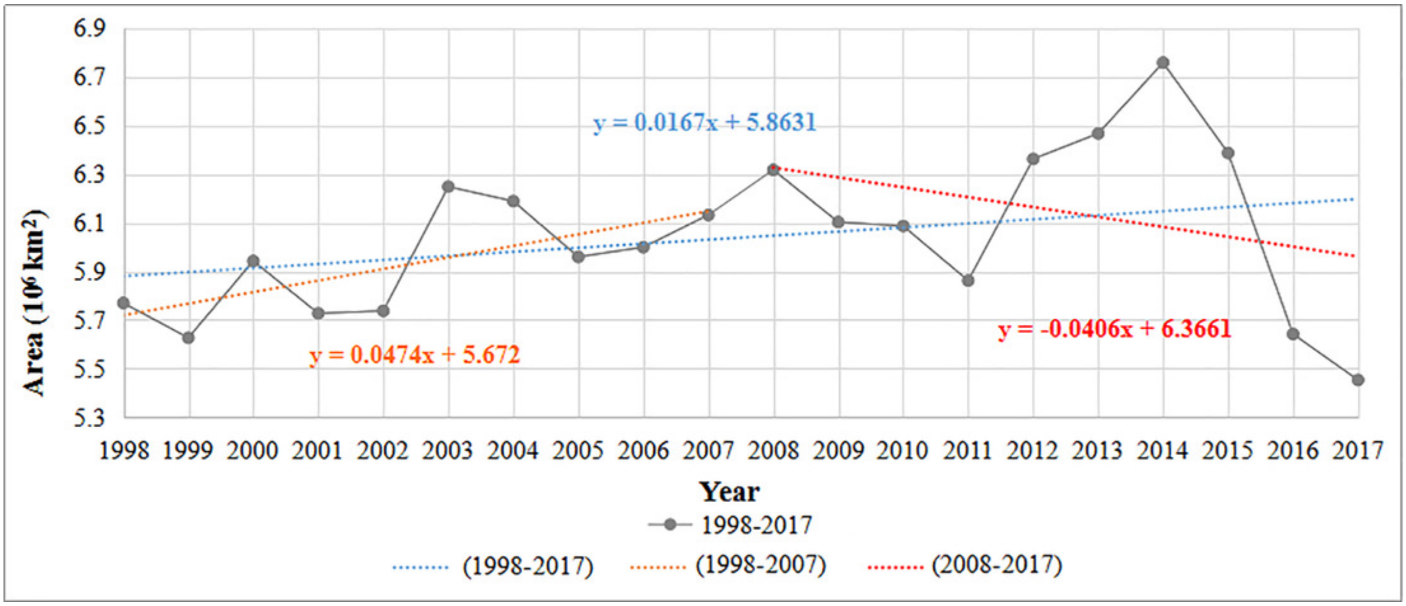

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Figure 7

The variation in first year ice area in Antarctic from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))

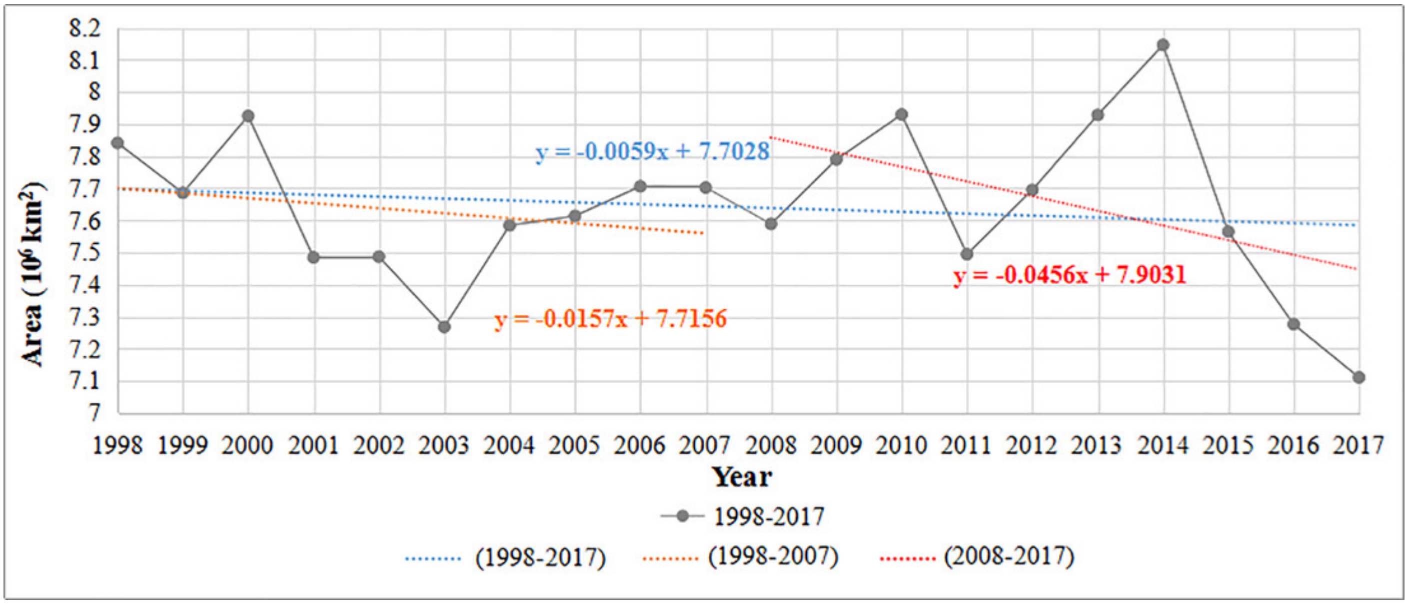

Figure 8

The variation in Antarctic first year ice melt duration from 1998-2017 (solid line: yearly data; dashed line: trends of change)

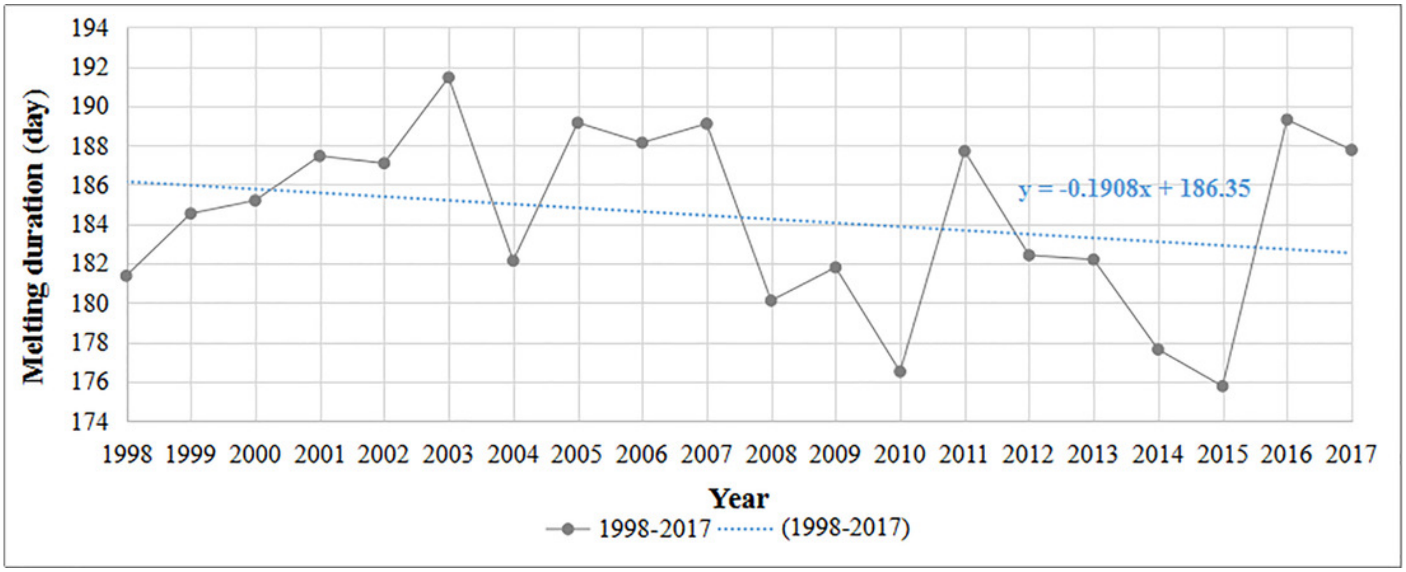

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Figure 9

The variation in first year ice area in WA from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))

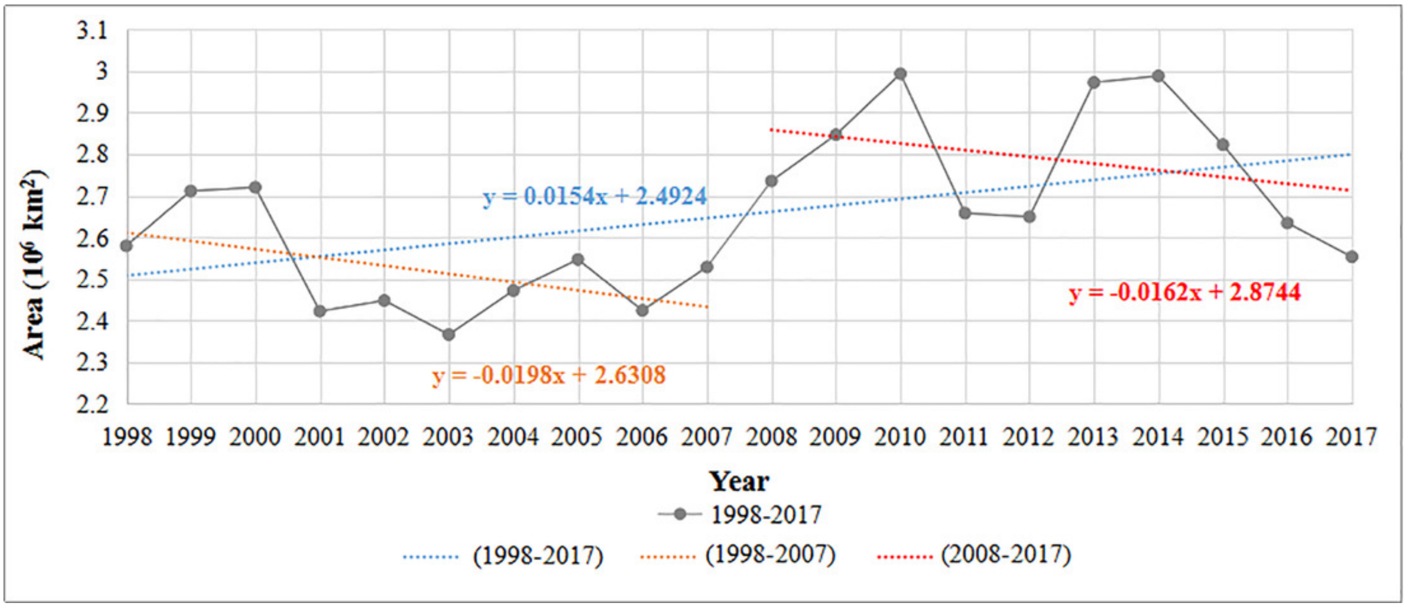


Figure 10

The variation in first year ice melt duration in WA from 1998 to 2017 (solid line: yearly data; dashed line: trends of change)

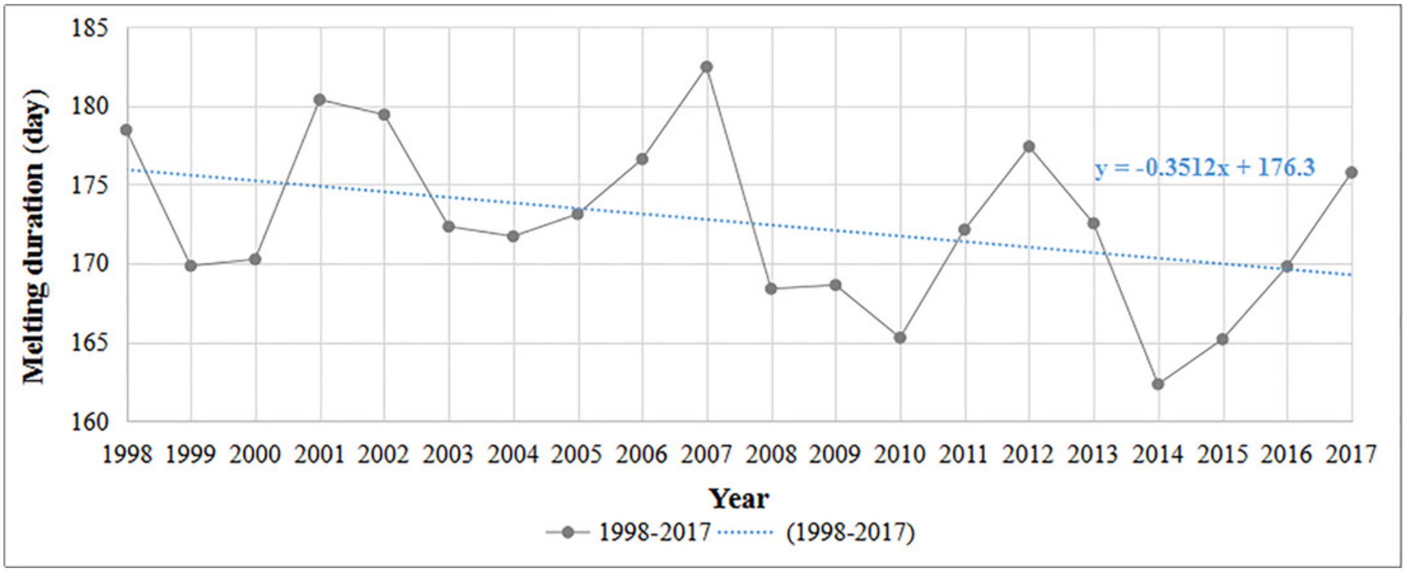


Figure 11

The variation in first year ice area in EA from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))

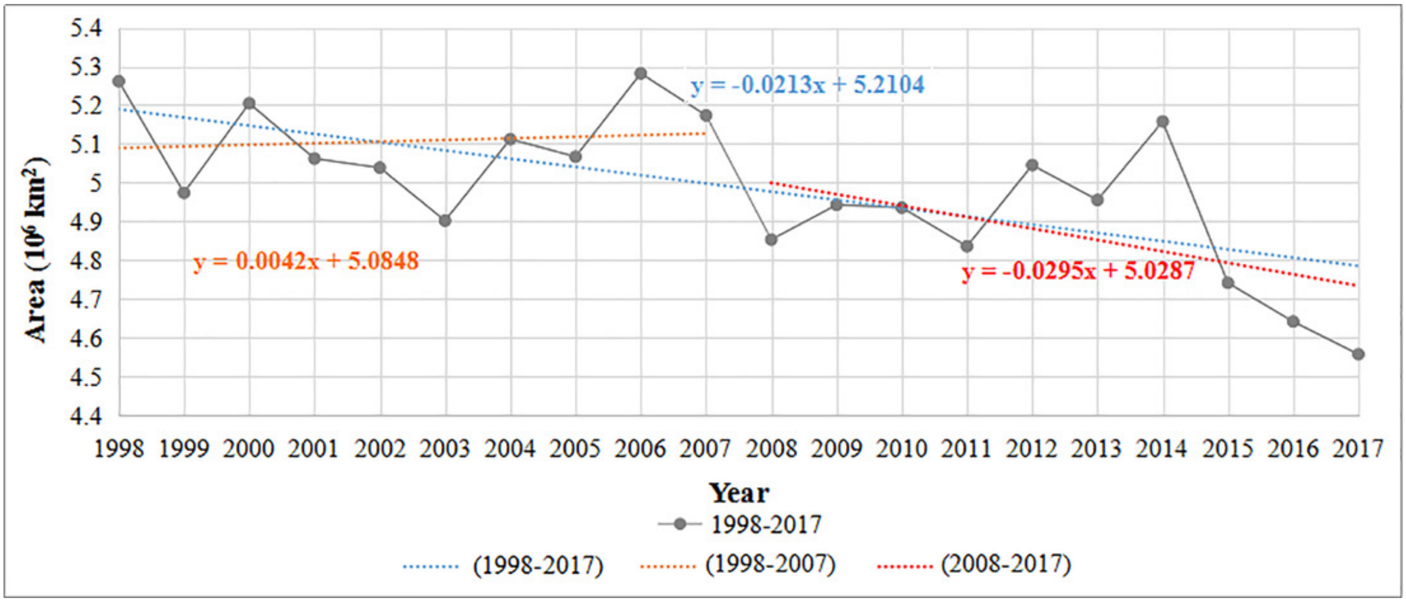


Figure 12

The variation in first year ice melt duration in EA from 1998-2017 (solid line: yearly data; dashed line: trends of change)

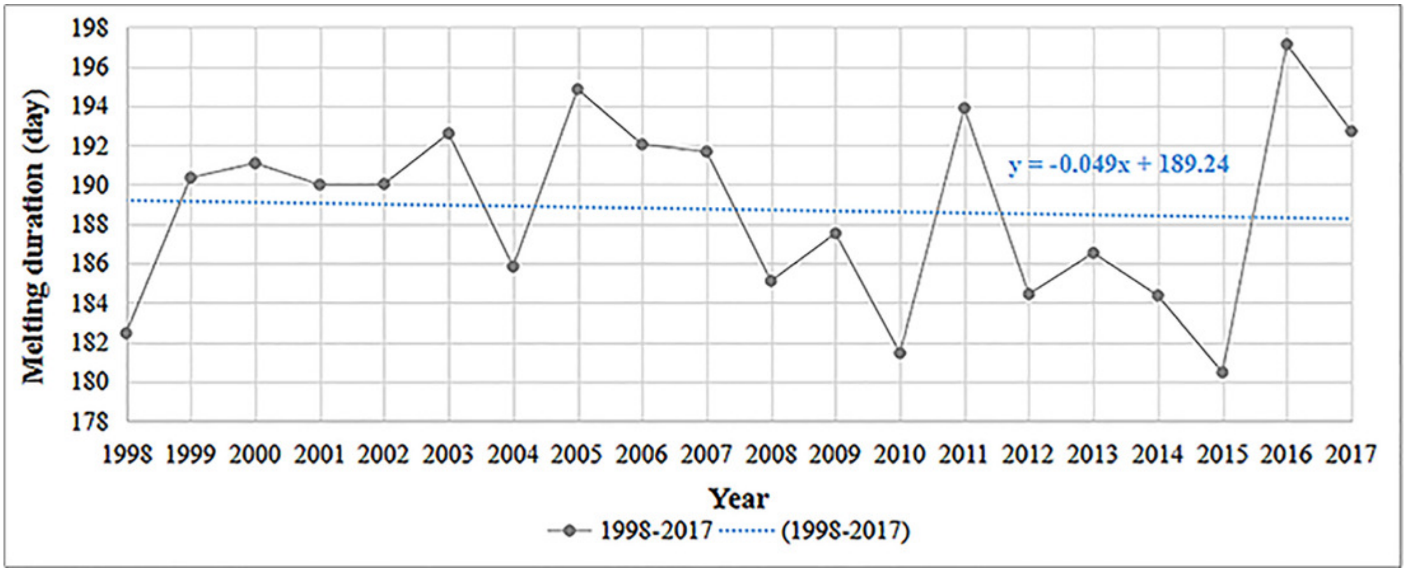


Figure 13

The variation in multiyear ice area in Antarctic from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))

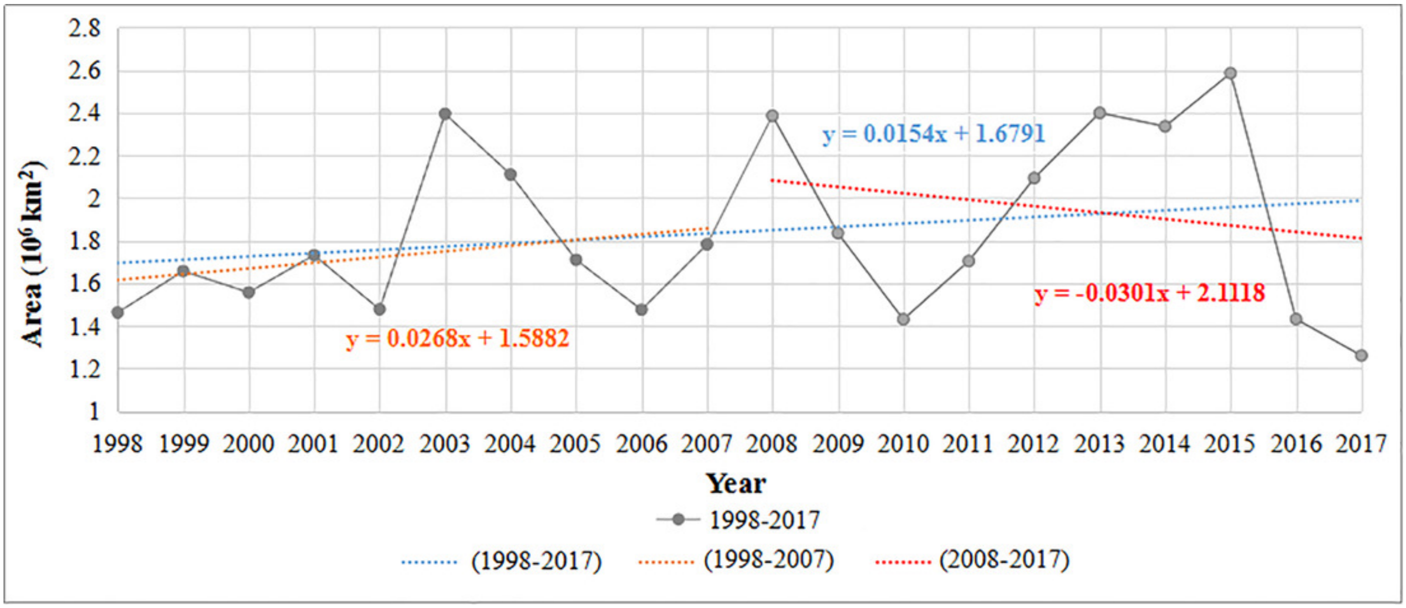


Figure 14

The variation in multiyear ice area in WA from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))

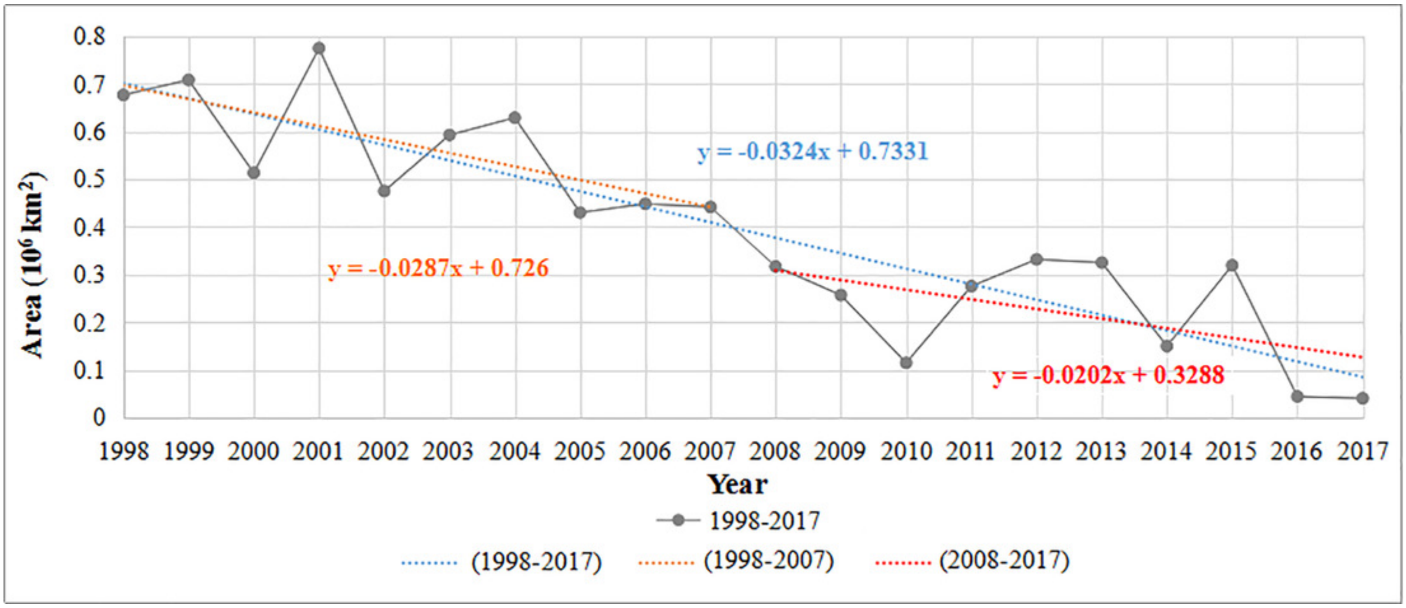
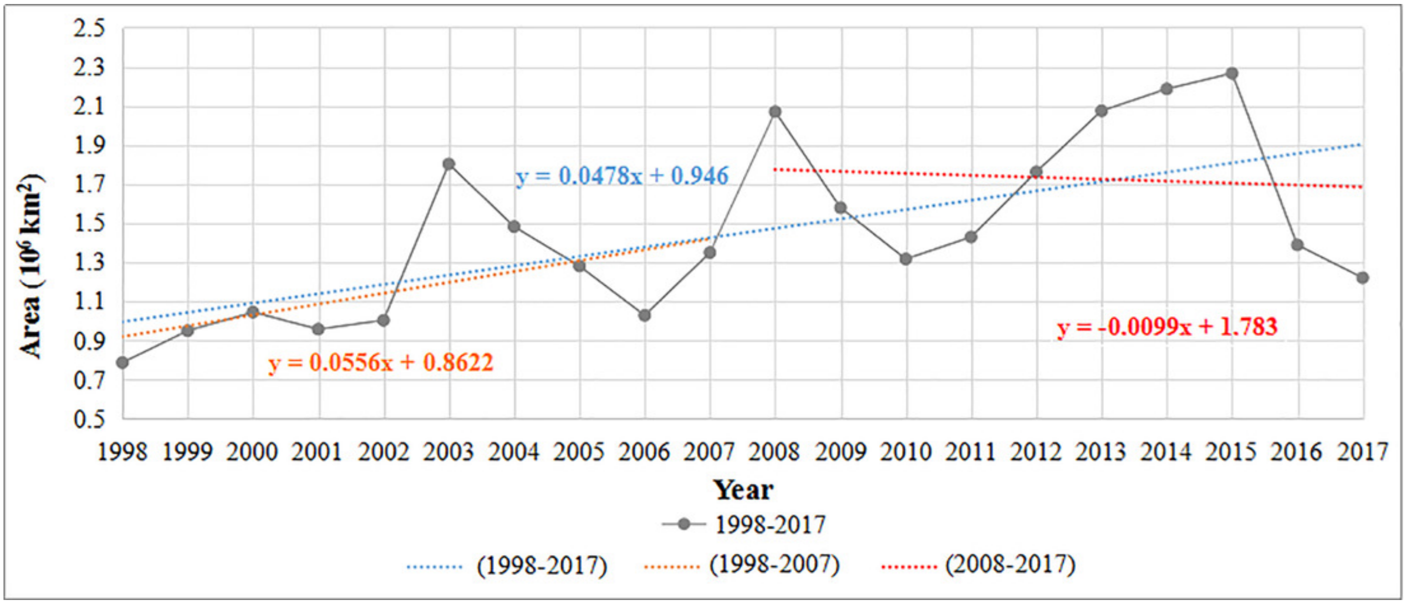


Figure 15

The variation in multiyear ice area in EA from 1998-2017 (solid line: yearly data; dashed lines: trends of change (blue dashed line: 1998-2017, orange dashed line: 1998-2007, red dashed line:2008-2017))



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