Spatial and Temporal Variations of Arctic Sea Ice From 2002 to 2017

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Abstract The variation of polar sea ice is an indicator of polar environmental change, which plays an important role in the study of regional and global climate change. In this paper, the latest sea ice data sets from the European Space Agency Climate Change Initiative were firstly combined to comprehensively analyze the spatial and temporal variation of Arctic sea ice concentration (SIC) and sea ice thickness (SIT) from 2002 to 2017. The results show that during this period, the SIC of the Kara Sea and the Barents Sea decreases the most significantly, reaching $-1.11\% \cdot \text{year}^{-1}$. The Arctic annual average sea ice extent (SIE) and sea ice area (SIA) exhibit noticeable decreasing trends, reaching $-0.0592 \times 10^6 \text{ km}^2 \cdot \text{year}^{-1}$ and $-0.0628 \times 10^6 \text{ km}^2 \cdot \text{year}^{-1}$, respectively. Both of Arctic SIE and SIA vary seasonally, and they reach the minimum values of $4.97 \times 10^6 \text{ km}^2$ and $3.96 \times 10^6 \text{ km}^2$ in September and the maximum values of $14.58 \times 10^6 \text{ km}^2$ and $13.35 \times 10^6 \text{ km}^2$ in March, respectively. Moreover, the Arctic SIE and SIA anomaly series from 2002 to 2017 were analyzed based on the linear regression method. It is found the most noticeable decreasing trends of the Arctic SIE and SIA are from July to October. The maximum variation of the SIE is $-1.06 \times 10^6 \text{ km}^2(10a)^{-1}$, and the maximum variation of the SIA is $-1.09 \times 10^6 \text{ km}^2(10a)^{-1}$. The Arctic SIE and SIA present the smallest decreasing trends from April to May, which are $-0.19 \times 10^6 \text{ km}^2(10a)^{-1}$ and $-0.2 \times 10^6 \text{ km}^2(10a)^{-1}$, respectively. The Arctic SIT also displays a pronounced decreasing trend with $-0.015 \text{ m} \cdot \text{year}^{-1}$ in autumn and $-0.018 \text{ m} \cdot \text{year}^{-1}$ in winter. The annual average SIT reaches a minimum of 1.28 m in 2013 and a maximum of 1.66 m in 2005. Particularly, the SIT of the Hudson Bay decreases the most significantly, reaching $-0.051 \text{ m} \cdot \text{year}^{-1}$. Finally, the Arctic average SIT was tested by the Mann-Kendall method. It is found that the SIT has a sudden change in 2007, from a slight increase in 2003–2007 to a significant decrease in 2007–2017. Overall, the decreasing trend of the Arctic sea ice (both SIC and SIT) is significant in the past decade. These findings can contribute to future research on polar regions and global climate change.

1. Introduction

Climate change has caused a far-reaching impact on global water resource, food production, sea level, and many other aspects, which is the biggest environmental challenge facing mankind in the 21st century. As a sensitive climate indicator, sea ice plays an important role in global climate change (Aagaard & Carmack, 1989; Curry et al., 1995; Hallikainen & Winebrenner, 1992). Sea ice is mainly distributed in the Arctic and Antarctic, which not only has obvious regional and seasonal characteristics but is also an important climate factor for the study of global change (Perovich & Polashenski, 2012). The Northern Hemisphere has a wide area of sea ice, ranging from 45°N to 90°N. The change of the Arctic sea ice is closely related to the change of the whole Arctic environment, and it has attracted considerable attention in recent years. Therefore, it is of significant importance to obtain the information of Arctic sea ice variation both in time and space.

Microwave remote sensing, both active and passive, can provide observations with all-time and all-weather coverage and has high sensitivity to sea ice permittivity. Thus, it has unique advantages in sea ice detection at large scales temporally and spatially, especially in the polar areas with complex geographical environment and extreme climatic conditions. Over the past few decades, a number of activities have been carried out to analyze the spatial and temporal variation of sea ice in polar regions. Stroeve et al. (2007) studied the Arctic sea ice variation from 1953 to 2006 and found that the sea ice extent (SIE) decreased significantly...
in September, and the reduction rate of the Arctic sea ice was much higher than expected. Parkinson and Cavalieri (2008) found that the Arctic SIE decreased by an average of $(-4.51 \pm 0.46) \times 10^2$ km$^2$ per year from 1979 to 2006 based on the sea ice concentration (SIC) product of Scanning Multichannel Microwave Radiometer and Special Sensor Microwave/Imager. Comiso et al. (2008) discovered that the Arctic SIC and sea ice area (SIA) decreased at a rate of 2.2% and 3.0% every 10 years from 1979 to 1996, respectively. Meehl et al. (2018) found that the trend for cold-season decreases in Arctic SIE from 2000 to 2014 was about a factor of 2 larger than the 1979–2000 trend and the warm-season trend was about a factor of 3 larger. Wu and Wang (2019) reported that the first-year ice extent increased at an annual rate of 0.0199 $\times 10^2$ km$^2$ from 1997 to 2016, and the multiyear ice area decreased by $-0.0711 \times 10^6$ km$^2$ per year from 1979 to 2016. However, the related research on the sea ice thickness (SIT) is relatively limited compared with the time series analysis of the Arctic SIE and SIA based on passive microwave SIC products. For instance, Giles et al. (2008) found that the average winter SIT anomaly, after the melt season of 2007, was 0.26 m below the 2002/2003 to 2007/2008 average by using satellite radar altimetry data. Kwok and Rothrock (2009) reported that the rate of average SIT reduction in winter/summer is $-0.10/-0.20$ m/year in the 5-year ICESat record (2003–2008). Kwok (2018) found that between the pre-1990 submarine period (1958–1976) and the CryoSat-2 period (2011–2018) the average thickness near the end of the melt season, in six regions, decreased by 2.0 m or some 66% over six decades.

The European Space Agency (ESA) proposed the Climate Change Initiative (CCI) to respond to the needs of the Global Climate Observing System (GCOS) and to make full use of existing satellite observation data (GCOS, 2011). The goal of ESA CCI is to systematically produce, preserve, and distribute Essential Climate Variable (ECV) long-term data sets to meet the needs of the United Nations Framework Convention on Climate Change (Mason et al., 2003). The member states of ESA approve the CCI program in 2008, which based on the existing work in Europe, especially the archived long-term Earth observation data. A series of actions were carried out closely around the necessary steps of ECV production, including long-term data maintenance, recalibration, periodic reprocessing, algorithm development, product production, and validation as well as quality assessment of climate data sets (Hollmann et al., 2013). The purpose of CCI program is to build remote sensing satellite data sets of ECV that can meet the needs of climate monitoring and analysis, while providing consistent access to data.

The study of the Arctic sea ice change has attracted increasing attention in recent years. However, few studies combine use of SIC and SIT data sets to fully analyze the spatial and temporal variation of the Arctic sea ice from the perspective of multiple geophysical parameters. Therefore, in this study, we analyze the Arctic sea ice variation by using the latest SIC and SIT data products produced by the ESA CCI sea ice project from 2002 to 2017. We also divided the whole Arctic into eight regions to investigate the regional trends of SIC and SIT in the past 15 years. Our goal is to further quantify the spatial and temporal variation characteristics of the Arctic sea ice comprehensively by using the new SIC and SIT data set merged from multiple satellite data sources, which is expected to provide a reference for the analysis of the Arctic environmental and global climate change. The paper is organized as follows. The SIC and SIT data used in the study are briefly introduced in section 2. Section 3 describes the data processing and analysis method. In section 4, the spatial and temporal variation characteristics of the Arctic SIC, SIE, SIA, and SIT are analyzed, and the MK (Mann-Kendall) mutation test of SIT is carried out. Finally, the conclusions are summarized in section 5.

2. Data Set

To date, ESA CCI has proposed nearly 20 CCI projects, including the sea ice project which provides remote sensing data sets for the SIC and SIT in both Arctic and Antarctic. The AMSR-E data and its successor AMSR2 data are used as the input data of the SIC, and the adaptive hybrid algorithm is used to optimize the processing to generate SIC product (Lavergne et al., 2019). AMSR-E and AMSR2 are more advanced multiband radiometers with higher spatial resolution and radiation accuracy than the traditional Scanning Multichannel Microwave Radiometer and Special Sensor Microwave/Imager. The ESA CCI SIC product (version 2.1) is available from 2002 to 2017 with a spatial resolution of 25 km (Toudal Pedersen et al., 2017). The ESA CCI SIT data (version 2.0) includes daily and monthly products in Arctic and Antarctic from October 2002 to April 2017 based on the Envisat and CryoSat-2 altimetry data (Hendricks et al., 2018a, 2018b; Paul et al., 2018). The spatial resolutions of the SIT product in the Arctic and Antarctic are...
25 km × 25 km and 50 km × 50 km, respectively. Since ESA CCI data sets have good product consistency and time continuity, it is convenient for researchers to use this product for polar climate change studies.

In this paper, the Arctic SIC and SIT products produced by ESA CCI sea ice project were used to analyze the spatial and temporal variation of Arctic sea ice from 2002 to 2017. It should be noted that although the SIC data is missing from 5 October 2011 to 22 July 2012 due to the failure of the AMSR-E sensor, the available SIC data accounts for 94.72% of the total data. It fully supports the analysis and study of the time series change of the Arctic sea ice from 2002 to 2017. In addition, from May to September in summer, the Arctic region is affected by the increasing melt ponds, resulting in an increase in the errors of SIT retrievals. Therefore, the Envisat and CryoSat-2 SIT data used in the ESA CCI only cover January–April and October–December of each year. The former covers the period from October 2002 to March 2012, and the latter is from November 2010 to April 2017. For the overlapping dates of Envisat and CryoSat-2 SIT (i.e., November 2010 to March 2012), the overall difference between these two satellites data is 0.119 m in hemispheric average, which indicates a reasonable consistency between them. Therefore, we believe the small difference between Envisat and CryoSat-2 SIT will not affect the finding of SIT variations in this study, and we chose the CryoSat-2 SIT data during the overlap period to construct the SIT time series. In addition, the orbits of the Envisat and CryoSat-2 are different and Envisat has a larger pole hole. There is no SIT data at latitudes >81.5°N in the Envisat data. Accordingly, the SIT data for latitudes >81.5°N is excluded in the CryoSat-2 SIT to be consistent with Envisat SIT. Users can find detailed documents concerning the SIC and SIT data sets on the ESA CCI website (http://esa-cci.nersc.no/) and download the relevant sea ice data sets freely through the FTP address (ftp://anon-ftp.ceda.ac.uk/neodc/esacci/).

3. Method

In this study, we divided the Arctic into eight regions (Wang, Bi, et al., 2019), which are the Arctic Ocean core region (mainly including the Arctic Ocean, Beaufort Sea, Chukchi Sea, East Siberian Sea, and Laptev Sea), Barents Sea and Kara Sea, Baffin Bay/Labrador Sea, Hudson Bay, Greenland Sea, Sea of Okhotsk and Japan Sea, Canadian Archipelago, and Bering Sea (Figure 1).

The Arctic monthly and yearly SIC was firstly calculated from 2002 to 2017. Then, the daily SIE and SIA derived from ESA CCI SIC data were obtained. The definition of SIE and SIA is usually used 15% as a certain concentration threshold (Cavalieri & Parkinson, 2012). The 15% was chosen because it on average corresponded with the true ice edge in validation studies when the algorithms were being developed (Cavalieri et al., 1991). The formulas of SIE and SIA are as follows (Su et al., 2011):

\[
\text{SIE} = \sum_{i=1}^{n} \omega_i A_i \begin{cases} 
\omega_i = 1 & C_i \geq 15 \\
\omega_i = 0 & C_i < 15 
\end{cases}
\]

\[
\text{SIA} = \sum_{i=1}^{n} \omega_i C_i A_i \begin{cases} 
\omega_i = 1 & C_i \geq 15 \\
\omega_i = 0 & C_i < 15 
\end{cases}
\]

where \(A_i\) is an area of the SIC grid cell, \(\omega_i\) is the weight coefficient, \(C_i\) is the SIC value, and \(n\) is the number of pixels.

Next, the yearly SIE and SIA were calculated. The seasonal variations of SIE and SIA were calculated by the average of the SIE and SIA in the same month from 2002 to 2017. Moreover, different studies used slightly different criteria for the division of seasons (Meehl et al., 2018; Wang, Bi, et al., 2019). In this paper, April–June, July–September, October–December, and January–March were classified as spring, summer, autumn, and winter, respectively (Wang, Bi, et al., 2019). In addition, the seasonal variation trends of the Arctic SIE and SIA were analyzed by the linear regression method (Weisberg, 2005), and the influence of seasonal variations was removed using the monthly sea ice anomalies (Comiso, 2010; Yuan & Martinson, 2000). It should be noted that the continuous absence of the SIC data in 2002, 2012, and 2017 has affected the overall trends of the yearly SIE and SIA, and thus, the data for these 3 years were removed when analyzing the interannual trends of these parameters. Finally, climate mutation is an important phenomenon in the complex climate system, which has been widely used in meteorology and other related fields (Burn & Elnur, 2002; Kang & Kug, 2000). The main mutation detection methods include sliding t test (Afifi & Azen, 1979; Chai &
Liu, 2016), MK method (Kendall, 1948; Liuzzo et al., 2016; Mann, 1945), and empirical orthogonal function method (Lorenz, 1956; Mori et al., 2014). Few studies used mutation detection to study the change of sea ice. MK method is a nonparametric statistical test method, which has the advantages of not being disturbed by individual outliers and being able to objectively represent the overall changing trend of the sample sequence. Therefore, the MK method was adopted in the study to analyze the variation characteristics of SIT in the Arctic region.

4. Results and Discussions

4.1. Annual Variation Characteristics of the Arctic Sea Ice

The spatial distribution of the Arctic average annual SIC is shown in Figure 2, with gray for land and white for sea water. As can be seen from Figure 2, the Arctic SIC shows a decreasing trend from 2002 to 2017. The largest SIC occurs in the Arctic Circle and remains stable during the study period, while the smallest SIC locates at the marginal ice zones where are found to remain some uncertainties in the satellite SIC products (Ivanova et al., 2015).
From the annual average SIC, the annual average anomaly can be further calculated (take the average of a certain year minus the average of all years) to investigate the fluctuation of SIC in each year. A positive anomaly means that the annual average of this year is higher than the average for all years, and a negative anomaly is the opposite. We calculated the annual average SIC anomaly in different sea areas defined in Figure 1 and obtained the annual average anomalous change of SIC, shown in Figure 3. Generally, the Arctic annual average SIC has noticeable negative anomalies in 2007, 2012, and 2016, reaching the minimum value during the study period. The annual average SIC fluctuations in different sea areas are not exactly the same. The annual average SIC anomalies in the Arctic Ocean core region, the Barents Sea and Kara Sea are relatively similar, and the determination coefficients $R^2$ are 0.51 and 0.63, respectively. They are all positive anomalies before 2005, and the maximum value of positive anomalies appears in 2003, reaching almost 15%. There are noticeable negative anomalies in 2007, 2012, and 2016, and the negative anomalies in 2016 are the most significant, exceeding $-10\%$. The SIC in Baffin Bay/Labrador Sea shows pronounced positive anomalies in 2008, 2015, and 2017, but there is a prominent negative anomaly in 2011. The Hudson Bay SIC exhibits obvious negative anomalies in 2006, 2010, and 2011. The positive anomaly of the

Figure 2. Spatial distribution of average annual SIC in the Arctic from 2002 to 2017.
Greenland Sea SIC is mainly concentrated in 2006–2012, but there is a noticeable negative anomaly in 2016. The SIC anomaly in the Sea of Okhotsk and Japan Sea fluctuates around zero and shows a decreasing trend overall. The Canadian Archipelago SIC anomaly mainly changes from positive anomaly to negative anomaly and reaches the maximum negative anomaly in 2012, exceeding −10%. The Bering Sea SIC does not show any conspicuous negative anomalies from 2005 to 2013, but it exhibits noticeable negative anomalies after 2014.

The average annual variations of the Arctic SIE and SIA from 2003 to 2016 are shown in Figure 4. The blue and red solid lines in the figure represent average annual variation of the SIE and SIA, respectively, and their trends are represented by dashed lines. It is observed that during the study period, the Arctic SIE and SIA illustrate decreasing trends, with the SIE decreases by $0.0592 \times 10^6$ km·year$^{-1}$ and the SIA decreases by $0.0628 \times 10^6$ km·year$^{-1}$. Furthermore, it is found that the SIE and SIA both reach the minimum in 2016. Wu et al. (2019) found that the Arctic SIA reached the minimum in 2016 during the period of 1979 to 2016, which was consistent with the results obtained in this study by using the ESA CCI data. Moreover, it is observed that the SIE and the SIA increase significantly in 2008 compared with the results of 2007. Giles et al. (2008) also found that the low summer SIE in 2007 leads to an abnormal decrease in the SIT in the following winter season, particularly in the Western Arctic.

4.2. Seasonal Variation Characteristics of the Arctic Sea Ice

The spatial distribution of the Arctic monthly average SIC is shown in Figure 5. The spatial pattern of Arctic SIC varies seasonally, as expected. The SIC gets the widest coverage in winter, while reaches its lowest value...
in summer due to the influence of temperature. In terms of geographical location, it can be further found that the SIC in the Sheri Hoff Sea, the Bering Strait, and the Chukchi Sea in the Northern Pacific region is between 50% and 80% in spring. The SIC in areas such as the Barents Sea, Kara Sea, and Davis Sea in the North Atlantic is less than 20%, which is relatively low. In summer, the SIC in the Arctic Circle is still basically maintained at 100%, while from the Beaufort Sea to the west to the Kara Sea, the SIC has

Figure 4. Variation trends of the Arctic average annual SIE and SIA from 2003 to 2016.

Figure 5. Spatial distribution of average monthly SIC in the Arctic from 2002 to 2017.
decreased. The SIC remains at about 50% in the East Siberian Sea in autumn, while there is almost no sea ice cover in the Barents Sea. In winter, the Arctic temperature becomes lower, and the SIC generally increases significantly in the Barents Sea, Kara Sea, and other regions, and the SIC in Siberia reaches 100% again.

The variations of the Arctic monthly average SIE and SIA from 2002 to 2017 are shown in Figure 6 (the black frame represents missing data). Similar to Figure 4, the blue and red solid lines represent the variation of the SIE and SIA respectively, and the dashed lines represent their temporal trends. It can be found that the variation trend of the Arctic SIE is consistent with that of SIA. The Arctic SIE and SIA own a high linear correlation and also have noticeable seasonal variation characteristics. The maximum values of the SIE and SIA usually appear around March of each year, and the minimum values often appear around September of each year. From the variation trend lines of the SIE and SIA, it can be seen that the overall SIE and SIA in the Arctic region show decreasing trends, which are closely related to the increase of the Arctic temperature caused by global warming (Zhao et al., 2015).

The seasonal variations of the Arctic SIE and SIA from 2002 to 2017 are shown in Figure 7. The blue and red solid lines represent the changes of the Arctic SIE and SIA, respectively. The variation trends of the Arctic
SIE and SIA are similar, which exhibit obvious seasonal differences. The Arctic temperature begins to warm up in spring, causing the SIE and SIA decrease and usually reach minimum values around September, which are $4.97 \times 10^6$ km$^2$ and $3.96 \times 10^6$ km$^2$, respectively (see the yellow and green squares in Figure 7). In addition, at the beginning of autumn, the Arctic SIE and SIA begin to increase as a result of lower temperatures, reaching maximum values around March, which are $14.58 \times 10^6$ km$^2$ and $13.35 \times 10^6$ km$^2$, respectively (see the gray and blue circles in Figure 7). Further analysis shows that the SIE and SIA in March are about three times that of September. Although the Arctic mean minimum and maximum temperatures generally appear in January and February and July and August, respectively, the extreme values of the SIE and SIA appear in March and September. This is because the melting and freezing of sea ice require endothermic and exothermic, and there is a process of energy accumulation, and thus, the seasonal variation of sea ice lags behind the seasonal variation of solar radiation and temperature (Wang et al., 2017).

### 4.3. Maximum and Minimum Variation of the Arctic SIE and SIA

Figure 8 shows the maximum and minimum values and their variation trends of the annual SIE. It can be found that the maximum and minimum SIE of the Arctic sea ice show obvious decreasing trends. The maximum reduction rate is $-0.052 \times 10^6$ km·year$^{-1}$, and the minimum reduction rate is $-0.112 \times 10^6$ km·year$^{-1}$, which is five times that of the maximum reduction rate. Figure 9 reflects the maximum and minimum values and their variation trends of the annual SIA, indicating that the maximum and minimum SIA of the Arctic sea ice decrease significantly in the past 15 years. The reduction rate of the maximum SIA is $-0.047 \times 10^6$ km·year$^{-1}$, and the minimum reduction rate is $-0.109 \times 10^6$ km·year$^{-1}$, which is about five times that of the maximum. The minimum SIE and SIA reach the minimum in 2007 and 2016, which are consistent with the average annual SIE and SIA.

### 4.4. Variation Trend of the Arctic SIC

Figure 10 shows the overall trend distribution of the Arctic SIC from 2003 to 2016, and the influence of seasonal variations has been removed using the monthly sea ice anomalies, with black dots representing statistically significant ($p$ value $< 0.05$) trends. It is seen visually that the Arctic SIC presents a significantly decrease in most areas, and the variation trend varies with different geographical locations. The dark blue parts represented by the Kara Sea and the Barents Sea show that the decreasing trend of SIC is the most significant, about $-2.5\%$·year$^{-1}$. The black dots ($p$ value $< 0.05$) are mainly concentrated in the Kara Sea and Barents Sea and their surrounding areas, indicating that these areas have significant decreasing trends. For the light blue parts represented by the Greenland Sea, the Beaufort Sea and their north, the Chukchi Sea and their north, and the Laptev Sea, the decreasing trends are about $-1\%$·year$^{-1}$. In recent years, the SIC has decreased obviously, and the decreasing rate in summer and autumn is faster than that in winter and spring. The decreasing trends in autumn and summer mainly cover the areas in south of the Arctic
Ocean, while winter and spring are mainly distributed in the Barents Sea and its surrounding seas (Wang, Bi, et al., 2019). The rise of sea surface temperature and thinning of the pack ice make it easy for large areas of the summer melting season to become ice free, coupled with an unusual pattern of atmospheric circulation, which will be the key factors behind these records ice loss in recent decades (Maslanik et al., 2007; Nghiem et al., 2007; Stroeve et al., 2008). Other studies have pointed out the Arctic may be on the verge of a fundamental transition toward a seasonal ice cover (Stroeve et al., 2008).

To quantify the seasonal variation trends of the Arctic SIE and SIA, the monthly SIE and SIA were calculated. Then the SIE and SIA in the same month were analyzed by using the linear regression method. Finally, the monthly anomaly series of the Arctic SIE and SIA from 2002 to 2017 were obtained, as illustrated in Table 1. It is observed that the monthly Arctic SIE and SIA show decreasing trends in terms of interannual variation. During the period from July to October, the decreasing trends of the Arctic SIE and SIA are the most obvious, and the largest decreasing trends of the SIE and SIA are $-1.06 \times 10^6$ km$^2$ (10a)$^{-1}$ and $-1.09 \times 10^6$ km$^2$ (10a)$^{-1}$, respectively. The excessive melting of sea ice in summer will increase the area of open water and decrease the surface albedo and, therefore, increase the solar radiation absorbed by the sea surface (Rothrock et al., 2008). This will further increase the temperature in autumn (Kwok, 2007) and then reduce the growth of sea ice in winter. As a result, the thinner first-year ice is completely melted in the summer of the following year, forming an ice-albedo positive feedback mechanism to accelerate the melting of sea ice (Kumar et al., 2010; Serreze et al., 2009). In addition, the decreasing trends of the Arctic SIE and SIA are the smallest from April to May, which are $-0.19 \times 10^6$ km$^2$ (10a)$^{-1}$ and $-0.2 \times 10^6$ km$^2$ (10a)$^{-1}$, respectively. The maximum decreasing trends of SIE and SIA are about five times of the minimum decreasing trends, and the differences between them are also significant.

4.5. Variation of the Arctic SIT

The SIT is not only an important parameter of the real state of sea ice but also reflects the energy balance response and indicates the freezing and thawing rate of sea ice. It also plays a crucial role in determining the variation trend of Arctic sea ice (Maslanik et al., 1996). Therefore, it is
particularly important to accurately understand the change and trend of SIT. The SIE and SIA begin to grow in October and reach their maximum in March each year (Wang et al., 2017). In addition, as mentioned before, the orbits of the Envisat and CryoSat-2 are different and Envisat has a larger pole hole. There is no SIT data larger than 81.5°N in the Envisat data, an area of much thicker ice.

The spatial distribution of the average annual SIT (e.g., the 2003 yearly average represents the period from October 2002 to April 2003) in the Arctic is shown in Figure 11. The SIT in the east of the Arctic is generally

| Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|------|------|------|------|------|------|------|------|------|------|------|------|------|
| SIE  | −0.44| −0.46| −0.48| −0.24| −0.19| −0.53| −0.97| −0.79| −1.01| −1.06| −0.63| −0.47| −0.53|
| SIA  | −0.47| −0.46| −0.46| −0.25| −0.20| −0.56| −0.93| −0.84| −0.93| −1.09| −0.75| −0.52| −0.56|

Figure 11. Spatial distribution of average annual SIT in the Arctic from 2002 to 2017.
smaller than that in the west. From 2003 to 2007, there is about 4 m (or even more than 4 m) of sea ice in the Canadian Archipelago and Greenland Sea, but from 2008 to 2013, the SIT in these areas decreases significantly. The SIT shows a decreasing trend in the overall interannual variation from 2003 to 2017.

The abnormal variation of annual average SIT in different sea areas of the Arctic is displayed in Figure 12. Overall, the Arctic SIT has experienced three sharp declines since 2007. First, the SIT decreased markedly in 2007, resulting the first low value in 2008 of the study period. This is followed by another massive reduction in 2011 and continued into 2012, causing the SIT reaches its minimum in 2013. Finally, the SIT decreased for the third time in 2015, leading to the low SIT value in 2016. The fluctuation of annual SIT in these areas is different, but the variation trend is similar, and almost all sea areas show a decreasing trend (except the Greenland Sea which exhibits a slightly increasing trend). The SIT anomaly in the Arctic Ocean core area is positive before 2007 and becomes negative in the following 6 years, and the negative anomaly is the most obvious in 2013. The annual average SIT anomalies of the Hudson Bay, the Bering Sea, the Barents Sea, and the Kara Sea are similar. The SIT anomalies are all positive before 2010 but negative after this year, with quite higher determination coefficients $R^2$ of 0.67, 0.68, and 0.81, respectively. The Baffin Bay/Labrador Sea shows pronounced positive anomalies before 2007 and negative anomalies after 2012. The SIT anomalies in the Greenland Sea and the Canadian Archipelago fluctuate significantly, with the former showing obvious positive anomalies in 2006 and 2015, and negative anomalies in 2011 and 2013, while the latter displays noticeable negative anomalies in 2013 and 2016. The thickness of the Sea of Okhotsk and Japan Sea exhibits an obvious positive anomaly before 2010 and becomes a negative anomaly in 2011, indicating
that the sea ice decreases significantly. Affected by environmental variables such as temperature and wind field, the Arctic sea ice underwent a major melting event in the summer of 2007, resulting in a significant decrease in the average SIT (Giles et al., 2008). Although there is a short period of recovery and rise (2008–2010 and 2013–2015), it cannot change the trend of the long-term decline of sea ice. Here we also notice that the SIT variation trend of Hudson Bay and Baffin Bay/Labrador Sea (Figure 12) is opposite to their SIC variation trend (Figure 3). The variation trend of SIC and SIT in the remaining areas shows good consistency.

The distribution of the Arctic SIT in October 2002–2016 is shown in Figure 13. As the Arctic sea ice enters the growth period in October, the SIT begins to increase. In October 2012, the average SIT is the lowest (~0.86 m) in the last 15 years, and the coverage of the SIT decreases significantly, while the average SIT in October 2004 is the highest (~1.17 m) in the last 15 years. The average SIT between the lowest and the highest value is about 0.31 m in October 2002–2016. The average SIT in October 2011 and 2015 is about 0.9 m.
Figure 14 shows the distribution of the Arctic SIT in March 2003–2017. In March 2012, the average SIT is the lowest (~1.57 m) in the last 15 years and reaches its maximum (~1.98 m) in March 2005. The closer to the North Pole, the greater the SIT, with a maximum thickness of about 4 m. Combined with the SIT distribution maps in March and October, it can be found that the Arctic SIT in March is significantly higher and wider than that in October.

The spatial distribution of variation trend of average annual SIT (e.g., the 2003 yearly average represents the period from October 2002 to April 2003) in the Arctic region from 2003 to 2017 is shown in Figure 15, and the black dots represent statistically significant ($p$ value < 0.05) trends. Similar to SIC, the influence of seasonal variations has also been removed using the monthly sea ice anomalies. The SIT decreases obviously in the Chukchi Sea, the Laptev Sea, and the Kara Sea, about −0.1 m-year$^{-1}$. Followed by the Greenland Sea, Beaufort Sea and their north, and Barents Sea and other sea areas, where the SIT also shows different
degree of decreasing trends. In addition, the black dots are mainly concentrated in the Chukchi Sea, the Laptev Sea, and the Kara Sea and their surrounding areas, indicating the SIT in these areas has a significant decreasing trend. The extensive loss of the multiyear ice is considered to be one of the important aspects of the reduction of the SIT (Maslanik et al., 2011).

The variation of the Arctic average SIT from 2002 to 2017 is shown in Figure 16 (e.g., the 2003 yearly average represents the period from October 2002 to April 2003), including the average SIT from January to March (winter), October to December (autumn), and the whole year (October to April of the following year). The Arctic SIT exhibits obvious decreasing trends in different time scales, with about $-0.015 \text{ m-year}^{-1}$ in autumn and $-0.018 \text{ m-year}^{-1}$ in winter, which is basically consistent with the average SIT in the whole year. In addition, the SIT is mainly between 1.4 and 1.9 m in winter. It reaches the maximum (~1.82 m) in 2005 and the minimum (~1.41 m) in 2013. The SIT is mainly between 0.9 and 1.4 m in autumn, and it reaches the maximum (~1.37 m) and minimum (~0.98 m) in 2004 and 2011, respectively. The annual average SIT reaches the maximum (~1.66 m) in 2005 and then begins to decrease and reaches its lowest (~1.28 m) in 2013, a decrease of 0.38 m compared with SIT in 2005. Previous studies have pointed out that the warmer atmosphere in Arctic exerts a progressive and significant impact on the decline in SIT (Bi et al., 2016).

Figure 17 shows the temporal distribution of the monthly average SIT in Arctic. Combined with Figure 16, it can be found that there are different trends in the variation of SIT from October to April during the period of 2003–2017. The Arctic sea ice begins to grow in October until around April of the following year. During this period, the SIT increases gradually, showing a decreasing trend with the maximum value (~2 m) appears around March. However, from the perspective of interannual variation, the SIT has decreased in
general from 2003 to 2017, especially with the decrease of the SIT and the loss of multiyear ice from March to April, which has an important impact on the variation of sea ice in the Arctic region. Previous studies have demonstrated that the summertime SIT decline is mainly due to a warmer Arctic Ocean through absorbing solar radiation induced by the albedo-feedback mechanisms (Steele et al., 2010). Moreover, hotter Pacific inflows will also bring extra heat to melting Arctic Ocean sea ice (Woodgate et al., 2010).

4.6. Mutation Detection of the SIT

The MK test method was used to test the abrupt change of the SIT, which can better analyze the variation of sea ice in the Arctic region. When MK mutation test is used, the significance level $\alpha = 0.05$ and the critical value $U_{0.05} = \pm 1.96$ are generally taken (Hamed & Rao, 1998). If the values of $U_{F_k}$ and $U_{B_k}$ are greater than 0, that means the sequence shows an increasing trend; while if the values of $U_{F_k}$ and $U_{B_k}$ are less than 0, that indicates the sequence shows a decreasing trend. When they exceed the critical point, the increasing or decreasing trend is significant, and the range beyond the critical line is determined as a time region of a sudden change. If the intersections of the $U_{F_k}$ and $U_{B_k}$ curves occur between the critical lines, then the corresponding times of the points are the times of the mutation (Kendall, 1948; Mann, 1945).

The MK test result of the Arctic SIT from 2003 to 2017 is shown in Figure 18. From the UF curve, it can be found that the value of UF statistic in 2005 is greater than 0, indicating that the SIT increases slightly from 2004 to 2005. However, the values of UF statistic in other years are all less than 0, and the values of UF exceed the critical value of $-1.96$ after 2011, implying that the SIT has decreased significantly in the past 10 years. It is further discovered that the intersection of UF and UB curve is located in 2007, which indicates that the variation trend of the Arctic SIT changes suddenly in this year.

Figure 19 shows the variation of the annual average SIT. The SIT exhibits a slightly increasing trend from 2003 to 2007, about 0.003 m·year$^{-1}$. However, the SIT demonstrates a noticeable decreasing trend from
2007 to 2017, about $-0.013$ m·year$^{-1}$. Combined with the result of MK mutation test, it can be judged that the SIT changes from a slightly increasing trend to a significant decreasing trend in 2007. Some studies have found that the ice conditions are changed with a large melt event due to the anomalously high temperatures and southerly winds in the summer of 2007 (Comiso et al., 2008), resulting in a significant reduction in the average SIT (Giles et al., 2008). Therefore, the change of the Arctic sea ice in 2007 is particularly special, which has been clearly presented in this study.

The Arctic sea ice is undergoing unprecedented changes. The important geophysical parameters of sea ice (e.g., SIC, SIE, SIA, and SIT) can well reflect the change process of sea ice. Meanwhile, it is noteworthy that the melting and freezing of sea ice will be affected by several complicated factors, such as temperature, melt ponds, snow cover, and so forth (Polashenski et al., 2012; Wang, Yuan, et al., 2019; Webster et al., 2014). Combining with the Arctic temperature, Ke et al. (2013) concluded that the annual average sea ice outer line area of the Arctic from 2003 to 2010 was negatively correlated with the annual average temperature, and the correlation coefficient was $-0.81$, indicating that the change of temperature had a significant effect on the

![Figure 18. MK test of the Arctic SIT from 2003 to 2017.](image1)

![Figure 19. Variation of the Arctic average annual SIT from 2003 to 2017.](image2)
freezing and thawing of sea ice. Thus, the total amount of sea ice was affected, which was consistent with the results of model simulations (Holland et al., 2006). Higher temperature can lead to an increase in sea ice melting and a reduction in sea ice freezing, resulting in less sea ice coverage and more solar radiation absorbed by the Arctic. Therefore, the warming of the Arctic and the reduction of sea ice would affect each other (Serreze et al., 2000). Some researchers found that the sea surface temperature of the Arctic Ocean increased obviously after 2000 (Steele et al., 2008). In the summer of 2007, the sea surface temperature was as high as 5°C, which made the SIE and SIA reach a historical low value (Steele et al., 2008). At the same time, warmer oceans would delay the growing season of sea ice and prolong melting time (Serreze et al., 2007). The variation of the Arctic sea ice would also be affected by North Atlantic Oscillation and Arctic Oscillation (Kwok, 2000; Liu et al., 2004). In addition, the Arctic sea ice is affected by atmospheric circulation, wind field and other factors, and the drift phenomenon is more obvious and complex (Docquier et al., 2017). The combined effects of these factors have accelerated the melting of the side and bottom of the Arctic sea ice (Maslanik et al., 1996), resulting in a significant decrease in the Arctic sea ice in the past decade.

5. Conclusions

A good knowledge of the temporal variation trend of sea ice is important for climate change research and ship's navigation in polar regions. In this paper, the variation characteristics of SIC, SIE, SIA, and SIT in the Arctic are analyzed in detail based on the latest SIC and SIT data of ESA CCI from 2002 to 2017, which has rarely done in previous studies. The regional trends of SIC and SIT in the past 15 years were also investigated by dividing the whole Arctic into eight regions. To our knowledge, it is the first attempt to combining use of ESA CCI SIC and SIT data to analyze the variations of sea ice in Arctic. The main conclusions of this paper are as follows:

1. There are obvious interannual variation characteristics of the Arctic SIC, SIE, and SIA. The Arctic annual average SIC, SIE, and SIA show decreasing trends. Particularly, the SIC of the Kara Sea and the Barents Sea decreases the most significantly, reaching −1.11%·year⁻¹. The SIE decreases by 0.0592 × 10⁶ km² per year, and the SIA decreases by 0.0628 × 10⁶ km² per year.

2. The Arctic SIE and SIA vary seasonally. The SIE and SIA reach the minimum in September, which are 4.97 × 10⁶ km² and 3.96 × 10⁶ km², respectively, while they reach the maximum in March, which are 14.58 × 10⁶ km² and 13.35 × 10⁶ km², respectively. In addition, based on the results of regression analysis method, it is found that the decreasing trends of Arctic SIE and SIA are the most noticeable from July to October. The maximum variation trend of SIE and SIA is −1.06 × 10⁶ km²(10a)⁻¹ and −1.09 × 10⁶ km²(10a)⁻¹, respectively. During the period from April to May, the decreasing trends of the Arctic SIE and SIA reach the minimum, which are 0.19 × 10⁶ km²(10a)⁻¹ and 0.2 × 10⁶ km²(10a)⁻¹, respectively.

3. From the variations of the maximum value of Arctic SIE and SIA, it is concluded that the decreasing trends of SIE and SIA are very similar, which are −0.052 × 10⁶ km·year⁻¹ and −0.047 × 10⁶ km·year⁻¹, respectively. Likewise, the variation trends of the minimum values of SIE and SIA are similar, and the reduction rates are −0.112 × 10⁶ km·year⁻¹ and −0.109 × 10⁶ km·year⁻¹, respectively.

4. There is a seasonal difference in the variation trend of the Arctic SIT. The SIT is mainly between 1.4 and 1.9 m in winter, and it reaches the maximum (~1.82 m) and minimum (~1.41 m) in 2005 and 2013, respectively. The SIT is mainly between 0.9 and 1.4 m in autumn and it reaches the maximum (~1.37 m) in 2004 and the minimum (~0.98 m) in 2011. In addition, the Arctic SIT shows obvious decreasing trends, about −0.015 m·year⁻¹ in autumn and −0.018 m·year⁻¹ in winter, which is consistent with the average SIT in the whole year. Particularly, the SIT of the Hudson Bay decreases the most significantly, reaching −0.051 m·year⁻¹.

5. Based on the MK test of the average annual SIT in the Arctic region, it is discovered that the SIT mutates in 2007, from a slight increase in 2003–2007 to a significant decrease in 2007–2017.

In this paper, the latest ESA CCI SIC and SIT products are used to systematically analyze the spatial and temporal variation characteristics of sea ice in the Arctic region. However, though the ESA CCI data sets are very valuable, the time series of the ESA CCI sea ice products is not long enough due to the limitation of data source. Moreover, there are still some uncertainties and discontinuity in the ESA CCI data sets, particularly the SIT data since the snow depth data used in this product is based on a snow depth climatology which
sometimes may not represent the actual snow conditions. The accuracy of satellite SIC products is also found to be lower in summer and marginal ice zones (Ivanova et al., 2015). With the increasing abundance of remote sensing products and the refinement of retrieval algorithms, long time series and more reliable sea ice data sets can be obtained by integrating multisource sea ice remote sensing products in the future, and the physical reasons behind the changes of the Arctic sea ice should be analyzed and discussed in more detail. This will better serve the study of environmental change in the Arctic and even global climate change.

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