Polar sea ice characteristics determined from the ENVISAT RA-2 altimeter

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Abstract: The ground tracks of ENVISAT satellite cover the high latitude area that of 81.4° over north and south hemispheres, which provides a special approach to monitor sea ice using the RA-2 radar altimeter onboard the ENVISAT satellite. In this paper, we developed a method using the backscatter coefficients σ_0 measured by RA-2 to detect the monthly changes of sea ice extent and surface properties over Arctic and Antarctic oceans. Based on the difference of scattering characteristics over the sea water and sea ice surface, we demonstrate that setting the RA-2 sigma0 to 13db as a threshold can separate the sea ice from sea water efficiently. Except in the summer of each hemisphere, the sea ice boundaries derived from the RA-2 altimeter and from the radiometer data by NSIDC are closely consistent. Due to the lack of measurements over central areas of Arctic, we estimated the sea ice extent of Antarctic zones only. The result of extents shows that the altimeter gives higher values in summer (southern hemisphere) compared to the radiometer, which is related to the excellent capacity of altimeter to monitor the dispersed thin ice. In cold seasons with high sea ice concentration, the disagreements of sea ice extent are very low as the mean difference is just 0.17Mkm^2. Differences of polar ice properties, including surface moisture and roughness, were also studied, and result shows that the sea ice surface is dryer and rougher in Arctic than in Antarctic in the cold season.

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Key words: backscatter coefficient, satellite altimetry, sea ice extent, sea ice boundary

1 Introduction

The sea ice, covering a significant fraction (5%-8%) of the whole Earth's ocean area, has remarkable seasonal variations and has a special position in the climate science and ocean ecosystem[1]. In addition, the distribution of sea ice has remarkable impacts on the navigation, oceanic constructions and resource explorations. In recent years, the polar sea ice coverage, especially over Arctic, is changing with the increasing emission of greenhouse gases that caused global climate changes [2-4]. It is predicted that the summer sea ice in Arctic ocean will be disappeared by the end of this century, which may bring tremendous influence to the polar ecosystem and the global climate[5]. The increasing importance of monitoring the sea ice extent and its properties by satellites remote sensors has long been recognized in the global climate change research. However, remote sensors at visible and infrared bands are limited over polar areas due to the polar night phenomenon and other weather reasons. The regular task of monitoring the sea ice over polar oceans relies mainly on microwave sensors, including active and passive ones.

However, most previous studies about the sea ice detection were based on data from the passive microwave sensors [6, 7]. The satellite radar altimeters , which have been widely used in the earth science[8, 9], could measure the sea surface height, significant wave height and backscatter coefficients. The ability of satellite altimeter measurements to distinguish between the sea ice and water was first researched by Dwyer and Godin[10]. Later research by Rapley from the US Seasat satellite suggested that radar altimetry can provide a powerful means of global synoptic monitoring of the interaction between ocean and ice[11]. In addition some observations have demonstrated the sensitivity of altimeter data to areas of thin ice and leads and shown the usefulness of altimetry as an adjunct to visible or infrared imagery[10]. Most of the previous study indicated that the key approach of monitoring the sea ice by the altimeter is the calculation of related parameters from the waveforms. Ulander calculated backscatter from waveforms and classed ice on the basis of backscatter[12]. Drinkwater found the theoretically inverse relationship between the integral of waveform power and ice concentration borne out in measurements[13]. Chase performed a sophisticated analysis of waveform shape, and empirically link shape to different ice types and concentrations[14]. Similar work was also done by Yang who pointed that using the correspondence between the satellite pulse altimeter waveform and reflector property and with the advantages such as the ability to make large-scale, high-resolution and long-duration observations, the altimeter can be used to determine sea ice concentration on a large scale[15]. Some researchers also combined the passive and active microwave sensors to study the sea ice. Using synergy of data radar altimeter and radiometer instruments onboard the TOPEX/Poseidon satellite Kouraev discussed time and space variations of ice extent in the Caspian and Aral seas during 1992–2002 and discussed the impact of climate change on sea ice, but the draw back was the relatively coarse cross-track coverage of T/P[16]. Previous works also showed great potential for satellite-based altimetry for estimating ice thickness and snow depth [17-19]. However, the researches mentioned above were only focused on regional area and the characteristic of sea ice distributions over the whole polar areas has not been analyzed.

In this article we will evaluate the monthly extent of sea ice in 2011 over Arctic and the sea around Antarctica by the ENVISAT radar altimeter RA-2. The sea ice extents, calculated from the altimeter, are compared to the National Snow and Ice Data Center (NSIDC) values which come from the Scanning Multi-channel Microwave Radiometer (SMMR) instrument and from Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS) instruments. For the year of 2011, the sea ice extent values of NSIDC are only provided by SSMIS. In addition to the extent, the seasonal variations of the sea ice surface moisture and roughness are also analyzed.

2 Principal and Data

2.1 Research principal

The Basic principal of the satellite radar altimeter is that it emits microwave pulses to the earth surface at the nadir point and receives the backscattered signal which then forms the altimeter waveform. From the altimeter waveforms, the sea surface height (SSH) and significant wave height (SWH) can be obtained with high precision. Besides the SSH and SWH measurements, the backscatter coefficient σ_0, directly related to scattering characteristics of reflected surface, is the key measurement for altimetry land and ice applications [20, 21]. Based on the sea ice retracking method, σ_0 at Ku band retrieved from the waveform amplitude can be expressed in [14]:

$$\sigma_0 = \mathrm{Ku}_{\mathrm{scale}} + 10 * \log_{10} A_{Ku}^{OCOG} \tag{1}$$

$$A_{Ku}^{OCOG} = \sqrt{\frac{\sum_{n=1}^{N} y^4(n)}{\sum_{n=1}^{N} y^2(n)}} \tag{2}$$

where Ku_{scale} is a power scaling factor which is obtained at Level 1b data; A_{Ku}^{OCOG} is the amplitude derived by OCOG waveform tracking algorithm (Offset Centre Of Gravity); N is the number gates of the leading edge; $\mathrm{y}(n)$ is the normalized power of waveform at *n*th gate. For more information about the waveform tracking algorithm and the sigma0 calculation readers can refer to the ENVISAT RA-2/MWR Product Handbook [22].

The backscattering coefficient results from two contributions: a surface scattering echo that is the scattering by an interface between two different media and a volume scattering echo that is the scattering by particles contained inside a medium. These two contributions depend on the target characteristics, the radar footprint (depending on surface roughness) and the quantity of surface scatterers within the footprint[23]. For the sea ice surface, beside the surface scattering there also exists volume scattering due to the scattering particles such as bubbles and salt granules inside the sea ice. For the sea water surface there is only the surface scatterings. In addition, there are also significant differences between the surface roughness of the sea water and sea ice, which will widen the scattering difference further. During the ice melting and freezing process the surface moisture and roughness will be changed accordingly, which will also influence the scattering features of the sea ice and enable us to analyze the surface properties by σ_0. Figure 1 presents an example of altimeter waveforms over the Bering Strait where is a transitional zone at the measuring time. According to the features of waveform from sea ice and water[24] we can find that in the north of 59.2° N the waveforms of red color and with high peak values are reflected by the flat sea ice. In the south of 58.9° N the waveforms, in green color lines, are typical ocean reflection. Between 59.2° N and 58.9 ° N the waveforms, in blue color, are generated by the mixing of sea ice and water present irregular shapes.

2.2 Research data

In this research we used ENVISAT GDR (Geophysical Data Record) from circle 98 to 110 of the year 2011 to analyze seasonal variations of the sea ice extent and surface properties. Since the sea ice is our interest, we only use σ_0 at Ku band calculated by the sea ice retracking algorithm from GDR data. ENVISAT RA-2, a new generation of satellite radar altimeter compared to T/P, was launched in 2002 and was operated by ESA. The pulse repetition frequency of RA-2 is 1795 Hz, which is corresponding to an along-track width of approximately 390m. Before

October 2010 the period of ENVISAT is 35-days and the space between nearby crossovers at the equator is 80km. After October 2010 the orbit was shifted and the period was altered to 30 days. As figure 2 illustrated, compared to T/P or Jason-1/2 which only cover the earth between 66°S and 66°N, the ENVISAT radar altimeter can reach to 81.4° on both hemispheres and covers most of the polar sea area. Because the satellite covers over the southern hemisphere is similar to the northern hemisphere, so that it is not shown in figure 2. In additional, satellite ground tracks are much denser in polar areas, which is beneficial for polar ice detection. For example, the gaps between adjacent crossover points are about 40km, 30km and 15km at the latitude of 60°, 70° and 80°, respectively.

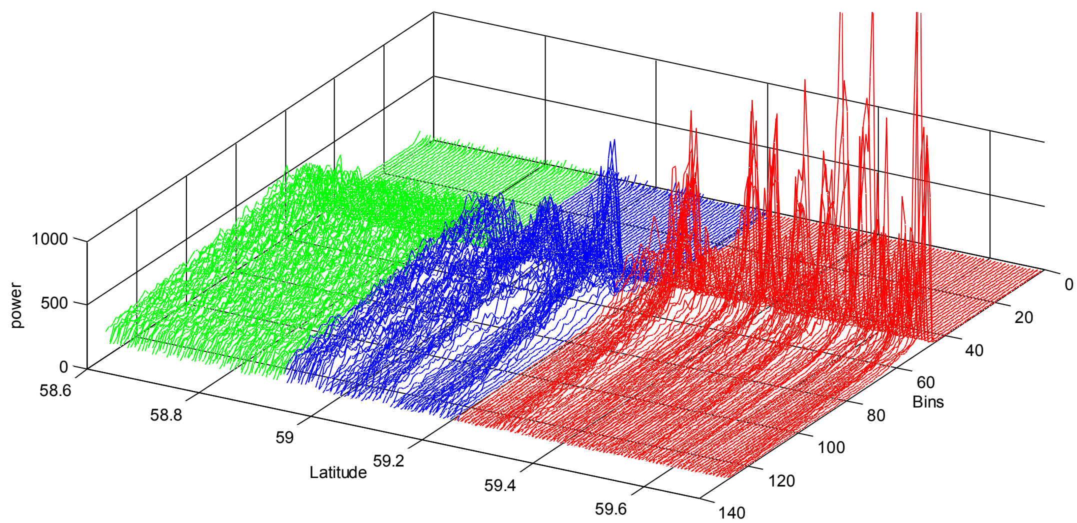

Fig.1 Typical satellite radar altimetry waveforms over the Bering Strait. The red color presents waveforms reflected by sea ice; the blue color presents waveforms reflected by the mixture of sea ice and sea water; the green color presents waveforms reflected by sea water.

The outline files of the monthly sea ice extent and the monthly extent values from NSIDC are used to valid our result. The format of outline files is the shapefile (shp) which are geospatial vector data and contain polylines of the sea ice boundary for both Northern and Southern hemispheres. The data files of the monthly sea ice extent are in ASCII text format, which are calculated from two intermediate versions of monthly gridded ice concentration fields: Sea Ice Index near-real-time monthly concentration fields and Sea Ice Index final monthly concentration fields. More information about the NSIDC data can be found at http://nsidc.org/data/docs/noaa/g02135_seaice_index.

Figure 3 shows the monthly spatial distribution of σ_0 of ENIVSAT RA-2 in 2011, which clearly demonstrates monthly changes of the sea ice cover over the whole year. The sea ice boundaries offered by NSIDC, based on passive microwave radiometers are also added to figure 3.

It is manifest that the sea ice and water can be separated clearly by σ_0 because of the significantly high σ_0 values over the sea ice and relatively low σ_0 values over the sea water. As the sea ice cover changes by seasons in two polar zones, the seasonal variations of the sea ice distribution can be monitored accordingly. Except the summer season (December, January and February for the southern hemisphere; June, July and August for the northern hemisphere), the altimetry and NSIDC boundaries are remarkably consistent. The primary reason to the summer diversity could be that altimeters are more sensitive than radiometers to the thin and small-scale ices which are discretely distributed on the sea in the warmer season[24]. In addition, figure 3 indicates that the differences last longer and wider in the Arctic area, which proves that there exists more discrete sea ice in warmer seasons. This phenomenon is consistent to the fact that the weather is colder in Arctic sea than Antarctica in summer.

Figure 3 also shows that over Arctic and Antarctic oceans the sea ice melts rapidly in summer. In the Northern hemisphere summer the sea ice closing to the

Arctic pole can be survived due to the extremely cold temperature. However, around the Antarctica the sea ice is almost vanished except some small regional areas such as the Weddell Sea and Ross Sea. Nevertheless obviously affected by the global climate change, mainly the global climate warming, the extent of Arctic sea ice in summer frequently refreshed its minimum records and will be probably vanished in the near future according to related researches [5].

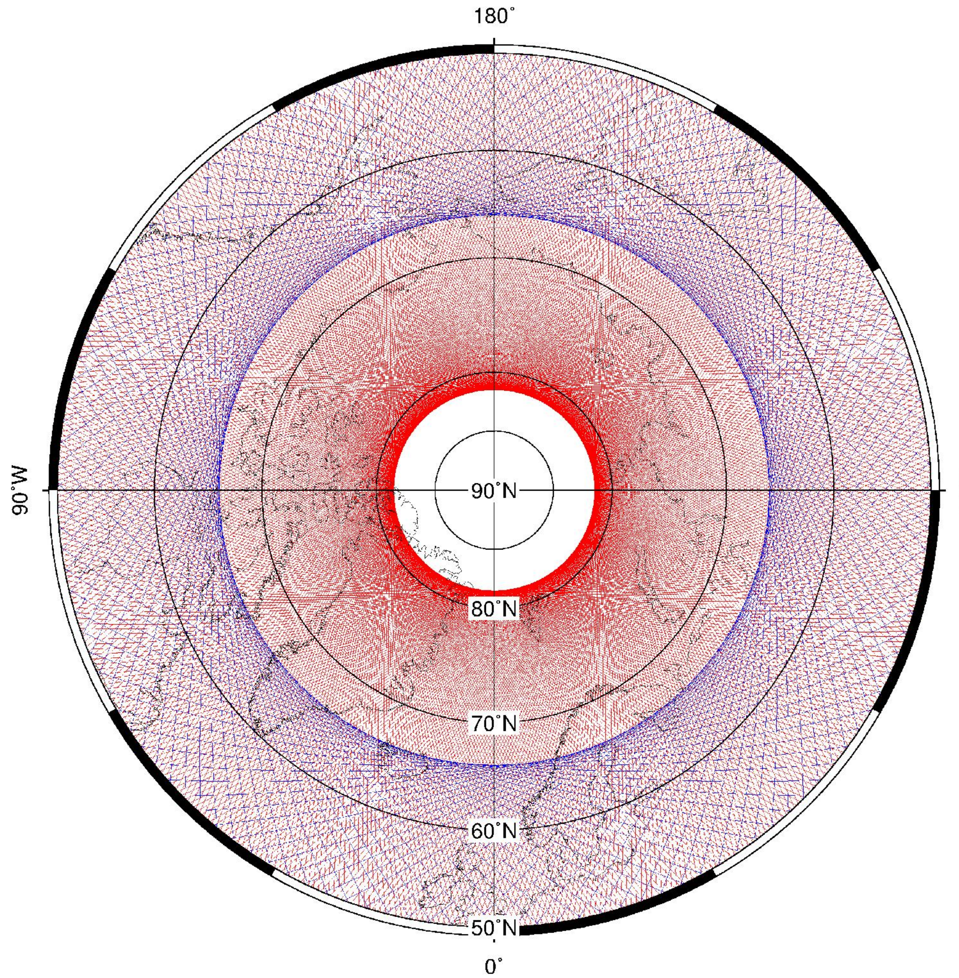

Fig. 2 Comparison of ground tracks between ENVISAT (red) and TOPEX/Poseidon, same orbits as Jason-1 and Jason-2, (green) over the northern hemisphere.

3 Polar sea ice characteristic analysis

In addition to sea ice boundaries, altimeter measurements are also used to calculate the sea ice extent around Antarctica. Data from the NSIDC are used to validate our result. Because accuracy tends to be best within the consolidated ice pack where the sea ice is relatively thick and the ice concentration is high. So we use the NSIDC sea ice outline of September, a relatively stable month for sea ice cover, to track our sigma0 grid data outside and inside the outline with different distances, and we get the average values for the track data. The statistic information indicates that sigma0 values are between 10-11db over sea water 50 km far from the sea ice boundary and sigma0 values are between 11-12db over the sea water less than 50 km away from the sea ice boundary. Along the boundary the sample result for sigma0 value is about 13db and inside the boundary the sigma0 values is about 17db over the sea ice 5km inside the boundary. So we choose 13 db as the sigma0 threshold value for calculating the sea ice extent. Figure 4 shows the comparison of monthly sea ice extents between results of the NSIDC and the altimeter. Table 1 presents the extents in detail. The average difference is 0.80Mkm^2 and the standard deviation of the difference is 1.35Mkm^2. The maximum of the difference is 4.42Mkm^2 that appears in January while the minimum is 0.03Mkm^2 that appears in April. However, the extent differences in winter (from June to September) are relatively low with the mean value of only 0.17 Mkm^2. The significant difference in summer (December, January and February) is shown in fig4 which is probably caused by the sensitive capacity of altimeter and radiometer to the discretely floating sea ice. While excluding summer data the average of difference is 0.20Mkm^2 and the standard deviation is 0.50Mkm^2.

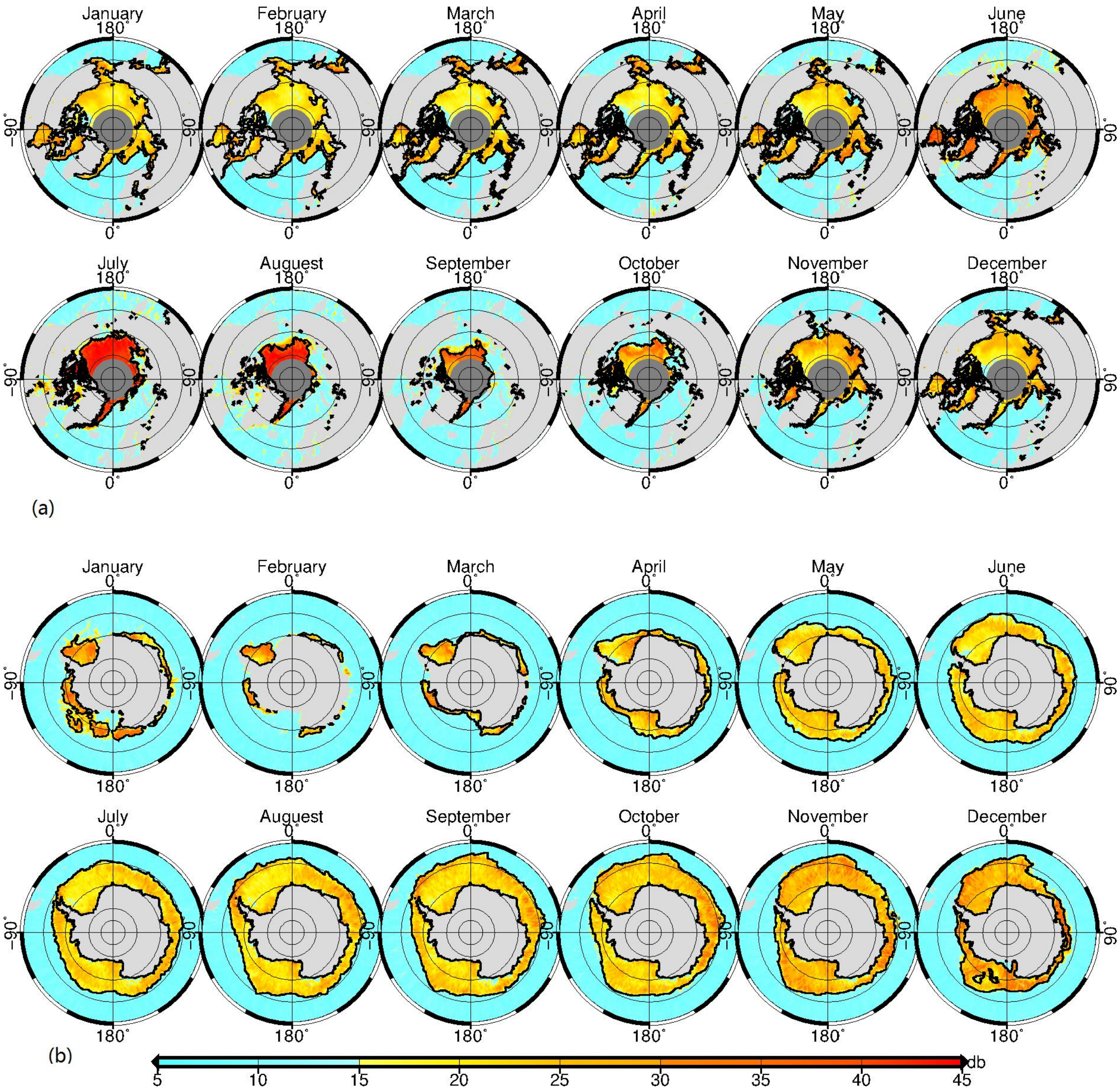

Fig. 3 Distribution of ENVISAT RA-2 σ_0 at the Ku band over Arctic (a) and Antarctic (b) and sea ice boundaries from NSIDC (in black line) in year 2011.

In additional to the applications on the sea ice boundaries and extents, the backscatter coefficients also reflect the physical factor of the sea ice such as the surface moisture and roughness. The monthly averaged σ_0 values of the sea ice are calculated and time series are shown in figure 5. Over the Arctic the σ_0 shows a significant rise since June owing to the surface snow melting which increases the surface moisture, and the σ_0 culminates in July with the average value of more than 30db which is mainly caused by the melting water ponds on the sea ice that enhances the reflecting ability of target surface to return power to the radar altimeter.

Then it decreases but still keeps high due to the relatively high surface moisture until September. After October the new ice will be formed and the sea ice distribution will be larger in Arctic which is also shown in figure 3. For the sea ice around Antarctica, however, the σ_0 values are relatively flat, which means that physical characteristics of the sea ice surface do not change significantly in the whole year. And this is consistent to the fact that over the Antarctica sea ice there does not have many water ponds and the surface moisture rise is not significant due to the quick melting of sea ice.

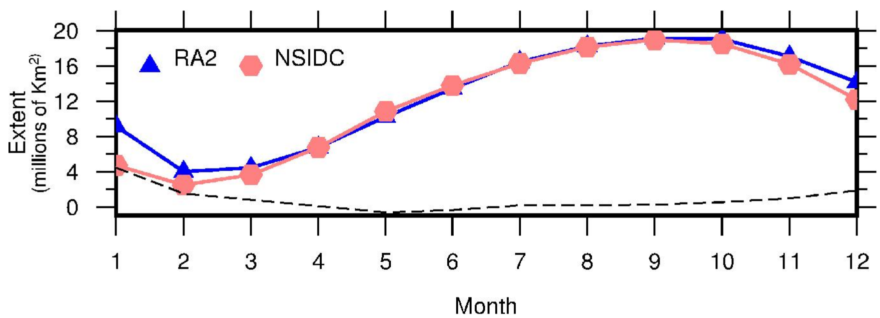

Fig. 4 Time series of monthly average extents of Antarctic sea ice in 2011 determined by RA-2 and microwave radiometers. The dash line is the difference value of RA-2-NSIDC.

Table 1 Statistic of the sea ice extent by RA-2 and NSIDC (unit: million of km^2)

Month / Resource	1	2	3	4	5	6	7	8	9	10	11	12
RA-2	9.10	3.97	4.42	6.77	10.21	13.40	16.44	18.23	19.11	19.00	17.07	14.07
NSIDC	4.68	2.47	3.61	6.74	10.82	13.76	16.28	18.09	18.90	18.48	16.15	12.20
RA2-NSIDC	4.42	1.50	0.81	0.03	-0.61	-0.36	0.16	0.14	0.21	0.52	0.92	1.87

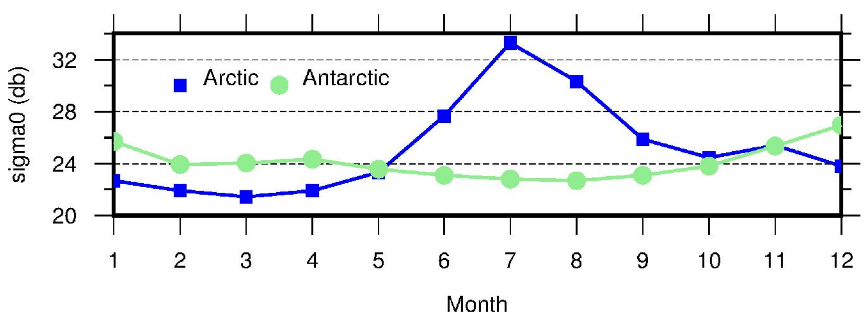

Fig. 5 Time series of monthly average values of backscatter coefficients over two polar sea areas.

4 Conclusions

In this paper, the backscatter coefficient σ_0 derived from an active microwave senior RA-2, a radar altimeter carried by ENVISAT satellite, was used to research the sea ice distribution features. Compared with the NSIDC sea ice data, RA-2 presents a powerful ability to detect monthly boundaries of the sea ice. Over the two polar areas the boundaries of the sea ice are closely consistent with the NSIDC data. But during the summer when the sea ice melts quickly there exist some larger differences. In order to evaluate the accuracy of the altimetry method we calculated monthly extents of the sea ice. Because there has data gap in the central Arctic, we only evaluate the Antarctic sea ice extents. The altimetry result closely agrees with the NSIDC data in the whole year except the southern hemisphere summer, which mainly caused by the discrete thin ice and the quickly melting speed. The average difference of the sea ice extent between the altimetry and NSIDC result is $0.80Mkm^2$ and the standard deviation of the difference is $1.35Mkm^2$. But when excluding the summer the average of difference is just $0.20Mkm^2$ and the standard deviation is $0.50Mkm^2$. The accuracy tends to be best within the consolidated ice pack where the sea ice is relatively thick and ice concentration is high. The average difference in southern hemisphere winter (from June to

September) is only 0.17 Mkm^2. In summer the radar altimetry presents higher values because it has the relatively small footprint and is more sensitive to the discrete ice than radiometers. In addition, the moisture changes of the sea ice surface can also be illustrated by σ_0 which is sensitive to the moisture of reflected surface. It reveals that the sea ice is wetter over Arctic than Antarctic oceans in the warm season and the sea ice is drier in over Arctic than Antarctic oceans in the cold season.

In the future research, obtaining the sea ice heights by satellite radar altimeters will be an interesting and challenging subject which could provide the variations of the sea ice volume caused by the climate change. Although the ENVISAT was already retired, the new altimeters, i.e., Chinese HY-2 and India–French Saral/AltiKa, can still provide active microwave measurements over oceans of high latitude where sea ice covers.

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