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The estimate of sea ice resources quantity in the Bohai Sea based on NOAA/AVHRR data

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Abstract
The research on sea ice resources is the academic base of sea ice exploitation in the Bohai Sea. According to the ice-water spectrum differences and the correlation between ice thickness and albedo, this paper comes up with a sea ice thickness inversion model based on the NOAA/AVHRR data. And then a sea ice resources quantity (SIQ) time series of Bohai Sea is established from 1987 to 2009. The results indicate that the average error of inversion sea ice thickness is below 30%. The maximum sea ice resources quantity is about 6×10^9 m^3 and the minimum is 1.3×10^9 m^3. And a preliminary analysis has been made on the errors of the estimate of sea ice resources quantity (SIQ).

Key words: sea ice in the Bohai Sea, sea ice resources quantity, NOAA/AVHRR, error analysis

1 Introduction

In winter, the Bohai Sea is the main freezing area in China. The existence of sea ice in winter has a negative impact on sea transport and production. Then sea ice engineering, sea ice disaster prevention and reduction are the main research on sea ice in the Bohai Sea (Yang, 2000; Ding, 2000; Zhang and Zhou, 2003; Guo et al., 2008). In recent years, due to the serious shortage of freshwater resources in the Bohai Sea region, the development of the Bohai Sea sea ice as freshwater resources has become a new research direction (Wang et al., 2003; Shi et al., 2002).

The development and utilization of sea ice as freshwater resources depend largely on the research of desalination technology and the evaluation of the sea ice reserves. The research of Chen and others (Chen et al., 2004; Xu et al., 2006; Xu et al., 2007) pointed out that the use of gravity or centrifugal desalination can make the sea ice of salinity 6–11 into freshwater. This shows that the use of sea ice as freshwater resources is technically feasible. The evaluation of the sea ice reserves contains two parts of estimates and analysis, one is the quantity and quality of the sea ice resources, the other is the spatio-temporal distribution. The two parts are the academic bases which determine whether the sea ice has the value of development.

The quantity of the sea ice resources depends on the area and the thickness of the sea ice. Based on the good relationship between the area of sea ice and the sea ice severity level in the Bohai Sea, Li et al. (2007) used the sea ice area to represent the quantity of sea ice in the Bohai Sea and then made an analysis of the interannual variation of the sea ice quantity. Guo et al. (2007) studied the sea ice area of the Bohai Sea by means of remote sensing. They estimated the precis-

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ion of the sea ice area from TM, MODIS and NOAA, and then built a sea ice area series of 1996–2005. Wu et al. (2006) and Huang et al. (1992) studied the thickness of sea ice in the Bohai Sea and built the relationship between the sea ice thickness and the reflectance based on piecewise-linear method and data from several tests of the ice thickness and the reflectance. Shi et al. (2002) used remote sensing methods to estimate the sea ice area and thickness. The thickness of sea ice can be simplified to two types (fast ice and drift ice) and one type with only one value based on experiences. Then they estimated the sea ice resources of the Bohai Sea in the winter of 2000. Xie et al. (2003) made use of remote sensing technology to estimate the sea ice area and thickness of the Liaodong Gulf in the Bohai Sea. They built a sea ice thickness inversion model based on remote sensing data and made a detailed analysis of the sea ice distribution in the Liaodong Gulf.

We can see from the above presentation that the quantity estimates of sea ice resources in the Bohai Sea have certain limitations. For example, the sea ice area and thickness can't be combined, simplify the sea ice thickness to estimate the sea ice quantity, only estimate part of the sea ice quantity (the Liaodong Gulf) in the Bohai Sea. In addition, these researches do not have the field investigation data to evaluate the precision level of the results. Therefore, it is important to establish a more practical method to estimate the sea ice area and thickness in the Bohai Sea.

Considering the above problems and shortage in the sea ice quantity (SIQ) estimates in the Bohai Sea, this paper comes up with a method to estimate the SIQ based on NOAA/AVHRR data (1987–2009). Then a time series of the SIQ in the Bohai Sea is built. And this paper makes an error analysis of the results based on field surveys and experiments.

2 Definition of the sea ice resources quantity

The sea ice resources contain two parts: the SIQ and the sea ice quality. The SIQ is the product of the sea ice area and the sea ice thickness. The sea ice in the Bohai Sea is annual sea ice in winter. So the sea ice has a growing process every year when the temperature below the freezing point. Then the SIQ will follow the pattern of 'zero-increase-maximum-decrease-zero'. This shows that the SIQ is changing not only in different winters, but also in different time in one winter. Then the SIQ has two definitions: (the maximum SIQ) and the average SIQ for the whole freezing period in one winter (the average SIQ). The maximum SIQ tells the maximum SIQ in one winter and reflects the cold degree of the winter. But the average SIQ gives an average state of the sea ice in the Bohai Sea. The long period of freezing and melting may hide the maximum SIQ in the winter. And it is hard to define the beginning day and the last day of the sea ice when there is only little sea ice. So we use the maximum SIQ of a day in one winter to represent the SIQ of the year in this paper.

3 Data and methodology

The area of the Bohai Sea is approximately 7.7 km^2. Taking into account current amount of labor force, material resources, financial support and technology, the most powerful and rapid method of detecting the SIQ is undoubtedly satellite remote sensing. Though several types of satellite data can be used to estimate the SIQ at present, those from NOAA/AVHR are considered the most effective to obtain long-term series data.

3.1 *Data source*

The RS data in this paper are NOAA/AVHRR images with a time series of 22 a (1987–2009). There are totally 1 200 images available which are from Webpanda network and the National Satellite and Meteorology Center (NSMC), State Meteorological Administration of China. All the images have been processed through basic geometric rectification and data calibration. Then the products of sea ice albedo and brightness temperature data are obtained. Neglecting the interference of clouds and nights, we finally use 580 NOAA/AVHRR images.

3.2 *Methodology*

3.2.1 *The subdivision of study area*

The water quality of the Bohai Sea varied with the diversity of coastal geology, hydrology, land use and human activities alongside the seashore, and specially, the sands in the sea ice have a great influence on area extracting and thickness inversion. In order to eliminate the impact of the water quality and guarantee the unity of the same subregion, this paper divided the Bohai Sea into five subregions based on the discrepancy analysis of sea ice spectrum between different subregions. And then the sea ice area extraction and the thickness inversion are done in each subregion.

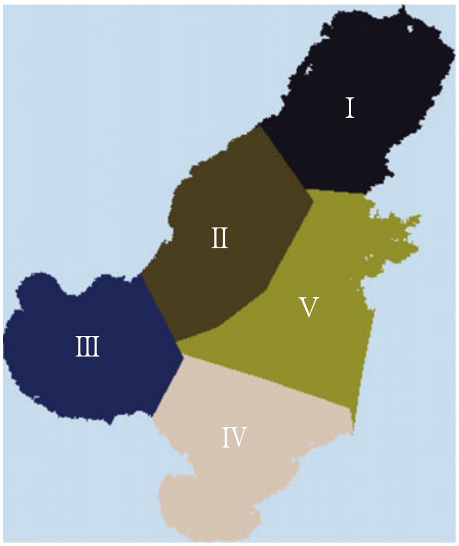

Fig.1. The five subregions in the Bohai Sea.

3.2.2 *The extraction of sea ice area*

Geographic and geometric rectifications were firstly operated on NOAA/AVHRR data, and then continent and ocean were segregated by means of GIS technique. Then the remote sensing data were simplified by removing continental information. In addition, the sea ice area of every pixel was calculated based on the spectrum differences of sea ice and seawater.

3.2.3 *The thickness inversion model of sea ice*

The inversion of the sea ice thickness is an important and difficult problem on estimating the SIQ. Inversion methods proposed in recent years include the thickness calculation with temperature data, albedo, thermodynamic relation and numerical model (Grenfell and Maykut, 1977; Grenfell, 1979, 1983, 1991; Allison et al., 1993; Unterstainer,1964). Based on the good correlation between the sea ice thickness and the sea ice albedo (Grenfell and Perovich, 1984), for one-year ice or ice less than 1 m thick, the RS inversion model has a temporal and spatial advantage. According to the relationship between the sea ice thickness and albedo, taking the exponential relation (Grenfell and Perovich, 1984) as a mathematical model, this paper comes up with a RS inversion model of the sea ice thickness in the Bohai Sea:

$$\alpha_{\mathrm{h}} = \alpha_{\max}[1 - k \cdot \exp(-\mu_\alpha h)], \tag{1}$$

where α_{h} is the sea ice albedo of the solar shortwave radiation and it varies from the ice thickness; $\alpha_{\max}$ is the albedo of the infinity ice thickness; α_{sea} is the albedo of the seawater; k is related to the $\alpha_{\max}$ and α_{sea}; μ_α can be calculated by the field experiment in the study area; and h is the sea ice thickness.

In Eq.(1), the values of $\alpha_{\max}$ and α_{sea} are 0.7 and 0.1. k equals to $1 - \alpha_{\mathrm{sea}}/\alpha_{\max}$ and $\alpha_{\mathrm{h}} = 0.423n_1 + 0.577n_2$ where n_1 and n_2 are the value of 1st and 2nd NOAA/AVHRR channel (Ma, 1977).

The coefficient μ_α is related to satellite data sources and the sea conditions. And the values are different in different studies (Flato and Brown, 1996; Lindasy and Rothrock, 1993, 1994; Maykut, 1982; Maykut and Perovich 1987; Ebert et al., 1995). Due to different conditions in the Bohai Sea, μ_α should be different in each subregion. In theory, we can significantly improve the accuracy of the inversion model to estimate the ice thickness by using more values of μ_α in different time and subregions. But this job is hard and meaningless to the inversion model. And it is not conducive to test the stability of the inversion model. To solve these problems, considering the measured ice thickness, the estimated ice thickness, the average ice thickness and its spatial distribution, this paper gives the μ_α for the five subregions (Table1). Then the SIQ and its distribution are carried out based on Eq. (1).

Table 1. The value of μ_α in different subregions

	Subregion				
	I	II	III	IV	V
μ_α	2.659 9	2.659 9	5.803 5	2.659 9	5.803 5

4 Results and analysis

4.1 *The distribution of sea ice*

Figure 2 is the distribution of the estimated sea ice thickness in the Bohai Sea selected from the 580 images. It is showed that the sea ice of the Bohai Sea is mainly located in the Liaodong Gulf and the Bohai Gulf. The average thickness of sea ice is about 10–20 cm, with the maximum of more than 40 cm. Such distribution of the sea ice thickness is basically the same as the conclusion of Yang (2000) whose description about the distribution characteristics of the Bohai Sea based on the materials of the 1980s.

4.2 *Error analysis of the sea ice thickness inversion*

Physical basis of Eq. (1) is the exponential relation between the thickness and albedo of sea ice. The studies by Xie et al. (2006) suggest that there is certain correlation between primary reflectance peak and the thickness of the sea ice of the Bohai Sea. If the sea ice contained sands and some other impurities in the

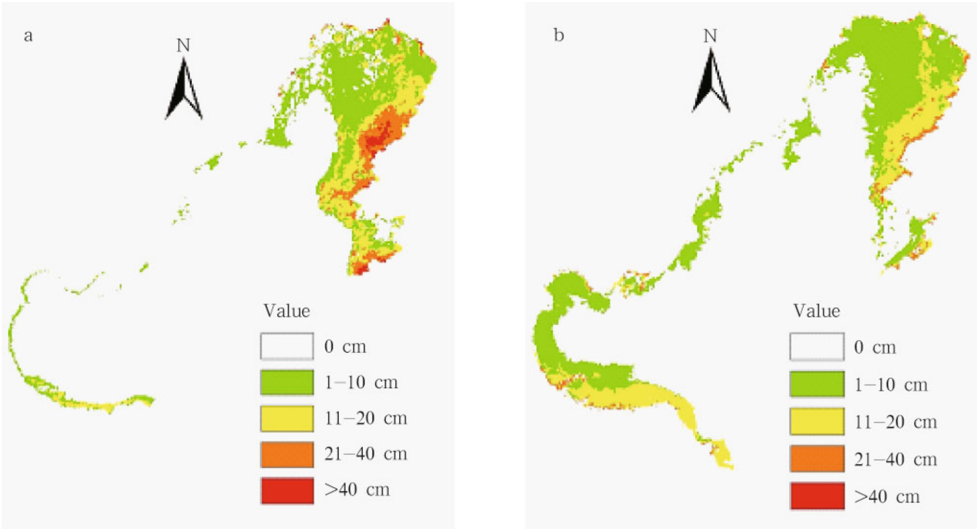

Fig.2. The distribution of the estimated sea ice thickness. a. 4 February 2003 and b. 31 January 2008.

sea ice, such correlation could be interfered and led to the phenomenon as the same thickness with different spectra and the same spectrum with different thickness. So the inversion of the sea ice thickness of the Bohai Sea will inevitably cause error to a certain extent. In order to test the accuracy of the RS inversion model of the sea ice thickness, the authors analyzed the error of the inversion model in this paper based on the data of the sea ice thickness obtained in the field investigation.

We investigated sea ice in January 2005, March 2006, January 2007, January and February 2008 respectively. The first three investigations focused on the coast of the Liaodong Gulf, and the last two investigations involved the maritime investigation of the Bohai Sea (Fig. 3). Comparing the sea ice thickness through the investigation with the estimated value from the inversion model, we got the error of the inversion of the sea ice thickness shown in Tables 2 and 3.

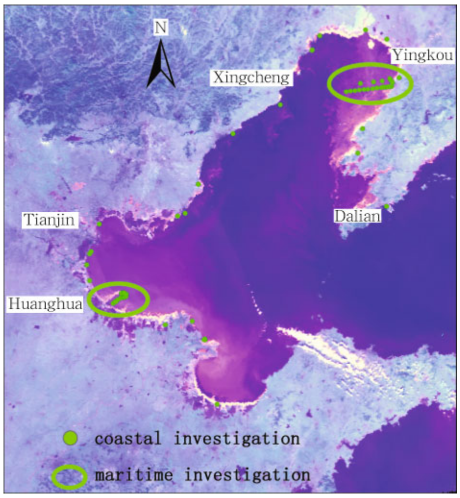

Fig.3. The field investigation of sea ice of the Bohai Sea in 2008. The coastal investigation lasts from 31 January to 21 February.

Table 2. Thickness error of the inversion model in 2005 and 2006

Date	North latitude	East longitude	Actual thickness/cm	Estimate thickness/cm	Error (%)
30 Jan. 2005	40°18′14″	121°50′38″	16.0	20.0	25.0
	40°18′54″	121°44′31″	8.0	6.0	25.0
	40°19′04″	121°34′04″	16.5	19.0	15.2
	40°18′50″	121°29′32″	7.0–22.0	12.0	0
	40°19′12″	121°21′35″	5.0–25.0	17.0	0
	40°19′21″	121°12′06″	12.0–20.0	14.0	0
2 Mar. 2006	40°17′22″	122°04′34″	10.0	8.0	–20.0
	40°16′59″	122°02′58″	11.0	9.0	–18.2
	40°20′28″	121°58′07″	15.0	19.0	26.7
	40°24′10″	121°53′06″	60.0	64.0	7.0
	40°25′47″	122°00′35″	10.0	7.0	–30.0
	40°20′15″	122°03′31″	5.5	7.0	27.2

Notes: Because of the image missing of 30 January 2005, the substitute data of the sea ice thickness are those of 31 January 2005.

Table 3. Thickness error of the inversion model in 2007 and 2008

Date	North latitude	East longitude	Actual thickness/cm	Estimate thickness/cm	Error (%)
29 Jan. 2007	40°20′52″	121°57′39′	5.0–8.0	9.0	12.5
	40°22′09″	121°55′39″	7.0	9.0	28.6
	40°26′45″	121°49′49″	8.0	10.0	25.0
	40°28′11″	121°46′52″	7.0–25.0	8.0	0
	40°34′05″	122°0′47″	8.0–10.0	12.0	20.0
31 Jan. 2008	38°20′35″	117°57′17″	0	11.0	∞
	38°21′46″	118°0′55″	20.0	9.0	–55.0
	38°21′52″	118°02′25″	7.2–30.0	29.0	0
	38°22′04″	118°03′32″	15.0–20.0	14.0	–6.7
	38°24′32″	118°01′12″	20.0–30.0	30.0	0
13 Feb. 2008	40°15′59″	122°02′13″	23.0	33.0	43.4
	40°15′59″	122°0′46″	20.0	21.0	5.0
	40°15′59″	121°59′36″	30.0	26.0	–13.3
	40°16′05″	121°49′32″	12.0	15.0	25.0
	40°15′56″	121°46′02″	12.0	19.0	58.3
	40°16′01″	121°30′57″	3.5	6.0	71.4

As can be seen from Tables 2 and 3, there are certain discrepancies between the estimated sea ice thickness and the sea ice thickness of the investigation with the maximum error of 71.4% and minimum of 0. The average error between the investigation data and the estimated ones is of great difference, which is 10.9% in 2005, 21.5% in 2006, 17.2% in 2007 and 29.8% in 2008. It should be noted that the field investigation of the sea ice thickness is represented by average value around the ship. If the sea ice thickness has great difference around the ship, the investigation data of the sea ice thickness is represented by a range of the thickness.

4.3 *Time series of the SIQ in the Bohai Sea from 1987 to 2009*

Calculating the sea ice thickness and the sea ice area selected from the 580 images of the Bohai Sea, we have chosen the maximum SIQ of 1d in every winter to represent the SIQ of that year. Then the time series of the SIQ of the Bohai Sea from 1987 to 2009 has been established (Fig. 4).

It is shown in Fig.4 that during the 21a from 1987 to 2009, the SIQ of the Bohai Sea is a single-peak on the whole, and that the year between 2000 and 2001 is a high value stage with a maximum of 5.6×10^9 m^3, while the years from 2001 to 2007 are a stage of low value stage with a minimum of 1.3×10^9 m^3. Furthermore, it is a minor fluctuation of the SIQ from 1987 to 1999, and a major fluctuation from 2000 to 2008. In addition, there are also some minor instabilities within the single-peak change. For example, there are local valley values in 2001–2002 and 2006–2007.

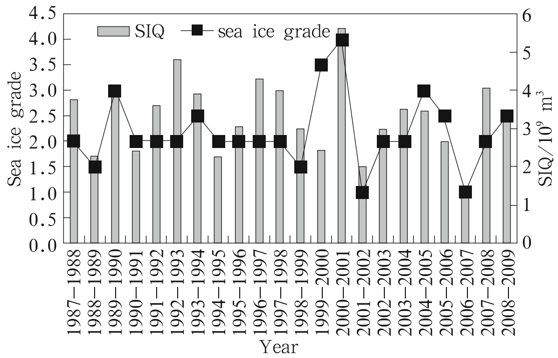

Fig.4. The SIQ time series and sea ice grade of the Bohai Sea from 1987 to 2009. The sea ice grade data come from the State Oceanic Administration of China.

5 Conclusions and discussion

5.1 *Conclusions*

(1) Considering the ice-water spectrum differences and the relationship between the sea ice thickness and the sea ice albedo, this paper comes up with a sea ice thickness remote sensing inversion model based on NOAA/AVHRR data. We can extract the sea ice thickness of each pixel (1.1 km×1.1 km) based on the model, so the SIQ in the Bohai Sea can be estimated efficiently. Compared with the data of field experiment, the average error of the results from the sea ice thickness inversion model is generally below 30%. At present, this method is practical and can be used to monitor the change of the SIQ in the Bohai Sea.

(2) Based on the processing and analysis of the NOAA/AVHRR data (580 images), this paper establishes a SIQ time series (1987–2009) of the Bohai Sea.

The results show that the maximum SIQ is about 6.0×10^9 m^3 and the minimum is 1.3×10^9 m^3. The SIQ in the Bohai Sea has minor fluctuation in period of 1987–2000 while major fluctuation in 2001–2009.

5.2 *Discussion*

5.2.1 *For the sea ice quantity (SIQ)*

In this paper, the SIQ time series (1987–2009) is established based on 580 images (selected from 1 200 NOAA/AVHRR images). And we defined the day with the maximum SIQ as the SIQ of the year. There are some limitations (data source, cloud cover, the imaging time, the impact of weather, etc.) for the NOAA/AVHRR data we have got. Additionally, the image number of each year is different and the time distribution (in terms of the whole ice period) is not consistent (Table 4). So the maximum SIQ may be not the maximum one of the year. However, it is a reference for the SIQ study in the Bohai Sea at the present stage.

Table 4. The distribution of NOAA/AVHRR data (580 images)

	1987–1988	1988–1989	1989–1990	1990–1991	1991–1992	1992–1993	1993–1994
Image number	16	30	27	24	6	21	39
	1994–1995	1995–1996	1996–1997	1997–1998	1998–1999	1999–2000	2000–2001
Image number	34	56	44	24	32	19	18
	2001–2002	2002–2003	2003–2004	2004–2005	2005–2006	2006–6007	2007–2008
Image number	37	43	40	23	20	11	16

As the heat (temperature) and power (currents, tides) conditions change, the sea ice is a dynamics changing process. When the seawater temperature below the freezing point (−1.4°C) in the Bohai Sea, the sea ice will freeze again after they are taken away. It means that the sea ice can regenerate in the winter. Considering the case of sea ice renewable (Gu et al., 2003), the sea ice will be much greater than the estimate number in this paper.

The sea ice in the Bohai Sea reduced gradually in these years due to the global warming. The SIQ time series in the Bohai Sea (only 21a) do not mean the long time changes of the sea ice (50–100 a). According to the literature (Ding, 2000), there have been three severe freezing periods in the Bohai Sea (1936, 1947 and 1969) since 1936. With the exception of the central part and the Bohai Sea Straits, the whole area was covered by sea ice. And there was ice hummock (2–4 m high) in the river mouth. So the SIQ should be much more than it is now.

5.2.2 *For the error of the estimated SIQ*

Here are the main causes for the sea ice estimated error:

(1) The spatial resolution of NOAA/AVHRR images is 1.1 km×1.1 km. It is hard to differentiate sea ice and seawater in one pixel. And we can not tell the differences of the sea ice thickness in an area smaller than 1.1 km×1.1 km. So the estimated thickness of the model is an average thickness for one pixel.

(2) There is little fast ice in the Bohai Sea and most of the ice is drift ice. The drift ice is changing all the time with the effects of current and winter monsoon. In theory, the field work only tells sea ice conditions of a certain time and space. Once a little change of the time (for example, a few minutes), the sea ice conditions may be different. Considering the sailing conditions and the cost, it is difficult to achieve large-scale, multipoint field observations at the same time. So we used a single ship to investigate the sea ice. Then the match of the investigated data and the remote sensing data may have some problems which will have an impact on the error analysis of the ice thickness.

(3) There is a relationship between the clean level ice and the ice albedo. According to certain study (feng et al., 2006), the albedo has a nonlinear, ladder-like growth with the increase of the sea ice thickness. The same thickness of sea ice may have different reflectance values. It is a certain range of reflectance (Fig. 5). For nonclean level ice, there are the problems of the same thickness with different spectra and the same spectrum with different thicknesses. In fact, there is little clean level ice in the Bohai Sea. The sea ice is not only with a certain degree of sands, but also with an uneven surface. Considering all the conditions, it is hard to reflect the sea ice thickness and albedo by a simple remote sensing inversion model. More detailed work should be done for the inversion model.

The coefficient μ_α in Eq. (1) depends on the time, sea conditions, and the sands in the sea ice and so on. The value of μ_α defined by experience in this paper may be not the best one, though the estimated thickness of the inversion model can match most of the field investigation data. It is necessary to define a rational coefficient based on more theory analysis and field experiments.

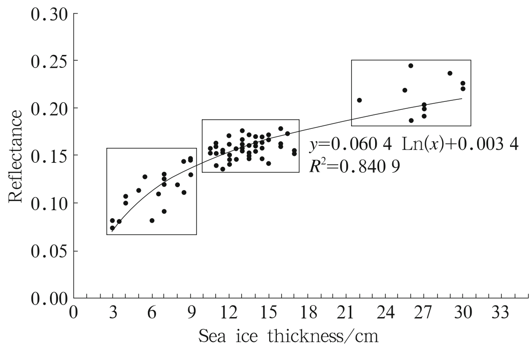

Fig.5. Main reflectance value of the spectrum with the changes of ice thickness (Xie et al., 2003; Feng et al., 2006).

5.2.3 *For the selection of remote sensing data*

We select the NOAA/AVHRR data to estimate the SIQ in the Bohai Sea, because it is old and available which is helpful to establish a long time series of the SIQ. However, the low spatial resolution of NOAA/AVHRR data has some problems to differentiate sea ice and seawater in one pixel. The use of the MODIS, ocean satellite, radar and other remote sensing information can improve the estimated accuracy (especially for the sea ice area). This is a main direction to estimate the SIQ in the Bohai Sea.

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