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Variation of sea ice extent in different regions of the Arctic Ocean

CHEN Ping[1]*, ZHAO Jinping[1]
[1] Key Laboratory of Physical Oceanography, Ocean University of China, Qingdao 266100, China

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Abstract

Sea ice in the Arctic has been reducing rapidly in the past half century due to global warming. This study analyzes the variations of sea ice extent in the entire Arctic Ocean and its sub regions. The results indicate that sea ice extent reduction during 1979–2013 is most significant in summer, following by that in autumn, winter and spring. In years with rich sea ice, sea ice extent anomaly with seasonal cycle removed changes with a period of 4–6 years. The year of 2003–2006 is the ice-rich period with diverse regional difference in this century. In years with poor sea ice, sea ice margin retreats further north in the Arctic. Sea ice in the Fram Strait changes in an opposite way to that in the entire Arctic. Sea ice coverage index in melting-freezing period is an critical indicator for sea ice changes, which shows an coincident change in the Arctic and sub regions. Since 2002, Region C2 in north of the Pacific sector contributes most to sea ice changes in the central Aarctic, followed by C1 and C3. Sea ice changes in different regions show three relationships. The correlation coefficient between sea ice coverage index of the Chukchi Sea and that of the East Siberian Sea is high, suggesting good consistency of ice variation. In the Atlantic sector, sea ice changes are coincided with each other between the Kara Sea and the Barents Sea as a result of warm inflow into the Kara Sea from the Barents Sea. Sea ice changes in the central Arctic are affected by surrounding seas.

Key words: Arctic, sea ice extent, period of 4-6 years, sea ice margin, sea ice coverage indices

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1 Introduction

As one of the most sensitive regions to climate change, the Arctic region has received extensive attention in recent years. The Arctic sea ice is an important component part of the Arctic climate system which is affected by both the changes of the atmospheric and oceanic process. On the other hand, the variation of sea ice regulates the surrounding climate system (Aagaard and Carmack, 1989). The sea ice acts as a barrier restricting the water vapor flux and momentum exchange between the ocean and atmosphere. Most of the solar radiation is reflected back to space as a result of the high albedo properties of sea ice (Zhou and Wang, 2008). In addition, the melting and formation process of sea ice has a great influence on the ocean surface layer, i.e., the brine rejection from sea ice formation would increase the salinity of sea water while the melting of sea ice results in colder and fresher sea water. The ocean circulation then transfer these changing water signals to large areas. Thus, the variation of sea ice is regulating the water properties of the ocean to a large extent (Comiso, 2002).

The Arctic sea ice cover is shrinking and the percentage of younger and thinner sea ice is increasing in the last three decades (Meier et al., 2007; Stroeve et al., 2012). The sea ice extent is declining with a rate of 3.4×10^4 km^2/a during 1979–1996 and this is much higher with 5.15×10^4 km^2/a in a longer period of 1979–2010 (Parkinson and Cavalieri, 2008, 2012). The Arctic sea ice cover has a significant seasonal difference and the most reduction happens in summer. The reduction rate of summer sea ice in the past 30 years is larger than 10% per decade (Zhang et al., 2009; Maslanik et al., 2007). Three extremely low sea ice cover appears in September 2002, September 2007 and September 2012 (Serreze et al., 2003; Stroeve et al., 2008; Kay et al., 2008). The recorded lowest sea ice cover in 2012 is lower than 4 million square kilometers and the retreating rate is increasing (Zhang et al., 2013; Parkinson and Comiso, 2013; Comiso et al., 2008). Since the 1980s, a large proportion of multiyear sea ice has been replaced by the first-year ice. This change appears in a large areas, even in the central area of Arctic Ocean and the Canadian Arctic Archipelago where the multiyear sea ice dominates. The proportion of multiyear sea ice was 75% in March in the mid-1980s while it reduced to 45% in 2011 (Maslanik et al., 2007, 2011; Nghiem et al., 2007; Fowler et al., 2004; Belchansky et al., 2005). This indicates a basin wide scale of thinner sea ice cover. The thickness of sea ice was ~3.64 m in the early 1980s in the central Arctic Ocean but it reduced to 1.89 m in 2008 (Kwok and Rothrock, 2009).

The melting rate of sea ice is relating to its location in the Arctic Ocean (Li et al., 2009; Zhao et al., 2003, 2010). The sea ice extent in most parts of the Arctic Ocean shows a unanimously declining since 1979 except for the Bering Sea region. The dense sea ice area are located at the Barents Sea and the East Siberian Sea in 1979–1988 while the sea ice dramatic decline in 2009–2012 especially in the Barents Sea in winter-spring and the Chukchi Sea

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*Corresponding author, E-mail: chenpinghappyevery@163.com

in summer-autumn (Parkinson and Cavalieri, 2012; Sui et al., 2015). The accelerating decline of sea ice extent is accompanied by larger ice-free area which results in a warmer upper ocean as more solar energy is absorbed (Dickson, 1999; Deng et al., 2013; Guo et al., 2015). In the current paper, we studied the variation of sea ice extent in different parts of the Arctic Ocean in order to understand the crucial role of sea ice in regulating the climate system of the Arctic region. Large number of studies on sea ice in the Arctic has been conducted. However, previous studies are mostly focused on sea ice changes in the entire Arctic or single marginal seas. Difference and links between different regions and their respective contribution to sea ice changes in polar region are lack of emphasis. Therefore, local ice changes in different regions are discussed along with their respective impacts on the entire Arctic Ocean. Section 2 is the data and our division of the study region in the Arctic Ocean. The analysis of sea ice extent and coverage in different regions and the proportion of different contribution is presenting in Section 3. Our conclusions are summarized in Section 4.

2 Data and the division of study region

The sea ice extent is calculated through sea ice concentration maps derived from the radiances obtained from satellite microwave radiometers. The temporal coverage from 1979 to 2013 is provided at http://nsidc.org/data/smmr_ssmi_ancillary/area_extent.html.

Daily sea ice concentration data are from the National Snow and Ice Data Center (NSIDC) and collected by microwaves radiometer AMSR-E and AMSR2 onboard the polar-orbiting satellite, with spatial resolution 6.25 km×6.25 km. AMSR-E failed in regular scanning as a result of an antenna problem in October 2011. AMSR2 was launched in 2012 onboard the GCOM-W1 satellite. So the daily sea ice concentration data are ranging from 1 July 2002 to 30 September 2011 and from 1 August 2012 to 31 December 2015. The data are available at http://www.iup.uni-bremen.de:8084/amsredata/asi_daygrid_swath/l1a/n6250/ and http://www.iup.uni-bremen.de:8084/amsr2/#Data_Archive.

There is no uniform standard definition for the Pacific sector, Atlantic sector and the central region of the Arctic Ocean due to various studying purpose. After comparing the region definition of Overland and Wang (2007) and Wang and Zhao (2012), we divide the Arctic Ocean into different regions for our study interests of the sea ice extent (Fig. 1). The Barents Sea and the Kara Sea are classified as parts of the Atlantic sector of the Arctic Ocean (the red dash line enclosed region). The Siberian Sea, the Chukchi Sea and the Beaufort Sea are belong to the Pacific sector of the Arctic Ocean (the blue dash line enclosed region). And above the northern edge of different marginal seas including the northern basin of the Canadian Arctic Archipelago is divided as the central Arctic Ocean. Furthermore, according to different features of the basin and considering the Lomonosov Ridge, we divide the central Arctic Ocean into three fan-shaped regions, i.e., C1 (10°W–135°E, in the north of the Atlantic sector and the Laptev Sea), C2 (135°E–130°W, in the north of the Pacific sector) and C3 (130°–10°W, in the north of the Canadian Arctic Archipelago).

3 Results and discussion

Our studies focus on the variation of sea ice extent in the Arctic Ocean while the Bering Sea and the Nordic seas are not in our consideration. We have nine different regions according to our definition in Fig. 1. Eight regions are fully covered by the sea ice in winter and the interannual variability of sea ice is largely determined by the extent of the ice cover in the summer. The Barents Sea is an exception where there is partial sea ice cover in winter and the sea ice coverage changes all year round. In the following discussion, first we study the overall changes of sea ice cover in the Arctic Ocean and then we present the results of our analysis of different changes of sea ice extent among different regions.

3.1 *The analysis of sea ice extent variation in 1979–2013*

The sea ice extent (SIE) is defined as a threshold of minimum

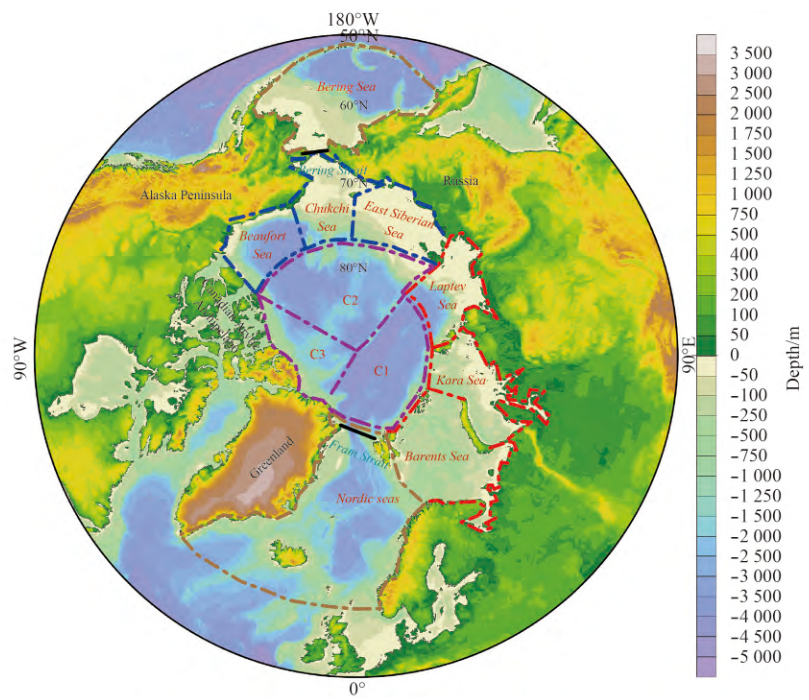

Fig. 1. Our definition of different regions in the Arctic Ocean.

concentration to mark the ice edge, the most common cutoff is 15% (Sui et al., 2015; Comiso and Nishio, 2008), i.e.,

$$SIE = \sum_{i=1}^{n} \omega_i A_i \begin{cases} \omega_i = 1, C_i \geqslant 15\% \\ \omega_i = 0, C_i < 15\% \end{cases}, \tag{1}$$

where C_i is the sea ice concentration in each grid area, ω_i is the weight coefficient, A_i is the area of each grid. The sea ice extent has shown a catastrophic decline since the 1970s and becomes more severity in this century (Zhang et al., 2009; Eisenman, 2010). The linear trend of sea ice extent is negative all year round in 1979–2013. The minimum descent rate is -3.02×10^4 km^2/a in May (spring) while the largest descent rate appears in July to September (summer) and culminates in September with a rate of ~-8.92×10^4 km^2/a. The edge of sea ice extent is retreating further to the north especially in September (Fig. 2a).

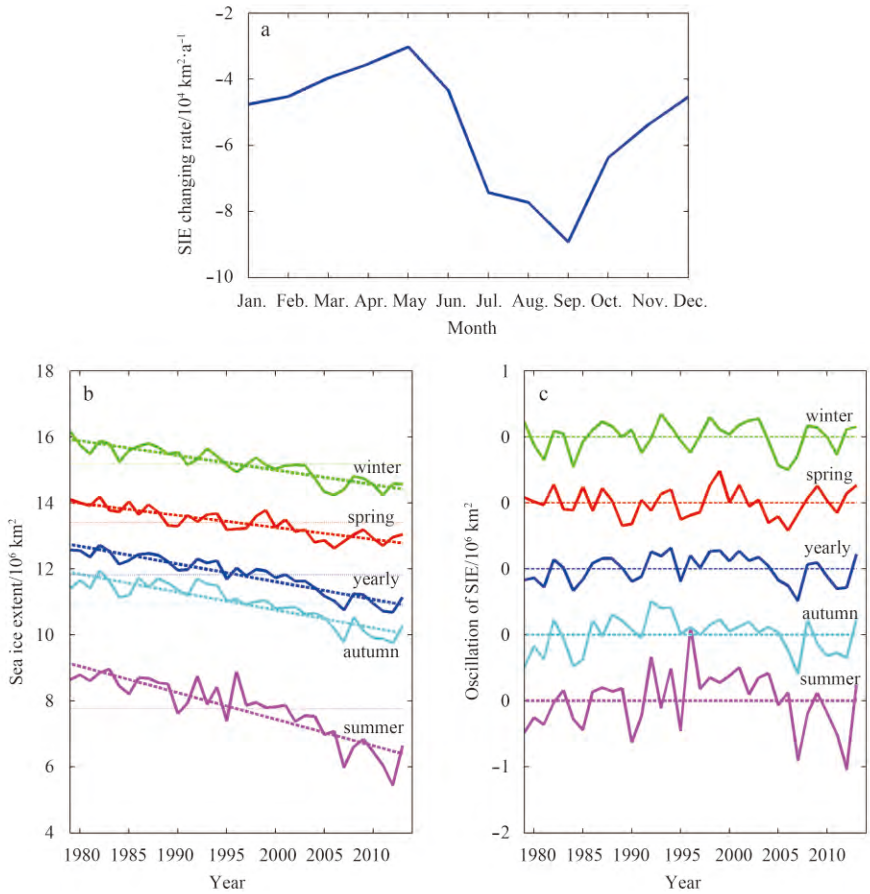

Fig. 2. Time series of sea ice extent from 1979 to 2013. a. Decline rate of linear trend for each month; b. average sea ice extents (solid curve) and their linear trends for all year round and for different seasons (dotted lines), and climatology sea ice extents in 1979–2013 (point line); and c. the long-term oscillation of sea ice extents with the linear trend removed for all year round and for each season.

We divide the variation of sea ice extent in 1979–2013 into four seasons for our analysis, namely the winter (January to March), spring (April to June), summer (July to September) and autumn (October to December). The sea ice extent reaches its maximum in winter and its minimum in summer while it is larger in spring than that in autumn. The sea ice extent is shrinking both in years and each season in 1979–2013. The linear trend of the yearly sea ice extent is $-(53.7\pm3.6)\times10^3$ km^2/a which is 4.27% higher than the estimates of Parkinson and Cavalieri (2012) in the period of 1979–2010 ($-(51.5\pm4.1)\times10^3$ km^2/a). The largest decline rate is in the summer (with a value of ~8.02×10^4 km^2/a) when the sea ice extent reaches its minimum. The annual mean sea ice extent during 1979–1994 is higher than the climatology value (1979–2013 mean) while it fluctuates in 1995–2000 with the ice-rich period in 1979–2000. The annual mean sea ice extent experienced an abrupt decline in 2001–2007 while in 2008–2013 it was lower than the climatology mean and with a larger inter-annual variability. The linear trend of sea ice extent in yearly and different seasons for the three periods, i.e., 1979–2000, 2001–2007 and 2008–2013 are listed in Table 1. The value in Table 1 shows that the overall trend of sea ice extent is declining in 1979–2013. The sea ice retreat is not so notable in 1979–2000 and the linear trend is lower than the interannual trend. The most significant retreat of sea ice extent happened in 2001–2007 with a linear trend more than three times larger than the interannual trend in 1979–2013. The sea ice extent shows a large variability in 2008–2013 with an

Table 1. The linear trend of sea ice extent variability in different time period (10^4 km^2/a)

	1979–2000	2001–2007	2008–2013	1979–2013
Yearly	−3.69	−17.44	−6.94	−5.37
Winter	−3.70	−17.22	−5.67	−4.41
Spring	−3.46	−11.87	−2.37	−3.63
Summer	−4.58	−24.44	−12.73	−8.02
Autumn	−3.04	−16.22	−7.00	−5.40

overall trend of decline. Except for the spring time, the decline trend of sea ice in other season is higher than the interannual trend.

Figure 2c shows the sea ice extent variability with the linear trend removed. In the periods of 1979–1995, the interannual oscillation altering with negative and positive phase indicates that a linear trend was dominated in that period. The oscillation value became positive in 1996–2004 that indicates an ice-rich period, while it was dominated by negative value in 2005–2013 (overlaying by an interannual oscillation) which means a great retreat of sea ice extent. The sea ice extent shows a great retreat in summer than the other season with the two lowest value appears in 2007 and 2012. Since 2012, the retreat trend becomes alleviate. We calculated the correlation coefficients between the interannual oscillating time series with different seasonal oscillating time series in Fig. 2c. The correlation coefficient is 0.673 6, 0.493 2, 0.810 6 and 0.843 2 in winter, spring, summer and autumn, respectively. The results indicate that the interannual variability of sea ice extent is dominated by the changes in summer and autumn.

Previous studies show the decreasing trend of minimum sea ice extent is superimposed by a significant interannual variability. For this purpose, the study periods could be divided into several segments and make a linear fitting for each segment to determine the rising and declining of sea ice extent (Wang et al., 2015; Comiso and Nishio, 2008; Zhang et al., 2009). This method is useful in some ways, but the division to different periods is kind of arbitrary. Different length of chosen periods results in different sea ice variability. What's more, such division only gives us the linear trend in different periods but misses the higher frequency of signals.

We adopt a running linear fitting method to determine the long-term variation of sea ice extent anomaly. That is making a linear fitting within a chosen window width and then the whole window shifts forward for one month and repeats the linear fitting. In this way, we have different value of linear fitting trend. The slope of the linear fitting trend indicates the variation of the detrended sea ice extent anomaly. Positive value means increasing sea ice extent while negative value means decreasing. There are 420 months within the study periods and all the slope of the linear fitting are shown in Fig. 3. In order to avoid the unrealistic value resulting from the choosing of different window width, the window width of 48, 54, 60, 66, 72, 78, and 84 months are chosen

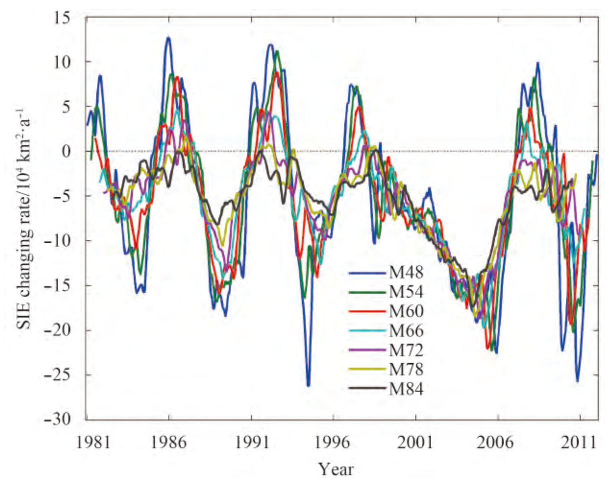

Fig. 3. Running linear trend using different windows width (e.g., M48 means a window width of 48 months) for sea ice extent anomaly.

for comparison. The results show an unanimous variation with different window width. The maximum value appeared in 1982, 1986, 1992, 1997, and 2008 while the minimum value appeared in 1984, 1989, 1995, 2006, and 2011. It is obvious that the variation is characterized by a 4–6 years' period before 1997 (Fig. 3). But the negative value persisted throughout the 1998–2007 indicating an abrupt decline of sea ice. There is a slightly recover of the 4–6 years' period since 2008. In fact, there is a slimsy maximum value in 1999 and a slimsy minimum value in 2002 indicating the persistent of the 4–6 years' cycle in the rapid decline periods. The average cycle period is 5.3 years for the sea ice extent anomaly in 1979–2013. But this periodically cycle is concealed by the dramatic decline of sea ice in the later years. The variation of sea ice extent was dominated by a cycle of 4–6 years in the ice-rich years while this cycle break down in the rapid retreat periods of 1998–2007.

3.2 *The contribution of sea ice variation from different region to the overall sea ice extent*

In the previous section, the overall variation of the sea ice extent in the Arctic Ocean is described. In fact, the sea ice has a significant regional difference. Figure 4 shows the average of the minimum sea ice edge in 2002–2015. The sea ice edge is retreat to the north of 80°N in the Atlantic sector of the Arctic Ocean. Except for some part of the Beaufort Sea and the Canadian Arctic Archipelago, most parts of the sea ice edge has retreated to the north of 75°N. The latitude of sea ice edge anomaly is obtained by the latitude of each year's minimum sea ice edge to minus the latitude of the average sea ice edge in 2002–2015. The latitude of sea ice edge anomaly against longitude is shown in Fig. 5. In this way, we could examine the contribution from different region in the Arctic Ocean to the overall changes. Positive (negative) value means sea ice lower (higher) than the interannual average value (Fig. 5).

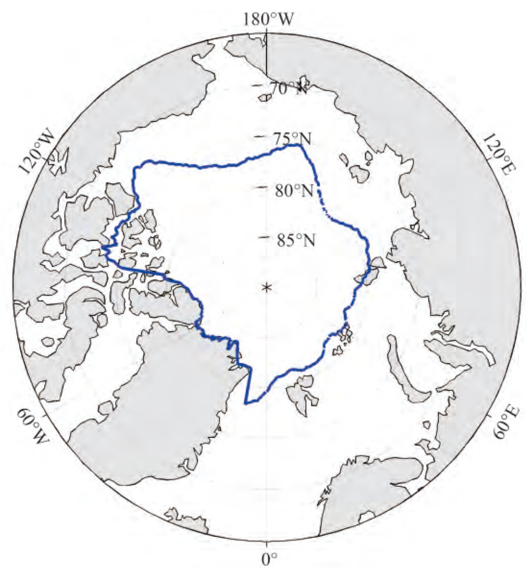

Fig. 4. Average of the minimum sea ice edge in 2002–2015.

The sea ice edge anomaly in the region north of the Canadian Arctic Archipelago (35°–65°W) is zero where there is covered by multiyear sea ice (Fig. 5). The year 2002–2006 is a typical ice-rich period with the sea ice edge larger than the average value in all divided regions. The sea ice edge extends to 4 degree south to the

Kara Sea, the Laptev Sea and the East Siberian Sea in 2003 and 2004. While in 2005–2006, the sea ice edge extends to 4–5 degree south to the Chukchi Sea and the Beaufort Sea resulting in the ice-rich years.

The year 2007–2008, 2011–2012 and 2015 are the typical years of poor ice with the sea ice edge around the Arctic Ocean all less than the average value. In 2007, the main regions of retreating sea ice are in the Chukchi Sea, the East Siberian Sea and part of the

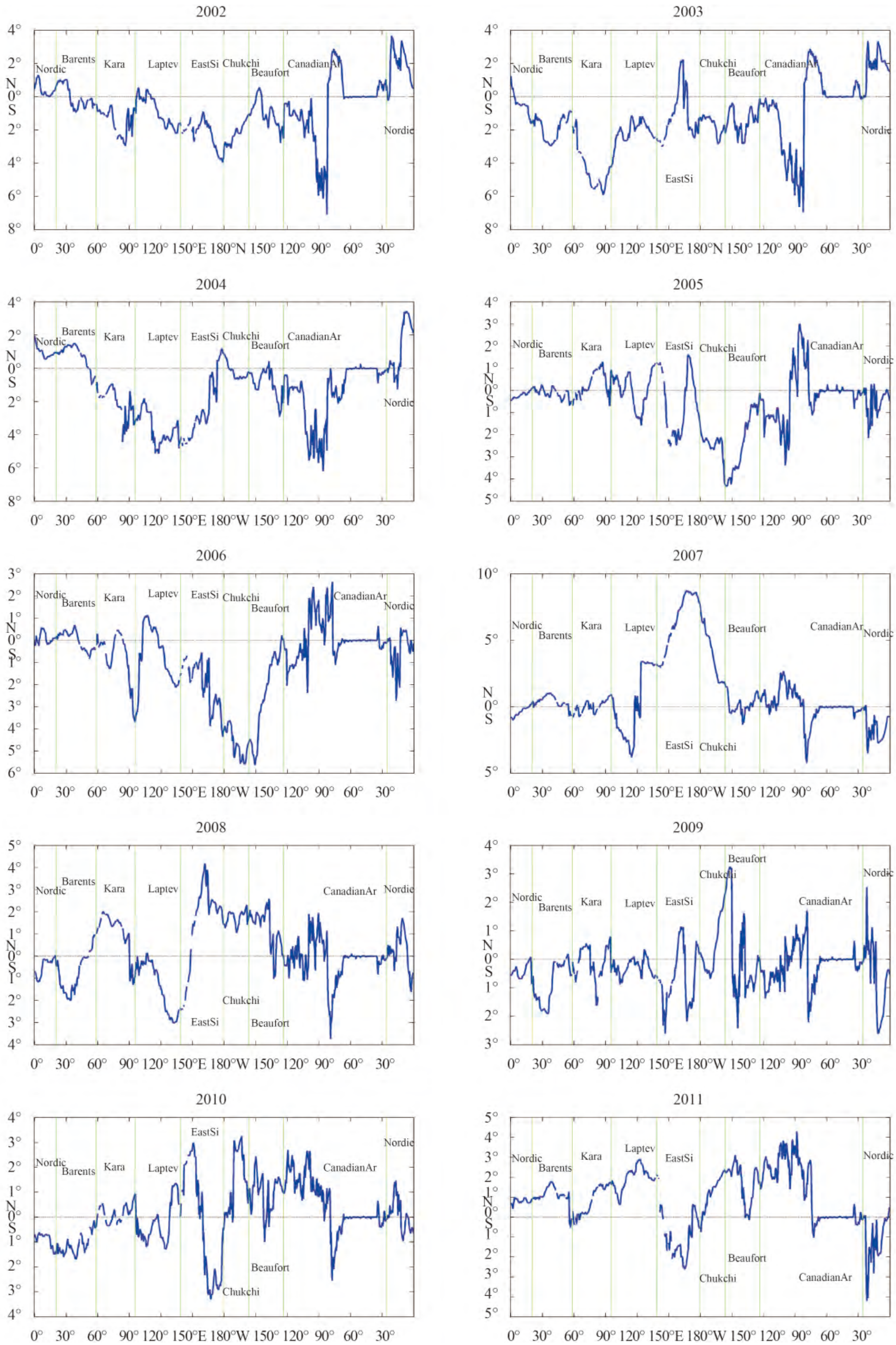

Fig. 5

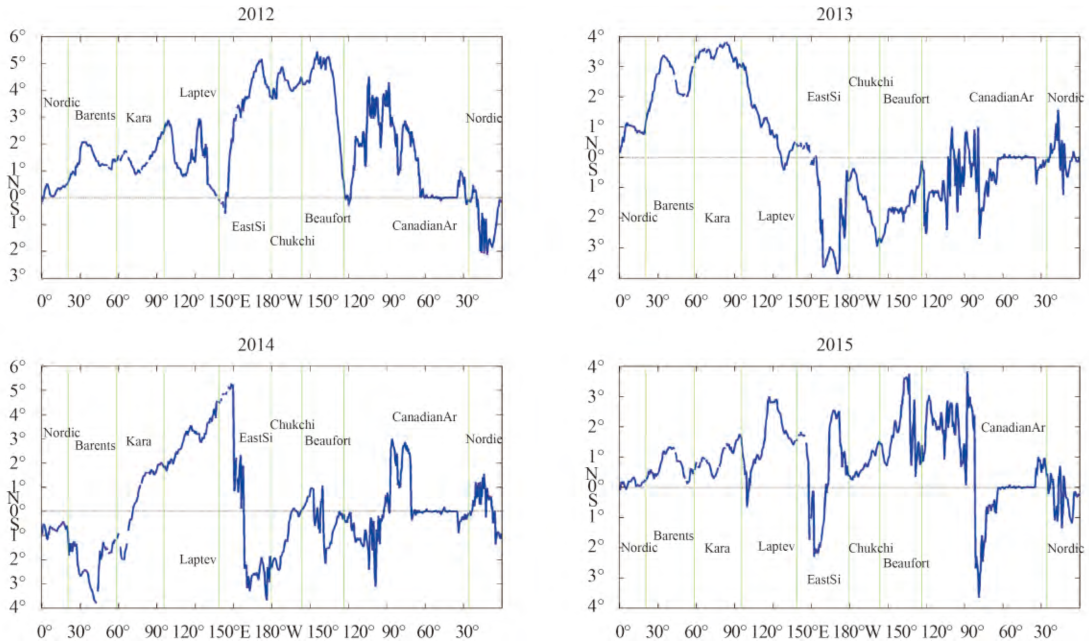

Fig. 5. The minimum sea ice edge anomaly against longitude in 2002–2015. Nordic, Barents, Kara, Laptev, EastSi, Chukchi, Beaufort, CanadianAr, Nordic represent Nordic Sea, Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, Chukchi Sea, Beaufort Sea, Canadian Arctic Archipelago, Nordic seas, respectively.

Laptev Sea with the ice edge retreats to nearly 9 degree to the north. The other regions does not experience such sharp decline. The sea ice edge retreats to only 2–3 degree to the north in several regions in 2008 and 2011. In 2012, the Beaufort Sea, the Chukchi Sea and the East Siberian Sea all experience a dramatic retreat to ~5 degree to the north along with the other regions. That results in the minimum sea ice extent in 2012. In 2015, all sea ice edge around the Arctic Ocean retreats to the north but with a medium value of ~3 degree to the north. And this medium retreat of sea ice hold back the decline trend to be a newly lowest sea ice extent in 2015.

The sea ice condition in 2010 is a special one for the different regions experience contrast changes of sea ice. The sea ice edge retreats to 2–3 degree to the north of the Kara Sea, the Laptev Sea and the Canada Basin but it is extend to 3 degree south of the East Siberian Sea. The years of 2013 and 2014 are the ice-rich years but with less ice in the Atlantic sector of the Arctic Ocean (the sea ice edge retreats to 4 degree to the north of the Kara Sea and the Laptev Sea). These three years are the periods with significant north retreating and south extending. The south extending areas are overall larger than the north retreating areas which result in a stable variation of sea ice extent (no significant increase or decrease).

It is noteworthy that the minimum sea ice edge in the Fram Strait region (0°–30°W) where its changes are contrast to the whole Arctic Ocean. When it is ice-rich year in the Arctic Ocean in 2002–2004, there is less sea ice than normal in the Fram Strait. While it is ice-poor year in the Arctic Ocean in 2007, 2012 and 2015, more ice appears in the Fram Strait. This contrast changes of sea ice show that in the ice-poor year the sea ice transport out of the Arctic Ocean through the Fram Strait while in the ice-rich year most of the sea ice remains in the Arctic Ocean.

3.3 *The variation of sea ice extent in the marginal sea of the Arctic Ocean*

The sea ice extent is an important indicator for studying the sea ice condition. Due to different size of the divided regions, the sea ice extent alone could not be used for comparison. The sea ice fraction of coverage $R(t)$ is adopted here. It is defined as the ratio of the sea ice area in each divided region to the region area S, i.e.,

$$R(t) = \int_s c(s,t)\mathrm{d}s/S, \tag{2}$$

where $c(s, t)$ is the sea ice concentration in each grid area s. The $R(t)$ is obtained using the daily average sea ice concentration data.

Figure 6 shows the sea ice coverage in the central Arctic Ocean is larger than the other regions. Even in summer, the sea ice coverage could remain as high as 80%. While all the marginal seas have a sea ice coverage less than 30%. The Beaufort Sea with the presents of multiyear sea ice has a higher sea ice coverage than the rest of marginal seas.

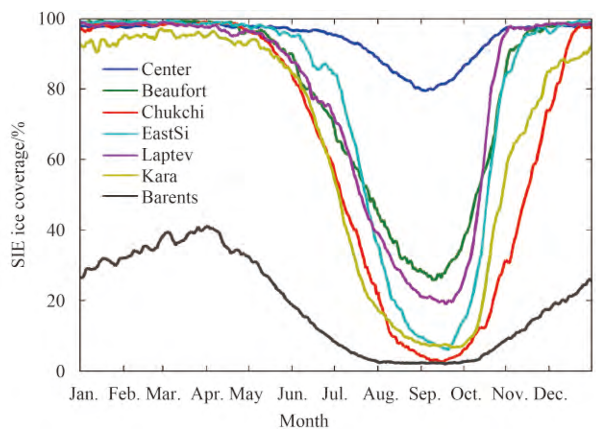

Fig. 6. The daily average for long-term variation of sea ice coverage for different divided regions.

The sea ice coverages in the central Arctic Ocean and the marginal seas all have a significant seasonal and interannual variation. According to the characteristic of the sea ice coverage anomaly, we could divide the variations into three types: (1) The variation curves of sea ice coverage that have a single crest/trough appears in those regions where covers by sea ice in summer, such as the central Arctic Ocean and the Beaufort Sea. (2) The variation curves of sea ice coverage that have a double crest/trough appears in the marginal sea with less sea ice in summer, such as the Chukchi Sea, the East Siberian Sea, the Laptev Sea and the Kara Sea. These four marginal sea have a low sea ice coverage in summer with stable fluctuation in the study period (the anomaly value nears zero). The melting season appears before the zero anomaly value while the freezing season appears afterward. The melting and freezing periods have different sea ice condition in some years. (3) The Barents Sea where the sea ice changes all year and changes of the winter sea ice coverage is far more than the summer condition (Fig. 7).

In order to give an overall assessment of the sea ice changes in each year, an index is defined for comparing. The interannual difference mainly comes from the melting and freezing periods. Ninty–five percent of the maximum multiyear mean value of daily sea ice coverage is chosen as a threshold to verify the start and end of melting-freezing period, from which the spanning time ($T_{\rm fm}$) of that period can be derived. The Barents Sea is partially covered by sea ice even in winter, C3 is covered by a lot of sea ice even in summer. The melting-freezing period are not available in the Barents Sea and C3. An index of sea ice coverage (I_S) in the melting and freezing periods is obtained by the arithmetic mean of daily sea ice concentration in the melting and freezing periods in different marginal sea (the Barents Sea is the arithmetic mean of whole year and the C3 is the arithmetic mean of 5.01–10.31), i.e.,

$$I_S = \frac{1}{n}\sum_{t=t_1}^{t_2} R(t), \tag{3}$$

where t_1 is the date of melt onset, t_2 is the date of frozen cease, n=t_2–t_1+1 is the length of the melting and freezing periods. The subscript of I_S represents different region and one value a year. This index is used to study the changes in the melting and freezing periods (Fig. 8).

Figure 8 demonstrates sea ice coverage indices during the melting-freezing season for each marginal sea (vertical bars), which represents mean sea ice coverage through a year. Sea ice coverage minimum (red dot-line) might be caused by an occasional storm, while sea ice coverage indices during the melting-freezing season can describe the overall state of sea ice in the Arctic. Sea ice changes in marginal seas coincide with sea ice evolution in the entire Arctic. In 2007 when sea ice cover reaches minimum in the Arctic, sea ice coverage minimum also occurs in the Chukchi Sea and East Siberian Sea, but not in other marginal seas as illustrated in Fig. 5. In 2012, as the sea ice concentration data are absent before September, the calculated sea ice coverage indices might be not as representative as those in other years, but it still shows sea ice cover minimum in the Beaufort Sea, Laptev Sea, Kara Sea, and Barents Sea. Sea ice coverage indices in all marginal seas in 2015 are lower significantly than long-term meaning, indicating the continuous reduction of sea ice in marginal seas.

Sea ice coverage in the central Arctic is much higher than that in the marginal seas (Fig. 9). In the Atlantic sector (C1), sea ice cover shows no decrease trend in 2007 when minimum is recorded for the entire Arctic. Nevertheless, sea ice minimum occurs and contributes to the minimum sea ice extent in the Arctic in 2012. Decreasing in C1 continues in 2013 but is offset by heavy sea ice in the other sectors. In the Pacific sector, significant sea ice reduction occurs in 2007 and 2012, indicating that sea ice minimum cover in these two years carries a direct impact on the central Arctic. Sea ice coverage in the central Arctic is maintained at a high level except these years. C3 is bounded by the North Pole and Canadian Arctic Archipelago, which is covered by multiyear ice with limited seasonal and annual changes, playing a key role in maintaining the stable state of sea ice coverage in the central Arctic.

The indices of sea ice coverage in the melting and freezing periods in Regions C1 ($I_{\rm C1}$), C2 ($I_{\rm C2}$) and C3 ($I_{\rm C3}$) are regress to the central Arctic Ocean to determine their contribution, i.e.,

$$I_{\rm C} = 0.302\ 2I_{\rm C1} + 0.466\ 7I_{\rm C2} + 0.232\ 1I_{\rm C3}, \tag{4}$$

where $I_{\rm C}$ is the index of sea ice coverage in the melting and freezing periods in the central Arctic Ocean.

Equation (4) indicates that sea ice variation in Region C2 dominates the variability of sea ice in the central Arctic Ocean. The contribution from Region C3 is the smallest.

Sea ice coverage minimum and spanning time of melting-freezing period are critical indicators for sea ice changes. Correlation coefficient between $I_{\rm n}$ and $I_{\rm m}$ shows that sea ice coverage changes in coincidence with sea ice coverage minimum in all regions except for the Chukchi Sea, proving that both $I_{\rm n}$ and $I_{\rm m}$ can present changes of sea ice in the Arctic. However, correlation between $I_{\rm n}$ and $T_{\rm fm}$ is negtive, indicating a shorter time of melting-freezing season with ice-rich years. In years with poor ice, sea ice begins to melt earlier and the end freezing time is delayed, making a longer time of melting-freezing period.

3.4 *The relationship of sea ice coverage between different regions*

The correlation coefficients of sea ice coverage are calculated for different region of the Arctic Ocean (Table 3). There are three kinds of relevance for different region. The first one is the high correlation coefficient between the Chukchi Sea and the East Siberian Sea. The sea ice in the East Siberian Sea flowing into the Chukchi Sea may be responsible for the sea ice variation in the Chukchi Sea. The second one is the high correlation coefficient between the Kara Sea and the Barents Sea. The warm current flowing from the Barents Sea and into the Kara Sea is responsible for their high correlation. The third one is high correlation coefficient between the central Arctic Ocean and its adjacent region (except for the Laptev Sea). The correlation coefficient is higher than the 90% confidence level test indicating a significant relationship between the central Arctic Ocean and its adjacent sea.

4 Conclusions

The variation of sea ice extent is a vital indicator for the climate changes and there are a bunch of studies exploring this issue. Base on the divided region, we explore the changes of sea ice in different region and focus on the regional contribution to the whole changes in the Arctic Ocean. Some new findings are listed below:

(1) The linear trend of sea ice extent is negative in all seasons in 1979–2013 especially in summer. It could be divide into three periods: the ice-rich period in 1979–2000, the rapid decline periods in 2001–2007 and the retarded period of sea ice retreat in

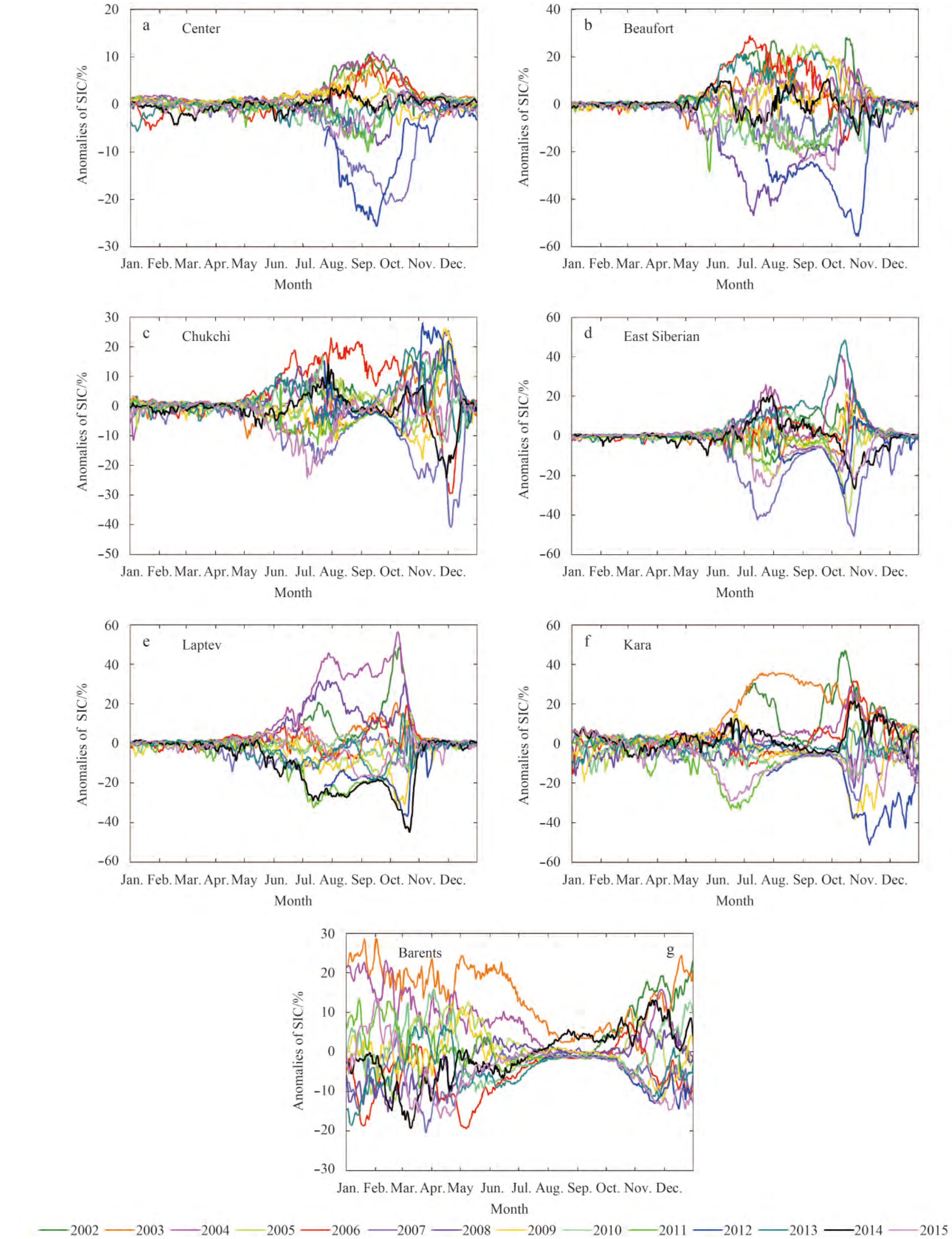

Fig. 7. Anomalies of the sea ice coverage for the central Arctic Ocean (a) and the marginal seas (b–g).

2008–2013. This stage changes are related to the periodic variation of sea ice. In the ice-rich years, the seasonal detrend variation of sea ice shows a period of 4–6 years. The sea ice experiences a continuous decline for ten years after 1997. Since 2008, the periodic change of sea ice seem to recover.

(2) The year of 2003–2006 is the ice-rich period with diverse regional difference, i.e., ice-rich condition appears in the Kara Sea, the Laptev Sea and the East Siberian Sea in 2003–2004 while it appears in the Chukchi Sea and the Beaufort Sea in 2005 and 2006. The ice-poor years are 2007–2008, 2011–2012 and 2015 with

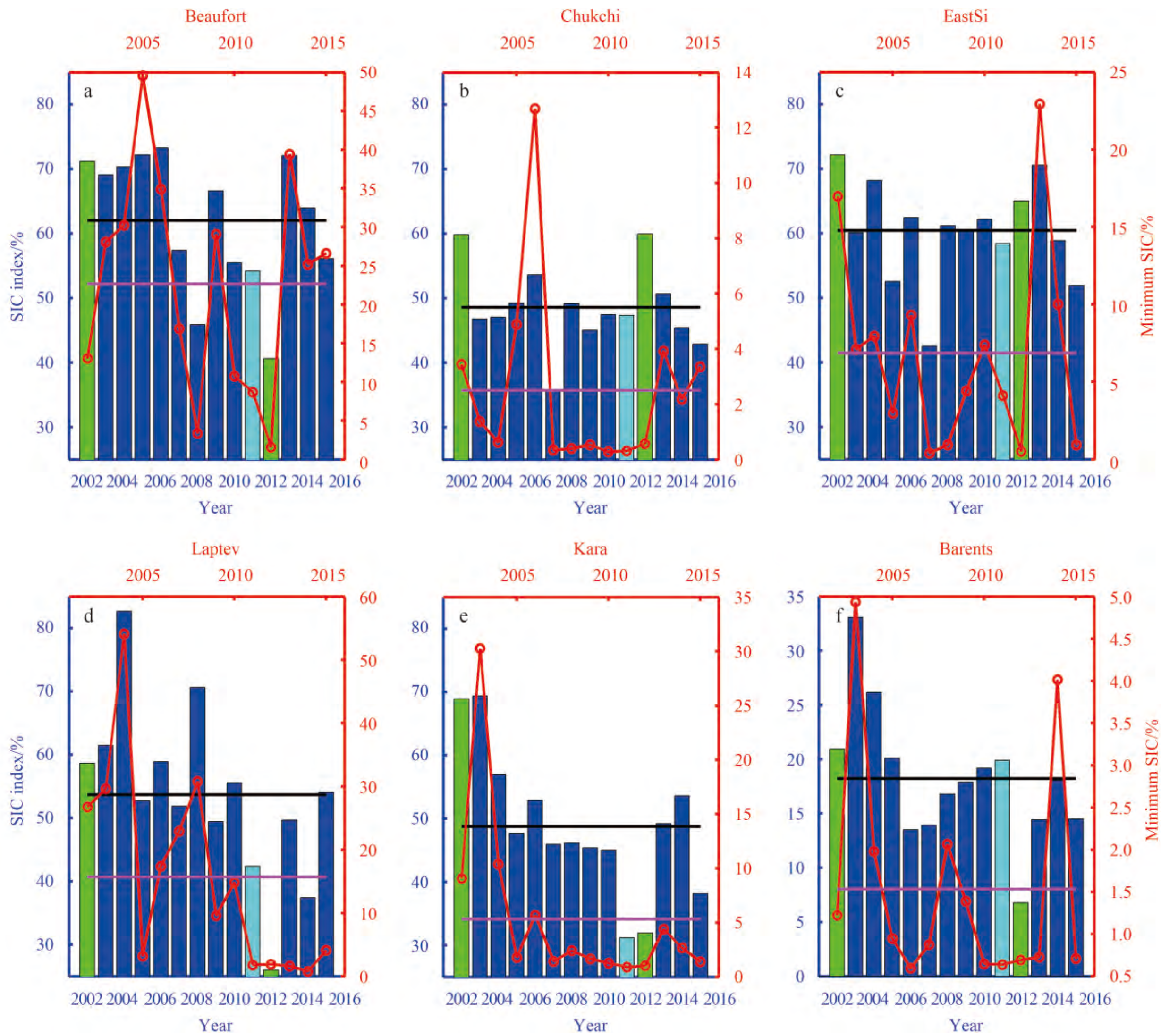

Fig. 8. The sea ice coverage indices during the melting-freezing period for each marginal sea. Due to data breach for almost one year, the indices of sea ice coverage in the freezing period (the green bar) and melting period (the light blue bar) may be incomplete. Although the indices may include the changes of the maximum and minimum sea ice extent, the mean value may have a large deviation. The red dot-line represents the minimum sea ice coverage for each year, the black line the long-term mean of sea ice coverage, and the purple line the long-term mean ofminimum sea ice coverage. Notice that the sea ice coverage of the Barents Sea has a different magnitude to the other marginal sea.

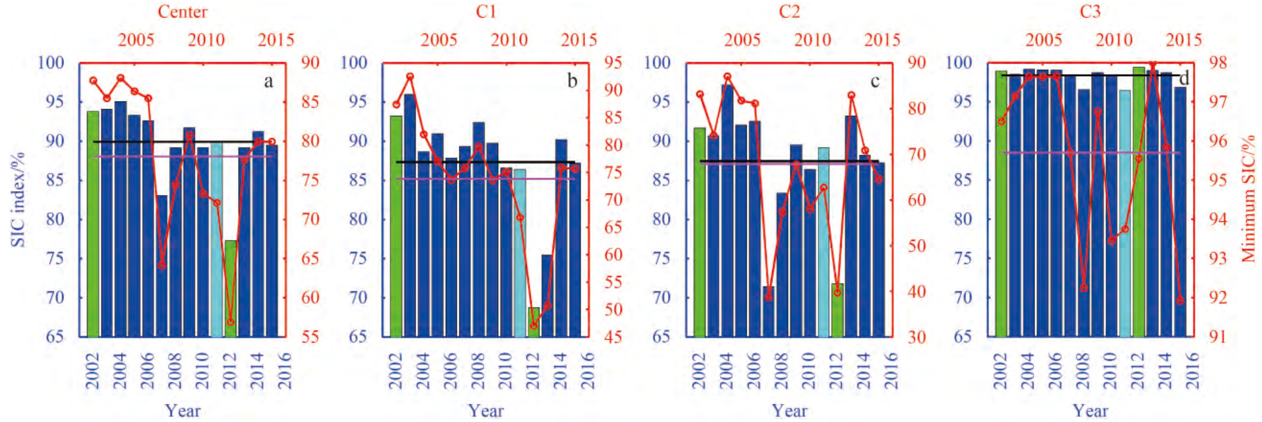

Fig. 9. The sea ice coverage indices during the melting-freezing period for the central Arctic Ocean and each adjacent sub-sea.The meaning of lines are same as Fig. 8.

Table 2. Correlation coefficient between sea ice coverage indices (I_n) and its minimum (I_m)/spanning time of melting-freezing period (T_{fm})

	Correlation coefficient (r)								
	Beaufort	Chukchi	EastSi	Laptev	Kara	Barents	C1	C2	C3
I_n/I_m	0.890	0.580	0.726	0.901	0.897	0.721	0.942	0.964	0.913
I_n/T_{fm}	–0.814	–0.437	–0.728	–0.853	–0.800	–	–0.781	–0.739	–

Table 3. The correlation coefficients of sea ice coverage between different regions

	Correlation coefficient (r)						
	Center	Beaufort	Chukchi	EastSi	Laptev	Kara	Barents
Center		0.595[1)]	0.630[1)]	0.555[1)]	0.345	0.566[1)]	0.630[1)]
Beaufort	0.595[1)]		0.401	0.340	–0.082	0.499	0.269
Chukchi	0.630[1)]	0.401		0.744[1)]	0.218	0.250	0.076
EastSi	0.555[1)]	0.340	0.744[1)]		0.336	0.345	0.241
Laptev	0.345	–0.082	0.218	0.336		0.269	0.424
Kara	0.566[1)]	0.499	0.250	0.345	0.269		0.804[1)]
Barents	0.630[1)]	0.269	0.076	0.241	0.424	0.804[1)]	

Note: [1)] The correlation coefficient higher than the 90% confidence level test.

the sea ice edge retreat to the further north. The sea ice extent reaches two minimum value in 2007 and 2012. The sea ice condition in 2010, 2013 and 2014 are special for some regions show obvious retreat while others covered with ice-rich. This feature could not be detected if considering the overall changes of sea ice condition. The variation of sea ice edge in the Fram Strait is contrast to other regions. Our results reveal that the sea ice condition in the Arctic Ocean is highly related with the ice export out of the Fram Strait.

(3) The indices of the sea ice coverage in the melting and freezing period are an important indicator for ice condition and could be used to reveal the inner relationship between different regions. The sea ice retreats in the Chukchi Sea and the East Siberian Sea dominate the overall retreat of sea ice in 2007 while all regions show an unanimously retreat in 2012. The variation of sea ice in Region C2 dominates the changes in the central Arctic Ocean. The variation of sea ice in the central Arctic Ocean is relatively stable in interannualtime scale. Our analyses suggest that when considering the controlling factors to the sea ice condition, regional diversity is needed to be considered.

(4) The indices of sea ice coverage have three distinguish characteristics, i.e., the first one is the high correlation coefficient between the Chukchi Sea and the East Siberian Sea. The second one is the high correlation coefficient between the Kara Sea and the Barents Sea. The third one is high correlation coefficient between the central Arctic Ocean and its adjacent regions (except for the Laptev Sea). These three features maybe relate to the variability of wind or current.

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