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Spatio-temporal Variation of Arctic Sea Ice in Summer from 2003 to 2013

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Abstract: The variation in Arctic sea ice has significant implications for climate change due to its huge influence on the global heat balance. In this study, we quantified the spatio-temporal variation of Arctic sea ice distribution using Advanced Microwave Scanning Radiometer (AMSR-E) sea-ice concentration data from 2003 to 2013. The results found that, over this period, the extent of sea ice reached a maximum in 2004, whereas in 2007 and 2012, the extent of summer sea ice was at a minimum. It declined continuously from 2010 to 2012, falling to its lowest level since 2003. Sea-ice extent fell continuously each summer between July and mid-September before increasing again. It decreased most rapidly in September, and the summer reduction rate was 1.35×10^5 km^2/yr, twice as fast as the rate between1979 and 2006, and slightly slower than from 2002 to 2011. Area with >90% sea-ice concentration decreased by 1.32×10^7 km^2/yr, while locations with >50% sea-ice concentration, which were mainly covered by perennial ice, were near the North Pole, the Beaufort Sea, and the Queen Elizabeth Islands. Perennial Arctic ice decreased at a rate of 1.54×10^5 km^2 annually over the past 11 years.
Keywords: sea ice; Advanced Microwave Scanning Radiometer (AMSR-E); climate change; Arctic; summer

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1 Introduction

Under the influence of a globally warming climate, Arctic sea ice is changing and generally shrinking (Rothrock and Zhang, 2005; Stroeve et al., 2007; Lindsay et al., 2009; Arntsen et al., 2015) as well as thinning (Rothrock et al., 1999; Wadhams and Davis, 2000; Cavalieri et al., 2003; Kwok, 2007; Zhang et al., 2008; Kwok and Rothrock, 2009; Kwok and Untersteiner, 2011). These processes are also occurring at a rapid pace (Comiso, 2002; Serreze et al., 2007; Comiso et al., 2008; Cavalieri and Parkinson, 2012; Meng et al., 2013). From 1953 to 2006, Arctic sea ice extent at the end of the summer melt season in September declined at a rate of 7.8% per decade. During the period of modern satellite observations (1979–2006) the trend is even larger (9.1% per decade) (Serreze et al., 2007; Parkinson and Cavalieri, 2008; Kwok and Rothrock, 2009; Shibata et al., 2013). Perennial sea-ice also showed a decreasing trend, with losses of 2.0% to 3.3% of the total area per decade between 1979 and 1996, and this rate has increased to 10.1% to 10.7% in the past decade alone (Smith, 1998; Comiso, 2002; Comiso et al., 2008; Ke et al., 2013). Recent studies suggest that the shrinking of Arctic sea-ice cover is more obvious in summer (Zhang et al., 2010; Shi et al., 2015). The significant decreasing trend of Arctic sea-ice cover, especially during summer (July–September), produces a larger open water surface, lowering the albedo of the Arctic sea surface and, consequently increasing the absorption of solar radiation (Rothrock et al., 2008; Day et al., 2012). This in turn results in higher sea surface temperatures and lower

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sea-ice coverage in winter, so that it forms a positive feedback between Arctic sea-ice and sea surface temperatures (Kwok, 2007; Sui et al., 2011).

Satellite remote sensing observations, available from the National Snow and Ice Data Center (NSIDC), show that Arctic sea ice fell to its lowest extent in the summer of 2012, breaking the record set in 2007 since monitoring began in the 1970s (Zhang et al., 2008; Tan and LeDrew, 2016). Furthermore, it began melting earlier than usual in summer with sea ice continuing to shrink (Kwok, 2007), resulting in rapid retreat of the sea-ice area across the full Arctic Ocean (Markus et al., 2009). Holland and Comiso project that the Arctic Ocean will be ice-free by the summer of 2040 (Holland et al., 2006; Stroeve et al., 2007; Comiso et al., 2008; Wang et al., 2016; Walsh et al., 2017).

Changes in Arctic sea ice not only affect the physical environment, but also have far-reaching impacts on the related ecosystems (Ke et al., 2013). Arctic sea ice provides breeding grounds for the planktons and microbes that form the bases of the Arctic's entire food chain, and platforms for animals, e.g., polar bears, seals, and walruses, to feed and rest. The gradually thawing of sea ice in Arctic sea area caused by climate warming has eroded the living area of polar bear (Stirling and Pakinson, 2006). Additionally, the changes in Arctic sea ice also have important implications for human activity. For example, the diminished sea ice has made the coastal areas more vulnerable to erosion (Kwok and Untersteiner, 2011). Accurately grasping the dynamics of sea ice, especially its spatial and temporal distributions, including thickness, and the corresponding driving mechanism in Arctic sea area are of critical importance in exploring its function and influence in the global climate system.

In this paper, we used the Advanced Microwave Scanning Radiometer (AMSR-E) sea-ice concentration data from 2003 to 2013 to monitor the spatio-temporal variation of Arctic sea-ice coverage, including the distribution and changes of sea-ice concentration and perennial sea-ice conditions. The results of this study could be used as evidence to support related climate change research.

2 Data and Methods

2.1 Study area

Geographically, the Arctic refers to the vast area north of 66°34′N (Arctic Circle), also known as the Arctic region. The Arctic covers a total area of about 2.1×10^7 km^2, including Arctic seas, islands, and parts of the northern part of Europe, Asia, and northern North America. Arctic land and island areas are about 8.0×10^6 km^2, and the ocean area is about 9.5×10^6 km^2, of which about 1/3 area is less than 200 m and only a small part in Canada and Eurasia is deeper than 4000 m in depth. The Arctic Ocean is almost entirely covered by sea ice, which is about 30% of the world's sea ice area (Kwok and Rothrock, 2009).

2.2 Data and processing

The latest AMSR-E passive microwave remote-sensing data were acquired. The AMSR-E instrument is a conical scanning total power passive-microwave radiometer system with six frequencies, from 6.9 to 89 GHz, and 12 channels, containing all frequencies of the SMMR (Scanning Multichannel Microwave Radiometer) and SSM/I (Special Sensor Microwave Imager). Each of these collects vertically and horizontally polarized measurements, including precipitation rate, water evaporation, and land surface water vapor (Snape and Forster, 2014).

AMSR-E sea-ice concentration images at a 6.25 km resolution in Hierarchical Data Format (HDF) are downloaded daily from the University of Bremen's official website (http://www.iup.uni-bremen.de/seaice/AMSR-Eedata/ and http://www.iup.uni-bremen.de:8084/AMSR-E2data/). This sea-ice concentration data set was the source data for the calculation of sea-ice extent and area. Sea-ice extent was calculated as the cumulative area of all grid cells in the images with at least 15% sea-ice concentration, and sea-ice area was sums of the pixel area times the ice concentration for all pixels with an ice concentration of at least 15%. The 15% threshold is widely used for both ice extent and area calculations (Parkinson et al*.*, 2008). These images covered the entire ice region north of 60°N. There were 1012 images in total during summer (July to September) for the period from 2003 to 2013. There was no data from July 1–23, 2012, so SSM/I data with the same resolution were used to fill the gap.

2.3 Methods

Sea-ice concentration was calculated based on the value of the polarization difference of the brightness temperatures, using the ASI (Arctic Radiation and Turbulence

Interaction Study Sea Ice) algorithm; namely the brightness temperature retrieval sea-ice concentration of two channels, with vertical and horizontal polarization (Spreen et al., 2008). One advantage of the ASI algorithm in contrast to other 85 GHz algorithms (Kern, 2004) is that it does not require additional data sources as inputs. The resolution of sea-ice concentration data is 6.25 km, about three times higher than SSM/I at an 85GHz frequency resolution (13 km × 15 km), making it the highest resolution for all algorithms (Wadhams and Davis, 2000; Spreen et al., 2008).

One disadvantage of the 89-GHz channels is the pronounced influence that atmospheric cloud water and water vapor has on the brightness temperatures. In particular, cyclones over open water can reduce the polarization difference to values that are similarly small as those of sea ice. Therefore, effective filters are necessary to remove spurious ice concentrations in open water areas. The ASI algorithm uses a low brightness temperature as its weather filter (Spreen et al., 2008) to more accurately reflect the sea-ice concentration distribution.

The specific process of the ASI algorithm is as follows (Spreen et al., 2008):

$$P = T\mathrm{b}(\mathrm{V}) - T\mathrm{b}(\mathrm{H}) \tag{1}$$

where P is the polarization difference of brightness temperature; T_b is the brightness temperature of sea surface; and V, H are the vertical and horizontal polarization, respectively. The brightness temperature in a pixel can be decomposed into the sum contribution of sea ice and sea water.

$$P = (C \times P_{\mathrm{si}} + (1 - C) \times P_{\mathrm{sw}}) a_c \tag{2}$$

where C is the sea-ice concentration; P_{si}, P_{sw} are the surface polarization differences for ice and water, respectively. The atmospheric influence a_c is a general function of the ice concentration (Svendsen et al., 1983, 1987).

If the sea-ice concentration is close to 0 or 100%, Equation (2) can be rewritten as equations (3) and (4), respectively:

$$C = \left(\frac{P_{\mathrm{sw}}}{P_{\mathrm{si}} - P_{\mathrm{sw}}}\right)\left(\frac{P}{P_0} - 1\right) \tag{3}$$

$$C = \left(\frac{P_{\mathrm{sw}}}{P_{\mathrm{si}} - P_{\mathrm{sw}}}\right)\left(\frac{P}{P_1} - 1\right) + \frac{P}{P_1} \tag{4}$$

where P_0, P_1 are the surface polarization differences for pure water and pure ice, respectively, referred to as the brightness temperature difference threshold. a_0, a_1 are the coefficients of P_{sw} and P_{si}, respectively.

$$P_0 = a_0 P_{\mathrm{sw}} \tag{5}$$

$$P_1 = a_1 P_{\mathrm{si}} \tag{6}$$

Assuming the atmospheric influence is a smooth function of the ice concentration C, a third-order polynomial can be selected for the sea-ice concentration between open water and 100% ice cover.

$$C = d_3 P^3 + d_2 P^2 + d_1 P + d_0 \tag{7}$$

With equations (3) and (4) and their first derivatives, the unknowns (d_i) in Equation (7) can be determined by solving a system of linear equations:

$$\begin{aligned}
&d_3 P_0^3 + d_2 P_0^2 + d_1 P_0 + d_0 = 0 \\
&d_3 P_1^3 + d_2 P_1^2 + d_1 P_1 + d_0 = 1 \\
&3 d_3 P_0^3 + 2 d_2 P_0^2 + d_1 P_0 = \frac{P_{\mathrm{sw}}}{P_{\mathrm{si}} - P_{\mathrm{sw}}} \\
&3 d_3 P_1^3 + 2 d_2 P_1^2 + d_1 P_1 = \frac{P_{\mathrm{sw}}}{P_{\mathrm{si}} - P_{\mathrm{sw}}} + 1
\end{aligned} \tag{8}$$

The uniform polarization brightness temperature difference thresholds (P_0 = 47 K, P_1 = 11.7 K) were selected for the product, while $\frac{P_{\mathrm{sw}}}{P_{\mathrm{si}} - P_{\mathrm{sw}}}$ is taken generally empirical value –1.14.

All these data were transformed and geometrically corrected using remote-sensing image-processing software and converted to ENVI product formats with the Stereo graphic North Pole projected coordinate system and in WGS84 geographic coordinates. After obtaining the data on daily sea-ice area for the summers between 2003 and 2013, and a US National Snow and Ice Data Center (NSIDC) dataset, a two-paired sample t test was performed using data-processing software. The results found a strong similarity between the two datasets, with a correlation coefficient of 0.989. The NSIDC synthesizes data from SSM/I, ESR-1 SAR, QuikSCAT, MODIS, and many other data sources, and has high credibility compared with a single data source (Spreen et al., 2008). Accordingly, AMSR-E microwave remote-sensing data can be considered to be sufficiently reliable to meet the test requirements.

3 Results and Discussion

3.1 Arctic summer sea-ice variation

Based on the average sea-ice concentration and the deviation in Arctic summer sea-ice concentrations between 2003 and 2013 (Fig. 1), a high-concentration center of Arctic summer sea ice was found at the North Pole, which reduces gradually in intensity moving south from the North Pole. Most of the area north of 80°N remained covered with sea ice. The most stable situation was observed in 2004, when only the sea-ice concentration of the Barents Sea and a small part of the Greenland Sea was reduced, while in all the other areas concentrations were higher than the average for the 11-year period. Other relatively stable years were 2003, 2005, 2006, and 2013, while sea-ice concentrations in 2007, 2008, 2010, 2011, and 2012 were relatively low. From 2010 onwards, the north polar summer sea-ice area reduced continuously, falling to its lowest level in 2012 and even melting completely at the ice edge.

3.2 Sea-ice area variation

The daily sea-ice area data were used to calculate monthly and yearly averages of sea-ice area and its linear regression (Fig. 2). The summer Arctic sea chart revealed a roughly similar trend of sea-ice area variation each summer over the 11 years: the melting stage started in July and sea ice reduced gradually to its lowest level in mid-September, until beginning to freeze again at the end of September. From July to September, sea-ice area reduced by 5.45×10^4 km^2/mon. Overall, the summer Arctic sea-ice area has seen a decreasing trend over the past 11 years by 1.35×10^5 km^2/yr. According to Parkinson and Cavalieri, it reduced by 53.41 km^2/yr, between 1979 and 2006 (Parkinson and Cavalieri, 2008), and the pace of melting over the past 11 years was 2.5 times that of 1979–2006. However, Ke et al. (2013) found a reduction of 1.39×10^5 km^2 between 2002 and 2011 (Ke et al., 2013), 4.50×10^3 km^2/yr, more than between 2003 and 2013, which means that the rate melting has slowed. The minimum sea-ice area in the past 11 years was 3.50×10^6 km^2, reached on September 16, 2012, while the maximum was 1.01×10^7 km^2 in 2004. Fig. 2a shows that the minimum value was observed in mid-September, yet the highest temperatures were in July and August (Zhang et al., 2010), indicating that the variation in sea-ice area has a lag behind the variation in temperature, as much heat is needed to melt sea ice in an energy-accumulating process (Ke et al., 2013).

The yearly average was calculated based on the monthly average sea-ice area in July, August, and September, to obtain the corresponding monthly deviations and associated linear regression (Fig. 3). From the variation in summer sea-ice area between 2003 and 2013, we found that the decreasing trend in each month was similar to that over the whole summer. The most stable situation was in 2004, while in 2012 sea ice reached a minimum. During 2003 to 2006, 2009, and 2013, values were above average, i.e., ice area was relatively large, while in 2007, 2010, 2011, and 2012 it was below average. The fastest decline in sea-ice area occurred in September (1.48×10^5 km^2/yr), followed by July (1.42×10^5 km^2/yr) and August (1.16×10^5 km^2/yr). Inland, July is the hottest month of the year, so sea ice near land began to melt in July and had melted completely in August; in addition, water absorption from solar energy did not occur, so it melted slower.

Two troughs appeared, in 2007 and 2012. Summer sea-ice area between 2003 and 2006 was above average, indicating stable ice conditions. It fell below average in 2007, then increased in 2008 and 2009. Sea ice area decreased again from 2010 to 2012, before rising rapidly in 2013 to its average level.

3.3 Sea-ice concentration variation

Sea ice in the Arctic Circle can be divided into nine concentration classes ranging from 10%–20% to 90%–100%. The sea-ice area in each class is shown in Fig. 4. The results found that sea-ice area in the 90%–100% class was far greater than in the other classes combined, with the 80%–90% class in second place; the remaining classes were all at about the same low level. Fig. 1 shows that thick sea ice with >80% concentration was distributed mostly north of 80°N, partly extending to the Beaufort Sea and the Queen Elizabeth Islands, while sea-ice concentrations in the region of the Barents and Kara Seas were <80%. Ice with <80% concentration occurred mainly in the Beaufort, Chukchi, East Siberian, Laptev, Kara, and Greenland seas. In summary, summer Arctic sea ice was thickest near the North Pole, where there is little low-concentration sea ice.

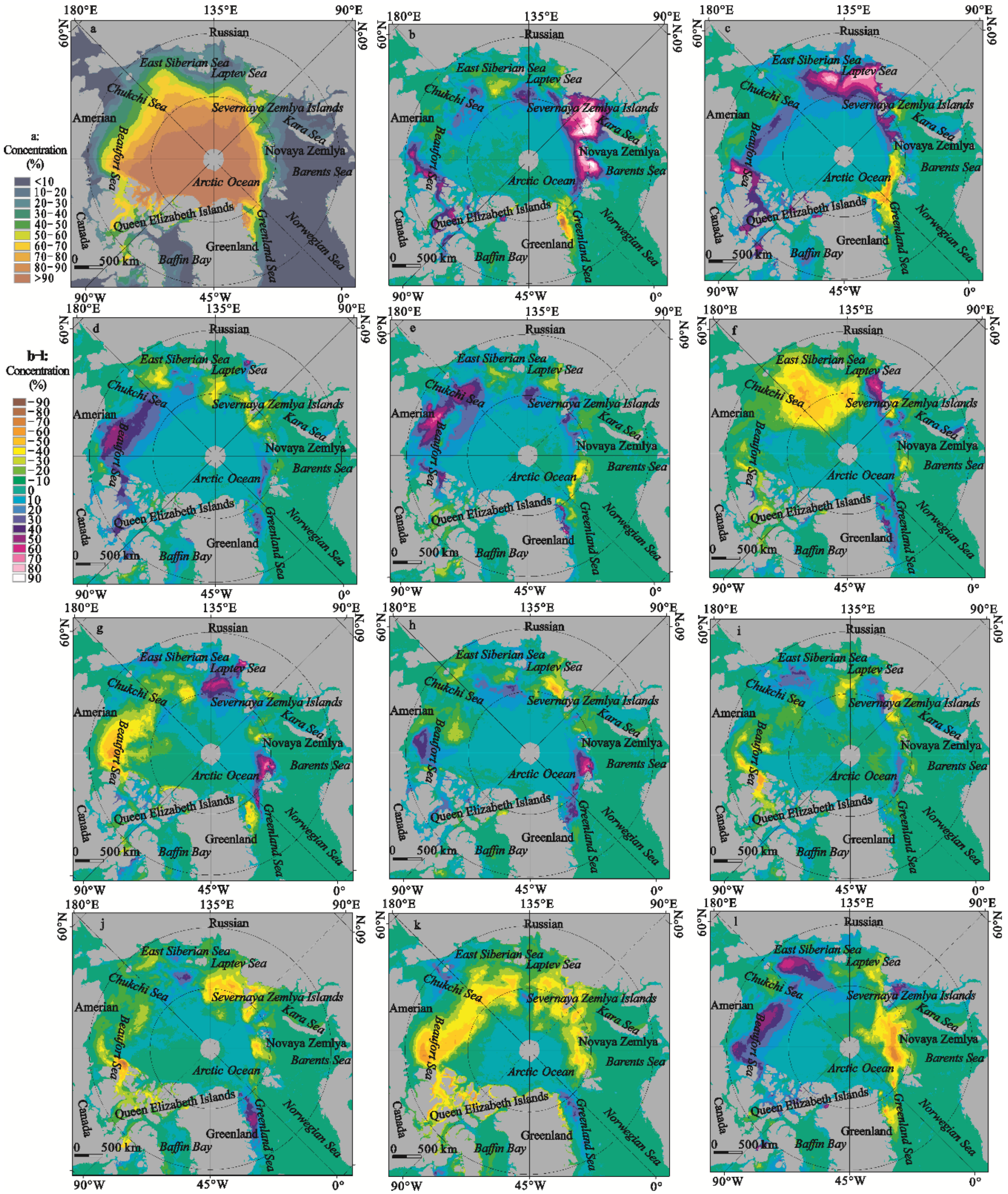

Fig. 1 Variation of summer ice in the Arctic from 2003 to 2013. a. Average Arctic summer sea-ice concentration, 2003 to 2013. b–l: Deviation of Arctic summer sea-ice concentration, 2003 to 2013

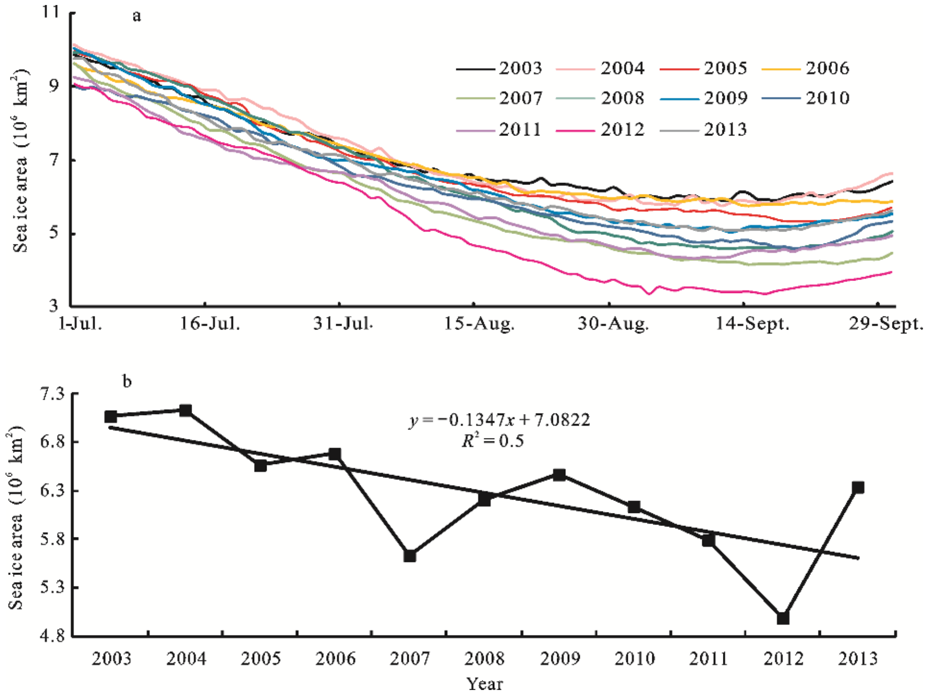

Fig. 2 Summer sea-ice area from 2003 to 2013. a. Daily; b. Annual

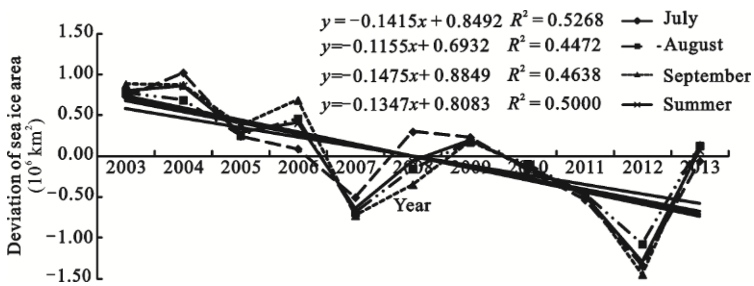

Fig. 3 Deviation of summer sea ice area from 2003 to 2013

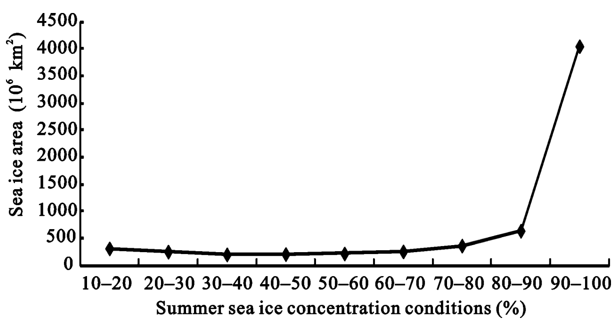

Fig. 4 Summer sea-ice concentration conditions from 2003 to 2013

After analyzing the sea-ice area in each class by month, results shows that the variability of sea-ice areas at <90% concentration was about the same, while the area with >90% concentration declined by 1.32×10^7 km^2/yr. Combined with summer sea-ice area at the Arctic pole (Fig. 2) and the summer sea-ice concentration variation from 2003 to 2013, it was found that the area of sea ice with <90% concentration greatly decreased, while sea-ice area in the 90%–100% concentration class increased during the stable year of 2004. In 2005, sea ice with >90% concentration decreased, while ice in all the other classes increased, and the overall total was reduced. In 2007, the sea-ice area with <70% concentration increased slightly, while that with >70% concentration fell dramatically. The minimum year of summer sea-ice area was 2012, followed by 2007. The total area increased in 2009, but there was a declining trend in classes other than >90%. In 2010, all classes except >90% tended to increase. The sea-ice area at the Arctic pole continuously decreased from 2010 to an 11-year minimum in 2012. The area in the 80%–90% class increased rapidly in 2013, causing the minimum value to rise above the average. This suggests that sea ice with >90% concentration determined the variability in summer sea-ice area at the Arctic pole.

3.4 Perennial sea-ice variation

According to the seasonal variation of sea ice, it can be divided into one-year ice and perennial ice, in which one-year ice refers to the newly formed sea ice in that year, and perennial sea ice is ice that remains frozen through at least one summer, i.e., it persists after the minimum sea-ice cover is reached. Thus the ice on the day of smallest sea-ice cover this year will be the perennial sea ice of next year. Consequently, the area and the extent of minimum sea-ice cover one year become those of the perennial sea ice in the following year (Comiso, 2002).

Based on the extent of perennial sea-ice from 2003 to 2013, an average extent was determined (Fig. 5), which showed that perennial ice, like summer ice, was thick and had a high concentration near the North Pole, gradually decreasing in concentration moving south from the North Pole. Perennial ice with >90% concentration was less widespread near the Eurasian side than near the American continent. Perennial ice with >80% concentration and summer sea ice with >80% concentration had the same extent and were distributed mainly to the south of 80° N, in the Beaufort Sea and near the Queen Elizabeth Islands. Areas with <80% concentration extended to the Beaufort and East Siberian Seas, while there was hardly any perennial ice distribution in the Chukchi, Laptev, Kara, and Barents Seas.

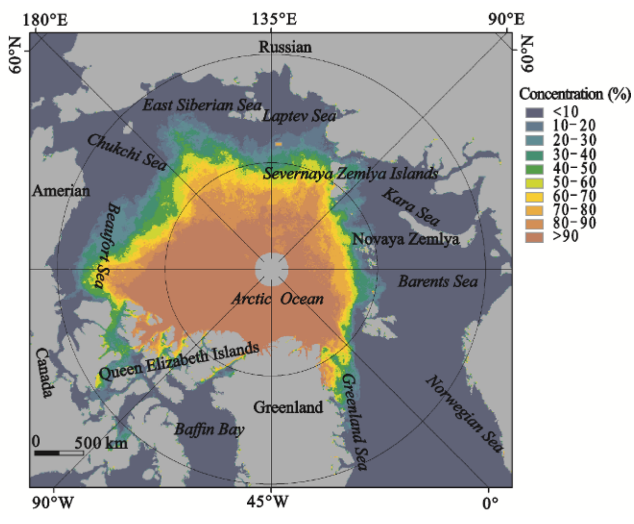

Fig. 5 Average concentration of perennial sea-ice during the summer from 2003 to 2013

Based on statistics of the perennial sea-ice area from 2003 to 2013, an average value was calculated to obtain the deviations and linear regression (Fig. 6). The change trend of perennial ice area was similar to that of summer ice area. From 2003 to 2006, 2009, and 2013, the perennial ice area was above average, while 2007, 2008, 2010, 2011, and 2012 were light ice years with less ice below the average value. From 2003 to 2007, perennial sea-ice volatility weakened, reaching a low point in 2007. It increased in 2008 and 2009, then dramatically reduced from 2010 to 2012, and again increased above the average in 2013. In 2008, 2009, 2010, and 2013, it was close to the average value over the previous 11 years. Overall, Arctic ice decreased at an annual rate of 1.54×10^5 km^2.

The statistical proportion of sea-ice concentrations from 2003 to 13 (Table 1) revealed that ice area with >90% concentration was the greatest, followed, in order, by the 20%–30%, 10%–20%, 60%–70%, 80%–90%, 70%–80%, 40%–50%, 30%–40%, and 50%–60% concentration classes. Accordingly, a large proportion of perennial ice was thicker near the North Pole (Fig. 5).

The Arctic sea ice showed significant reductions over the past 10 years, and a series significant environmental factors have been found closely related with this process. The annual average temperature in the Arctic was below –10℃ in the 1970s while in this century it is above –8℃, an increase of about 3℃ over the past 40 years (Mark, 2007). The temperature variation, especially the universal Arctic warming, is the main reason for the large volume sea ice melting (Rothrock and Zhang, 2005). In addition to temperature, Arctic sea ice is also affected by the north Atlantic oscillation (NAO) (Kwok, 2007) and arctic oscillation (AO) (Liu, et al., 2004). The warming and sea ice variation in the Arctic region have coupling relationship. For example, the Arctic region could absorb more solar radiation when the sea ice coverage decreases with increasing temperatures (Serreze et al., 2000). A warming sea will cause

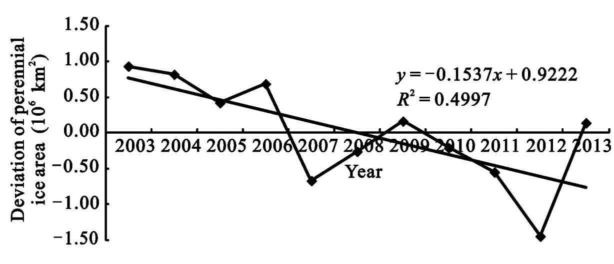

Fig. 6 Variation of perennial ice from 2003 to 2013

Table 1 Proportion of perennial ice concentration

Concentration (%)	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
Proportion (%)	9.63	12.79	6.18	6.80	5.20	7.64	6.95	7.16	37.65

shorter sea ice season, i.e., delayed the start of sea ice growing season and extended melt season lengths, as well as smaller sea ice thickness and coverage (Stroeve et al., 2007), and this trend will persist as the greenhouse gases increased and global warming continued (Ke et al., 2013).

4 Conclusions

Based on AMSR-E concentration data for summer Arctic sea ice from 2003 to 2013, we analyzed the characteristics of sea-ice variability during the Arctic summer.

(1) Generally, summer sea ice with high concentrations at the Arctic pole, especially in the Arctic Ocean, is distributed north of 80°N and gradually reduces in area from north to south. Over the past 11 years, the most stable ice conditions were observed in 2004, when the extent was the greatest and the concentration was the highest. The minimums between 2003 and 2013 were observed in 2007 and 2012, when the sea-ice concentrations in most areas reduced and sea ice with a low concentration at the edge melted.

(2) Sea-ice area followed the same trend every summer from 2003 to 2013, declining from July to mid-September and then rising, but with a decreasing trend overall. The minimum area each year was reached in mid-September, and the minimum years were 2007 and 2012 with an area in 2012 of 3.50×10^6 km^2. The most stable ice conditions occurred in 2004, with an area of 1.02×10^7 km^2 in summer. The trends during individual months of July, August, and September reflected the overall situation throughout the summer, in which all were decreasing with a maximum melting rate achieved in September, followed by July. Overall, the area decreased by 1.35×10^5 km^2/yr, 2.5 times faster than the rate from 1979 to 2006, but less than that between 2002 and 2011, mainly because sea ice in 2013 increased sharply so that the minimum value in 2012 then rose above the average.

(3) Summer sea ice in the Arctic had a high concentration, rarely being <90%, and maintained a continuous trend, so the areas with >90% concentrations determined the variation in Arctic sea-ice area: in 2007 and 2012, years when sea ice was at a minimum, areas with >90% concentration underwent a substantial reduction, while they increased significantly in 2004 and 2013. Overall, sea ice with >90% concentration decreased by 1.32×10^7 km^2 per summer.

(4) In the past 11 years (2003 to 2013), perennial ice, mainly situated near the North Pole, Beaufort Sea, and Queen Elizabeth Islands, has been much thicker, with >90% concentration. The perennial ice variation was similar to the overall trend for all summer sea ice, with 2007 and 2012 being the minimum years for perennial ice. However, in 2003 the perennial ice area was greater than in 2004, the most stable summer of the past 11 years. The Arctic perennial ice reduced at a rate of 1.54×10^5 km^2/yr.

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