MULTI-SCALE CHANGE ANALYSIS OF SEA ICE EXTENT IN ARCTIC

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ABSTRACT:

The extent of polar sea ice is one of the key parameters of cryosphere and polar environmental change, which plays an important role in the study of global climate change. In this paper, the monthly product of sea ice extent, recorded from 1979 to 2016, was selected to analysis the change characteristics in multi time scales, which are annual, seasonal and monthly. It is found that the sea ice in Arctic was melting continuously for past four decades. And the melting rate was accelerated significantly since 2000. Furthermore, the Arctic was divided into thirteen sub-regions, and the change mechanism of sub-regions was discussed. Different change trends for sub-regions in four seasons were presented. Four active sub-regions were found, and the periodical analysis with the method of wavelet analysis was further carried out. The results show that the changes in the four active regions are periodic and the change period is over 10 years during the period from 1979 to 2016.

1. INTRODUCTION

The extent of polar sea ice is one of the key parameters of cryosphere and polar environmental change, which plays an important role in the study of global climate change. The extent of Arctic sea ice shows obvious decreasing trend with the approximate loss of 13.3% per decade, comparing with the mean extent in September during the period from 1981 to 2010 (Serreze and Stroeve, 2015). It is predicted that Arctic sea ice extent will continue to decrease significantly in the coming decades. In order to respond to the reduction of arctic sea ice timely, it is of great necessary to describe the correlation and mechanism of Arctic sea ice extent changes in long-term, medium-term and short-term exactly.

There are several methods to obtain sea ice extent based on characteristics of sea ice using different satellite remote sensing data. For example, it is widely used to detect sea ice based on reflection characteristics using visible and infrared satellite imagery. This method could separate sea ice from open water with high effectiveness. However, both the misidentification of cloud and new sea ice and the effectiveness with insufficient illumination are major difficulties (Laura Siitam, 2017; Riggs et al., 1999; Wand et al., 2017). In order to deal with this difficulties, some researchers detect sea ice according to the ice surface temperature (IST) derived from Advanced Very High Resolution Radiometer (AVHRR) data carried on Moderate Resolution Imaging Spectroradiometer (MODIS) satellite, which is not depended on the illumination, and effective during nighttime. However, the accuracy of IST retrievals will be lower when it is cloudy (Kang et al., 2014; Kilpatrick et al., 2015; Riggs et al., 1999). Different from AVHRR data, passive microwave remote sensing data could extract sea ice on all sky conditions based on polarization difference and brightness temperature difference. But the low identification accuracy of the ice cover over small inland water bodies and along the coastal line couldn't be ignored, limited to the coarse resolution

and confusion of mixed land-water scenes with water scenes having small concentration of ice (Comiso et al., 1997; Garrity et al., 2002; Romanov, 2017; TONBOE and TOUDAL, 2005). Moreover, Synthetic aperture radar (SAR) satellite data shows great advantages for sea ice extraction thanks to high spatial resolutions and independence of illumination and sky conditions, which works well for monitoring sea ice with methods such as co-polarization ratio, penetration depth, scattering entropy and polarization difference. But lower accuracy of identification of thin, low concentration and melting ice and limited to the incidence angles are the challenge (Casey et al., 2016; Johansson et al., 2017). In addition, spaceborne LiDAR measurement data under clear sky conditions, such as CALIOP LiDAR, can also be used to study sea ice cover based on the relationship of colour ratio and depolarization ratio, since it has reliable measurements during all-day at low solar angles through considerable aerosol loads thin clouds (Lu et al., 2017).

In this paper, the extent product with spatial resolution of 25km ×25km (Fetterer et al., 2017), downloaded from the website of the National Snow and Ice Data Center (NSIDC), was selected for the change analysis in recent four decades. The data resources of this product include Scanning Multi-channel Microwave Radiometer (SMMR), Special Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS). It is available and produced in a consistent way that make the time-series appropriate for use when paying attention to long-term trend in sea ice cover about 40 years. The change characteristics were described in multiple time scales, such as seasonal, annual, and decade. And the analysis results were presented in Section 3.

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2. METHODS FOR CHANGE ANALYSIS OF SEA ICE EXTENT

In order to estimate the change characteristics of sea ice extent in Arctic, both change trend and change cycle are analysed in this Section. Change trend, which can indicate the rate of accumulate or retreat of sea ice over a specific period, is calculated according to sea ice extent data in various time scales, including annual, seasonal and monthly. What's more, the Arctic is divided into sub-regions, and the change trends in sub-regions are further discussed. The change cycle, which can reveal the periodic pattern of sea ice, is performed in several active sub-regions by using wavelet analysis method.

2.1 Fitting of linear trend

The linear trend of sea ice extent is calculated by using the least-squares method. Suppose that $X(i)$ is the sea ice extent in Arctic at time $t(i)$ (i =1, 2, 3…n), the linear change trend CT is estimated by equation (1) (Stepniak, 2011):

$$CT = (\sum_{i=1}^{n} X_i t_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} t_i / n) \sum_{i=1}^{n} t_i^2 - (\sum_{i=1}^{n} t_i)^2 / n \tag{1}$$

The sign (positive or negative) of CT indicates an accumulation or retreat trend of sea ice. And the magnitude of CT indicates the rate of change.

2.2 Estimation of change cycle

Considering the change trend in long-term, the change of sea ice extent has a certain periodic signal, accompanying by randomness, mutability and "multi-time scale" structure. Wavelet analysis is one of effective ways to explore the periodic information hiding in the time sequence data in different time scales. The basic idea of wavelet analysis is to express or approximate a signal with a cluster of wavelet functions. As a result, the wavelet function is the key of wavelet analysis, which refers to the function that are oscillatory and can be attenuated rapidly to zero, as described in equation (2) (Zayed, 2011):

$$\int_{-\infty}^{+\infty} \varphi(t)dt = 0 \tag{2}$$

where $\varphi(t)$ = the base wavelet function

Then, the base wavelet function can form a cluster of wavelet functions by scaling the scale and shifting the time axis, as shown equation (3) (Zayed, 2011):

$$\varphi_{a,b}(t) = |a|^{-1/2} \varphi(\frac{t-b}{a})dt \tag{3}$$

where $\varphi_{a,b}(t)$ = the wavelet function
    a = the scale factor
    b = the translation factor

3. RESULTS AND DISCUSSION

The results of annual, seasonal, monthly change trend are calculated according to equation (1). It is shown that the sea ice extent in Arctic has decreased 2.14×10^6 km² from 1979 to

2016, and the average melting rate is 5.35×10^4 km²/y. The annual anomaly of sea ice extent is defined as the difference between sea ice extent in a particular year and average sea ice extent from 1979 to 2016. The piecewise curve fitting strategy is adopted when using equation (1), considering that the trend of anomalies change shows differences obviously. As shown in Figure 1, the anomalies curve turns to negative Since 2000, and the average melting rate is 3.52×10^4 km²/y during the period from 1979 to 2000. In contrast, the average melting rate is 6.78×10^4 km²/y during the period from 2000 to 2016, which reveals that the melting rate of Arctic sea ice extent is accelerated significantly during recent 20 years.
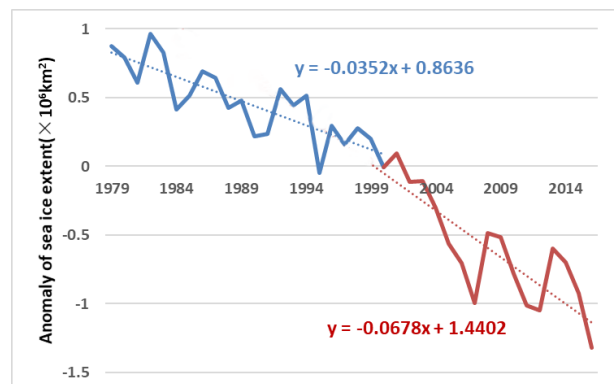

Figure 1. Annual anomaly of sea ice extent in Arctic from 1979 to 2016

There are various technical definitions of seasons in Arctic. According to (Xia et al., 2014), it is defined that spring is from April to June, summer is from July to September, autumn is from October to December, and winter is from January to March. In figure 2, the seasonal change trends of sea ice extent in Arctic are presented. It is shown that sea ice is melting in all seasons, and the melting rate is 7.85×10^4 km²/y in summer, which is the fastest season in a year.
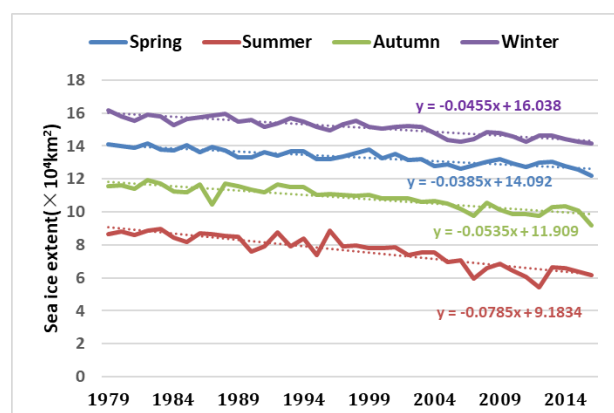

Figure 2. Seasonal change trend of sea ice extent in Arctic from 1979 to 2016

The monthly change trend from 1979 to 2016 is shown in Table 1 and Figure 3. It is shown that the sea ice extent is the largest in March, while smallest in September. On the other hand, the fastest melting rate appears in September, while the slowest melting rate appears in May.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.
Melting rate ($10^4 km^2/y$)	4.64	4.63	4.17	3.72	3.40	4.44
Month	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Melting rate ($10^4 km^2/y$)	7.25	7.60	8.71	6.60	5.51	4.64

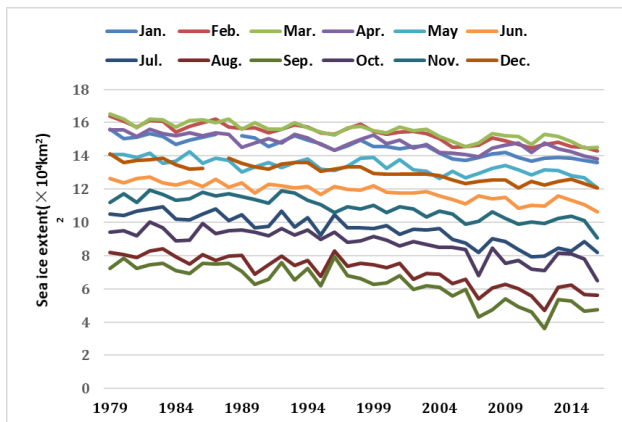Table 1. Monthly melting rate of sea ice extent in Arctic from 1979 to 2016

Figure 3. Monthly change trend of sea ice extent in Arctic from 1979 to 2016

In order to analysis the change characteristics of sea ice extent in Arctic in detail, the Arctic is divided into 13 regions according to (Xia et al., 2014; Fetterer et al.,2017), as shown in Figure 4. The total reduction of Arctic sea ice in 13 regions from 1979 to 2016 is presented in Figure 5.
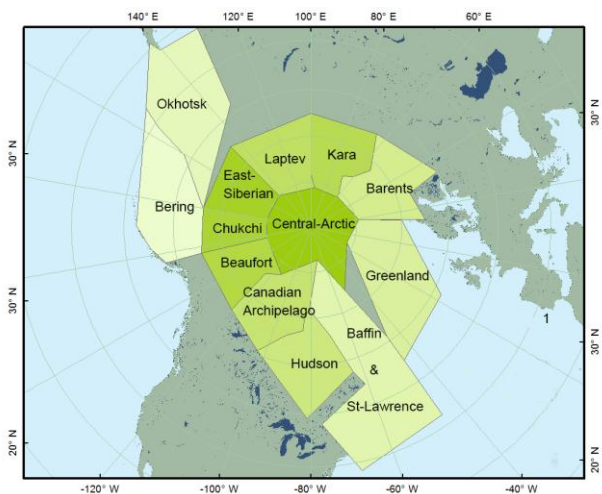

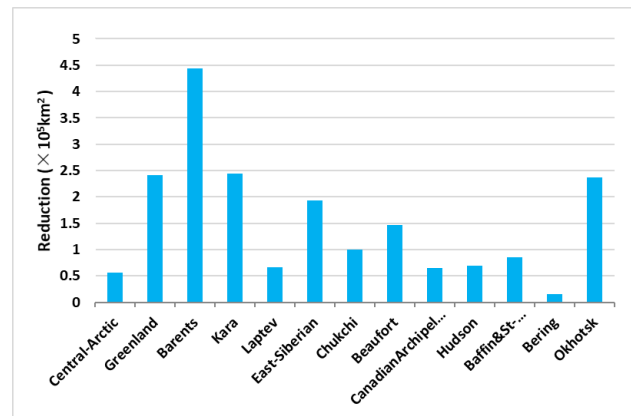
Figure 4. Distribution of 13 regions in Arctic

Figure 5. The total reduction of sea ice extent of 13 regions in Arctic from 1979 to 2016

Besides the annual melting rate, the standard deviation of sea ice extent in each region is also be considered, which can indicate the divergence between the data of sea ice extent and the trend line fitted by equation (1). The melting rate and corresponding standard deviation of 13 regions in Arctic during both melting period (spring and summer) and freezing period (autumn and winter) are shown in Figure 6. It is found that the sea ice in Barents, Greenland, Okhotsk and Baffin & St-Lawrence is more active than other regions.

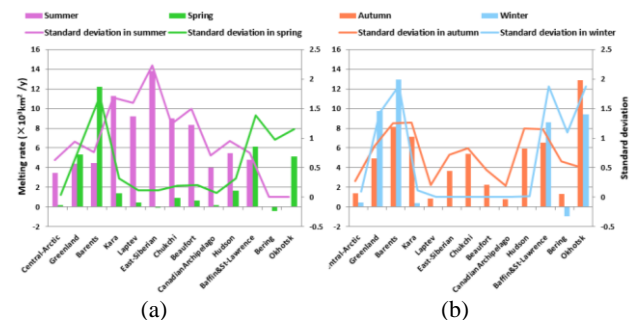(a)   (b)

Figure 6. The melting rate and corresponding standard deviation of 13 regions in Arctic during (a) melting period and (b) freezing period

The change cycles of these four active regions are further investigated based on wavelet analysis. The results are shown in Figure 7. Based on the wavelet graph of real part coefficient and energy significant area in Figure 7(a), it is indicated that there is a cyclical swing in time scale of 6 ~ 8 years and 20 ~ 25 years during the period from 1979 to 2016 in Barents. At the same time, the periodic oscillation is hidden under the time scale of 12~17 years from 1979 to 1997. Similarly, we can find a cyclical swing in the time scales of 20 ~ 23 years and 26 ~ 28 years in Greenland. And there is hidden the periodic oscillation in time scale of 13 ~ 17 years from 1979 to 2000. In Baffin & Lawrence, there are periodic oscillations at the time scale of 25~30 years in the whole time domain from 1979 to 2016. Meanwhile, in the period from 1979 to 1995, the period under the time scale of 12~15 years is hidden, but the oscillation is less significant. Finally, there are periodic oscillations at the time scale of 13~18 years in the whole time domain from 1979 to 2016 in Okhotsk.
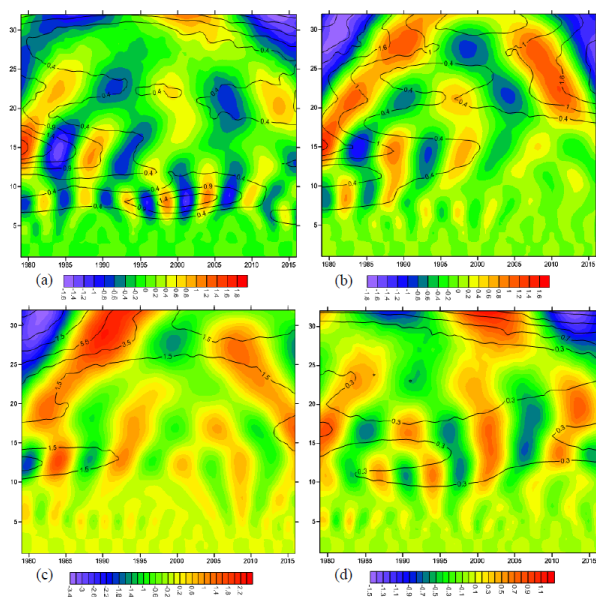
Figure 7. Wavelet analysis results for change cycle of sea ice extent in (a) Barents, (b) Greenland, (c) Baffin & Lawrence and (d) Okhotsk

4. CONCLUSION

The change characteristics, including change trend and change cycle, of sea ice extent in Artic during the period from 1979 to 2016 are presented in this paper. It is shown that the sea ice extent is reducing continually. And the annual melting rate accelerated significantly since 2000. According to the analysis of the variation trend of sea ice of sub-regions in Arctic, four regions, which are Barents, Greenland, Okhotsk, and Baffin & St-Lawrence are more active, while Bering, Central-Arctic and Canadian Archipelago are relatively stable. With the wavelet analysis of four active regions, the changes of the four regions are periodic and the change period is over 10 years generally. For the further research, we will focus on the extraction method of sea ice in active areas by using multi-source high-resolution remote sensing data.

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