Using MODIS data to estimate sea ice thickness in the Bohai Sea (China) in the 2009–2010 winter

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1 To estimate sea ice thickness over a large spatial scale is a challenge. In this paper, we propose a direct approach to effectively estimate sea ice thickness over a large spatial area of the Bohai Sea using EOS MODIS data. It is based on the model of an exponential relation between albedo and thickness of sea ice. Eighteen images of EOS MODIS L1B data in the 2009–2010 winter were used to estimate the sea ice thickness and to monitor its spatiotemporal evolution in the Bohai Sea. The estimated thickness results are in accordance with results based on the Lebedev and Zubov empirical models as well as the forecasting data from the National Marine Environmental Forecasting Centre of China. Model correlation coefficients ($R^2 = 0.864$ and 0.858) and close similarity in thickness prediction attest to the reliability and applicability of the proposed method. The average ice thickness of the whole Bohai Sea ranged from 3 to 21 cm, with an estimated maximum about 40 cm in Liaodong Bay. Multiple-temporal maps of sea-ice thickness show that the sea ice formed initially along the coastline, and gradually expanded away from the shore. Sea ice first appeared in the Liaodong Bay, and hugged the coast southwards to Bohai and Laizhou Bay. During melting the inverse sequence occurred. Our results also show that sea ice coverage and thickness are significantly correlated with the value of $\theta$, the difference between cumulative FDD (Freezing Degree Days) and TDD (Thawing Degree Days).


1. Introduction

[2] Sea ice appears in the polar and high-latitude seas with typical seasonal and annual variations. It has a dramatic impact on marine hydrology, ocean circulation, and ocean-atmosphere-ice interactions [Barry et al., 1993; Dickson, 1999], as well as human activities [Bai and Wu, 1998]. The Bohai Sea in North China freezes to varying degrees every winter for about 3–4 months. The winter of 2009–2010 was the most severe in nearly 30 years. During this winter, the Bohai Sea experienced severe ice accumulation being densely and with uneven thickness distributed along the coast because of continuous cold snaps from the North, which severely impacted marine transport. Research concerning sea ice thickness distribution is essential in guiding shipping transportation navigation.

[3] Estimating sea ice thickness on a large spatial scale is challenging. Several approaches have been proposed to monitor sea ice thickness, including in situ sampling methods, numerical simulations and remote sensing measurements. Among these last ones are hyperspectral, microwave, and synthetic aperture radar methods [Ning et al., 2009]. Field expeditions and drilling surveys for measuring sea ice thickness are of course trustworthy and rigorous. They have as major drawback the time, effort and money required to conduct in situ manual drilling sampling measurements in adverse winter marine conditions [Ning et al., 2009]. Moreover, its low efficiency and high cost are not commensurate with large scale scientific sea ice investigations [Sun et al., 2003]. Another approach involves numerical sea ice distribution studies [Holland et al., 1993], coupled ice-ocean models [Cheng and Preller, 1992] and thermodynamic models [Wang et al., 2010] to estimate sea ice thickness. These are effective and accurate in simulating sea ice thickness over a limited spatial range. However, they are lacking in simulating accurately the thickness of ice near the coast [Bai and Wu, 1998]. Remote sensing data including hyperspectral, microwave, altimetry, and synthetic aperture radar have been applied to estimate sea ice thickness on a large spatial scale with the help of numerical models [Guo et al., 2000; Jin et al., 2001; Connor et al., 2009].

[4] In this paper, we propose a direct approach to effectively estimate sea ice thickness over a large spatial area using EOS MODIS data. It is based on a retrieval model of an exponential relationship between albedo and ice thickness. Validation of our method showed it to be robust and relatively accurate in predicting ice thickness and distribution.
Our method, combined with previous work illustrates the feasibility of studying the spatiotemporal distribution of sea ice coverage and thickness.

2. Study Area and Data

[5] The Bohai Sea (between 37°07′-41°0′N and 117°35′-121°10′E) is a partially enclosed sea in China, surrounded by land on three sides and connected to the Yellow Sea in the East (Figure 1). It is the most southern sea on the northern hemisphere where sea ice occurs during winter (NSDIC, 2010, http://nsidc.org/seaice/intro.html). The Bohai Sea covers 78,000 km² with an average water depth of 18 m. There are three primary bays surrounding the Sea: the Liaodong bay in the north, the Bohai bay in the west, and the Laizhou bay in the south. The water temperature of the Bohai Sea varies in accordance with a northern continental climate with a mean temperature of 0°C in February and 21°C in August [Xie et al., 2003]. The shores along the sea are always frozen in winter [Shi et al., 2003]. In early March, the sea ice melts concomitantly with drift ice. The Liao River, Luan River, Hai River, and Yellow River carry large amounts of sediments and freshwater into the Bohai Sea causing the salinity of the seawater to be only 30PSU, the lowest in all coastal waters of China [Shi et al., 2002].

[6] In this study, MODIS data were used from Terra (EOS AM) which passes daily across the study region in every morning at about 10:30 A.M. local time. It provides seven-band L1B MOD02HKM data with radiation calibration, from NASA LAADS (Level-1 and Atmosphere Archive and Distribution System). Channel 1–2 have a spatial resolution of 250m (CH1-CH2) and 3–7 one of 500m (CH3-CH7) (Table 1). Data were selected from Dec. 5, 2009 to March 11, 2010, covering the whole region of the Bohai Sea without or with only slight cloud and snow coverage. In this study, 18 images of MODIS data in a time series were used.

[7] Meteorological data were collected from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/) including the lowest, average, and highest daily temperature at 14 meteorological stations around the Bohai Sea. These stations are labeled in Figure 1. These data are used to calculate FDD and TDD in the following sections.

3. MODIS Data Pre-processing

3.1. Georeference

[8] The MODIS L1B data provided by NASA LAADS were processed for geometric correction or geo-referenced. The “bow-tie” effect of the images, a kind of geometric

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**Figure 1.** The map of the study area showing Liaodong, Bohai and Laizhou Bays of the Bohai Sea and 14 meteorological stations (solid circles) around the sea.

**Table 1.** Spectral Ranges and Spatial Resolutions of MOD02HKM Data

<table>
<thead>
<tr>
<th>MODIS</th>
<th>CH1</th>
<th>CH2</th>
<th>CH3</th>
<th>CH4</th>
<th>CH5</th>
<th>CH6</th>
<th>CH7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial (m)</td>
<td>250</td>
<td>250</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>
distortion induced by image pixel overlapping was removed. In this paper, the geometric correction and removal of the “bow-tie” effect were carried out using the “Georeference MODIS” tool provided by ENVI 4.3 software by RSI Inc.

3.2. Atmospheric Correction

[9] Using FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) atmospheric correction model in the ENVI software, we retrieved pixel surface reflectances in all MODIS sensor channels (channel 1 to channel 7) from MODIS L1B TOA radiance images (MOD02HKM). Based on the MODTRAN4 radiation transfer code, FLAASH is suitable for atmospheric correction in the 400–2500 nm wavelength range of multispectral and hyperspectral remote sensing images to retrieve surface spectral reflectance. FLAASH starts from a standard equation for spectral radiance backscattered by the sensor pixel (L) that applies to the solar wavelength range. The equation is as follows [Research Systems, Inc., 2001]:

\[ L = A\rho/(1 - \rho_S) + B\rho_e/(1 - \rho_eS) + L_a \]  

(1)

where \( L \) is the spectral radiance at a sensor pixel; \( \rho \) is the pixel surface reflectance; \( \rho_e \) is an average surface reflectance for the pixel and a surrounding region; \( S \) is the spherical albedo of the atmosphere; \( L_a \) is the radian scatter backscattered by the atmosphere; \( A \) and \( B \) are coefficients that depend on atmospheric and geometric conditions but not on the surface.

[10] Each of the above variables depends on measurements of specific spectral channels. The first term in equation (1) corresponds to radiance reflected from the surface directly to the sensor, whereas the second term corresponds to radiance from the surface scattered by the atmosphere into the sensor. The third term corresponds to radiance backscattered by the atmosphere to the sensor.

[11] The values of \( A, B, S \) and \( L_a \) which depend strongly on the amount of water vapor in the column and the aerosol optical depth are determined from calculations using MODTRAN4. They deal with the viewing and solar angles, scene center location, and the mean surface elevation after assuming a specific model atmosphere, aerosol type, and visibility. After water and aerosol retrieval [Kaufman et al., 1997] have been established and the rest parameters are determined, equation (1) is solved for the pixel surface reflectance values in all the sensor channels. The input parameters for FLAASH atmospheric correction of one-scene MODIS L1B imagery in this study are shown in Table 2.

### Table 2. The Input Parameters for FLAASH Atmospheric Corrections of One-Scene MODIS L1B Imagery

<table>
<thead>
<tr>
<th>Flight Date</th>
<th>Atmospheric Model</th>
<th>Flight Time GMT</th>
<th>Aerosol Model</th>
<th>Solar Zenith Angle</th>
<th>Initial Visibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-1-22</td>
<td>Midlatitude</td>
<td>2:30:00</td>
<td>Maritime</td>
<td>63.32°</td>
<td>40 km</td>
</tr>
</tbody>
</table>

3.3. Sea Ice Extent Extraction

[12] The key and first step in sea ice extraction lays in distinguishing between land versus water and water versus ice. It is easy to separate land, seawater and sea ice using ratio-threshold segmentation because their spectra are significantly different in channel 1 and channel 2 of the MODIS data at TOA (Top of Atmosphere). The ratio of channel 1 and channel 2 showed that the value of sea ice and water is much larger than that of land and clouds whereas the ch1/ch2 value of sea ice is ranging between those of land and seawater. Therefore, land, seawater and sea ice can be separated by setting multiple thresholds [Su et al., 2012]. In this paper, we extracted the sea ice extent using a ratio-threshold segmentation method proposed by Su et al. [2012]. Figure 2 is a case image illustrating sea ice extraction by this method, clearly showing good separations between land versus water and water versus ice, respectively.

4. Retrieval Sea Ice Thickness

[13] Ice forms hexagonal crystals. Its main components are ice crystals, water, brine, and air bubbles. Changes in sea ice thickness are associated with changes in its physical structure and composition [Xie et al., 2003]. The type, color, and structure of the sea ice vary with its thickness [Wu, 1992]. As a consequence, the sea ice albedo recorded by the satellite sensor is directly affected by the change of sea ice thickness. Previous studies have shown that the thickness of sea ice is closely related to its surface albedo, which is determined by the thermodynamics of sea ice growth. Generally, thick sea ice results in a higher reflectance of solar energy and a higher surface albedo. Thin ice on the other hand causes absorbance of solar energy inducing melting and a lowering of the surface albedo [Barry et al., 1993]. Grenfell and Perovich [1984] and Grenfell [1991] concluded that its thickness is related to the albedo based on the optical theory of sea ice, and he observed a relationship of synchronization increment between the albedo and the thickness of sea ice. Allison et al. [1993] reported a similar result. Sea ice albedo generally ranges between 0.10 and 0.70. Both theoretical and experimental studies have proven that snow has a substantially higher albedo than thin ice [Xie et al., 2006]. The surface albedo increases with snow coverage. We therefore must mask snow coverage when extracting sea ice for thickness estimation, and choose when possible snow-free MODIS data.

[14] Grenfell [1991] and Allison et al. [1993] showed that the albedo increased from 0.11 to 0.24 with sea ice thickness
Increasing from 2 cm to 9 cm, Grenfell [1991] proposed the following exponential relationship between the thickness of the sea ice and its albedo:

\[ \alpha(h) = \alpha_{\text{max}}[1 - k \exp(-\mu_s h)] \]  (2)

where \( \alpha(h) \) is the shortwave broadband albedo of the sea ice, which varies with the sea ice thickness; \( \alpha_{\text{max}} \) is taken to be 0.7, the albedo of the sea ice at infinite thickness; \( k \) is a correlation coefficient which is \( k = 1 - \alpha_{\text{sec}}/\alpha_{\text{max}} \); \( \alpha_{\text{sec}} \) is set at 0.06, the albedo of seawater; \( \mu_s \) is set at 1.209, the attenuation coefficient of the albedo [Xie et al., 2003]. In this study, we retrieved the sea ice thickness through equation (2) using the shortwave broadband albedo derived from MODIS data directly.

4.1. Generation the MODIS Albedo

4.1.1. MODIS Narrowband Spectral Albedo

[15] Surface albedo is a dimensionless quantity. It is simply defined as the ratio of the surface upwelling flux \( (F_u) \) and the downward flux \( (F_d) \) the flux of radiation:

\[ \alpha = F_u/F_d \]  (3)

\[ \alpha(\theta; \Lambda) = \frac{F_u(\theta; \Lambda)}{F_d(\theta; \Lambda)} = \frac{\int_{\lambda_1}^{\lambda_2} F_u(\theta; \lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} F_d(\theta; \lambda) d\lambda} \]  (4)

where \( \Lambda \) denotes the wave band from wavelength \( \lambda_1 \) to \( \lambda_2 \), \( \Lambda \in (\lambda_1, \lambda_2) \), \( \theta \) is the solar zenith angle (SZA).

[16] In this study, we employed the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) code instead of MODTRAN. SBDART has a user-friendly interface that is easily set up for effective simulation, and enables us to run the code without using real surface reflectance spectra [Liang, 2001]. We ran SBDART three times with three surface reflectances (0.0, 0.5, and 0.8) for each atmospheric condition and solar geometry. According to Liou [1980] and Liang [2003], assuming the surface is a Lambertian one, the surface downward radiation flux \( F_d \) and upwelling radiation flux \( F_u \) can be expressed by the following equations:

\[ F_d = F_0 + \frac{r_s}{1 - r_s} \pi \mu_s E_0 \gamma(\mu_s) r \]  (5)

\[ F_u = L_p + \frac{r_s}{1 - r_s} \mu_s E_0 \gamma(\mu_s) \gamma(\mu_v) \]  (6)

where \( \mu_s \) is the cosine of solar zenith angle (SZA), \( \mu_v \) corresponds to the viewing zenith angle, \( F_0 \) and \( L_p \) are the downward radiation flux and path radiance without surface contribution (i.e., surface reflectance is zero, \( r_s = 0 \)), \( r \) is the surface spectral reflectance, \( r \) is the spherical albedo of the atmosphere, \( E_0 \) is the TOA downward radiation flux, and \( \gamma(\mu_s) \) and \( \gamma(\mu_v) \) are the total atmospheric transmittance of the solar illumination path and the viewing path. Results from the three runs of the SBDART give six equations enabling us to determine these unknowns \( (F_0, L_p, E_0, \gamma(\mu_s) \) and \( \gamma(\mu_v) \) in the above equations. With these unknowns determined, it is straightforward to calculate the surface downward and upwelling radiation fluxes with any surface spectral reflectance by using equation (5) and (6). After determining downward and upwelling radiation fluxes at the surface, MODIS narrowband spectral albedos \( (\alpha_1 \) to \( \alpha_7) \) were generated by using equation (3).

4.1.2. MODIS Shortwave Broadband Albedo

[17] We used primarily experimental models to obtain the surface broadband albedo from the surface narrowband albedo over the past years. The model parameters were obtained by linear regression models of large data sets. This procedure has proven to be an effective way to get good universal conversion equations and is easily validated using surface measurement data [Liang, 2001]. For MODIS shortwave broadband albedo, the conversion formula can be expressed as

\[ \alpha_{\text{short}} = 0.160\alpha_1 + 0.291\alpha_2 + 0.243\alpha_3 + 0.116\alpha_4 + 0.112\alpha_5 + 0.081\alpha_7 - 0.0015 \]  (7)

[18] The MODIS shortwave broadband albedo of the Bohai Sea was generated by using equation (7) for each Band 1 to 5 and Band 7. According to Liang [2001] and Liang et al. [2003], the albedo model is accurate as inferred from the small root mean square error (RMSE) of 0.019 between shortwave albedo thickness and ground measurements. In this study, all MODIS data were used to calculate the albedo by using equation (7). Figure 3 shows an albedo image of January 22, 2010 as an example of our results.

5. Results and Validation

[19] After establishing the MODIS shortwave albedo using equation (7), the ice thickness in the Bohai Sea in the 2009–2010 winter was calculated using equation (2).
Eighteen estimated thickness images of sea ice in Bohai Sea are shown in Figure 4. From the multitemporal image of sea-ice thickness, it is clear that sea ice formed and expanded gradually with a maximum thickness of 40 cm. The spatiotemporal evolution of sea ice together with the thickness distribution is noticeable from Figure 4.

[20] Bohai Sea ice in the 2009–2010 winter started to appear in early December 2009 and remained till the middle of March 2010. To delineate the formation of the sea ice better, we calculated the cumulative FDD (Freezing Degree Days) and cumulative TDD (Thawing Degree Days) as the sum of average daily degrees below the freezing point and above the melting point for a specified time [Assel, 1986, 1990]:

\[
\text{cumulative FDD} = \sum_{D_s}^D (T_O - T_{AF}) \tag{8}
\]

\[
\text{cumulative TDD} = \sum_{D_s}^D (T_{AT} - T_O') \tag{9}
\]

\[
\theta = \text{cumulative FDD} - 3 \times \text{cumulative TDD} \tag{10}
\]

where the cumulative FDD and cumulative TDD are the cumulative days of freezing and melting, respectively; \(T_O\) and \(T_{AF}\) are the freezing and melting point respectively; \(T_{AF}\) and \(T_{AT}\) are the average daily temperature below the freezing point and above the melting point; \(D_s\) and \(D_E\) are the start and end date of the period considered; \(\theta\) is the difference between cumulative FDD and 3 * cumulative TDD in the Bohai Sea according to Xie et al. [2003] and Ding [1999]. Here, the freezing point \(T_O\) and the melting point \(T_O'\) were set at \(-2.0^\circ\text{C}\) and \(0^\circ\text{C}\). These temperatures are in accordance with the salinity of 30 PSU in the Bohai Sea; \(T_{AF}\) and \(T_{AT}\) were set as the mean values of average daily temperature below the freezing point and above the melting point of 14 meteorological stations around the Bohai Sea. Due to seawater and sea ice are in a critical state between \(-2^\circ\text{C}\) to \(0^\circ\text{C}\), both the FDD and TDD are set to zero when \(T_{AF}\) and \(T_{AT}\) are between \(-2^\circ\text{C}\) to \(0^\circ\text{C}\).

[21] Compiling our results, we discovered some noteworthy trends. The continuous cold snap from the north caused sea ice to expand faster with a rapid increase in \(\theta\), i.e., cold days. According to previous studies, most sea ice exhibits several developmental stages, from first-formed ice to nilas, pancake, gray and gray-white, as well as cumulative ice with a change of \(\theta\) [Ning et al., 2009].

[22] By Analysis of the spatiotemporal evolution of ice thickness in the Bohai Sea from Dec. 5, 2009 to March 11, 2010 (Figure 4), we established the extent and thickness of the sea ice: (1) Emerging sea ice started along the coastline, and gradually expanded from the shore to the central ocean; Sea ice first appeared in the northern bay, the Liaodong Bay in early December, gradually hugged the coast southwards to Bohai Bay, and finally Laizhou Bay during ice growth; In late January and middle February, sea ice coverage reached a maximum; By March, the sea ice thinned, and gradually disappeared along with the intensive melting; Melting of sea ice started in the Laizhou Bay, next in the Bohai Bay, and

Figure 4. The spatiotemporal evolution of ice thickness retrieved from MODIS data under clear-sky conditions in the Bohai Sea (unit: cm). There are a total of 18 scene images from 5 Dec. 2009 to 11 Mar. 2010. The solid-line frame is the magnification of the dotted-line frame in the first row and last row of images.
finally in the Liaodong Bay, presenting a melting trend from south to north opposite to the trend of sea ice growth; (2) The average ice thickness over the whole Bohai Sea ranged from 3 to 21 cm, somewhat correlated with \( q \) (Table 3); The general ice thickness ranged from 2 to 32 cm, with a maximum between 6 to 40 cm over the whole Bohai Sea; In late January and middle February, the sea ice thickness reached a maximum of about 40 cm. In the nascent stage (in December) and melting stage (in March), the ice was relatively thin, about 5 to 10 cm in general, also correlated with changes in \( q \) (Tables 3 and 4); (3) The spatial distribution of sea ice was extensive, but its thickness distribution was uneven. Among the three bays of the Bohai Sea, the spread of ice showed distinct spatial heterogeneity at different dates. The general thickness in the Liaodong Bay was greater than that in the Bohai Bay, whereas the general thickness in the Laizhou Bay was the lowest. In the Liaodong Bay, the ice thickness at the east coast was generally greater than that in the west. In the Bohai and Laizhou Bay, the ice was thicker near the coast than offshore.

Our results show that sea ice coverage and its thickness are correlated with \( q \). Sea ice thickness increased progressively with increasing \( q \), and gradually melts and becomes drift ice with decreasing \( q \) (Table 3 and Figure 4).

Two empirical models have been developed to estimate sea ice thickness from growth models using cumulative FDD and cumulative TDD: the Lebedev, and Zubov models [Maykut, 1986]. In this study, we deployed these two models to validate the results of ice thickness retrieval by MODIS data:

Lebedev model: 
\[
H = 1.33 \times q^{0.58}
\]

Zubov model: 
\[
H^2 + 50H = 8q
\]

where \( H \) is the average thickness of the Bohai sea ice; \( q \) is the difference between cumulative FDD and 3* cumulative TDD. Figure 5 is a comparison between sea ice thickness estimated from MODIS and the results calculated by using Lebedev and Zubov models, which we used to validate the

<table>
<thead>
<tr>
<th>Date</th>
<th>General Thickness (cm)</th>
<th>Maximum Thickness (cm)</th>
<th>Average Thickness of Bohai Sea Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-12-5</td>
<td>3–5</td>
<td>10</td>
<td>2–5</td>
</tr>
<tr>
<td>2009-12-17</td>
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<tr>
<td>2010-3-11</td>
<td>5–10</td>
<td>10</td>
<td>3–12</td>
</tr>
</tbody>
</table>

Source: NMEFC.
sea ice thickness inversion by MODIS. It is clear that the average thickness of the Bohai Sea ice retrieved by MODIS is generally consistent with modeling curves according to Lebedev and Zubov. Most of the MODIS data points fall between the Lebedev and Zubov curves and present nearly linear distribution (Figure 5). Statistical analysis indicates that the retrieved sea ice thickness values are significantly correlated with those from the Lebedev and Zubov models, $R^2$ being 0.864 and 0.858, respectively (Figures 6 and 7). The Lebedev and Zubov models well validate the MODIS-retrieved results.

We also validated the sea ice thickness retrieved by MODIS data by using the forecasting data of the general and maximum thickness of the Bohai Sea ice published by the National Marine Environmental Forecasting Centre (NMEFC). We list the actual forecast values of general and maximum thickness of the sea ice in the Bohai Sea and the MODIS estimation thickness values in Table 4. Note that our estimated thickness results are very close to the forecast results, suggesting that our proposed method is reliable, robust, and applicable.

6. Conclusion

We proposed a direct method to estimate sea ice thickness over a large spatial area with remote sensing. Eighteen images of MODIS L1B data from EOS Terra (AM) in the 2009–2010 winter were successfully used to effectively estimate sea ice thickness and to monitor its spatio-temporal evolutions in the Bohai Sea. EOS Terra which passes across in the morning should be chosen in order to avoid the effect of ice melting, which can reduce albedo due to the surface water. The MODIS images should be selected without or with slight cloud and snow cover as far as possible, and cloud and snow cover should be masked when sea ice was extracted for estimating thickness because the albedo of the two is different from sea ice.

The average ice thickness of the whole Bohai Sea in 2009–2010 winter ranged from 3 to 21 cm. The maximum sea ice thickness was estimated to be about 40 cm in Liaodong Bay. The development of sea ice clearly presented spatial heterogeneity at different dates among the three bays of the Bohai Sea. Multiple-temporal maps of sea ice thickness show that the sea ice first forms along the coastline, and gradually expands from the shore to the central ocean. Sea ice appears first in the Liaodong Bay, and gradually expands southwards to the Bohai Bay and Laizhou Bay. This sequence is inverted upon melting.

Our results show that sea ice coverage and thickness correlate with $θ$, the difference between cumulative FDD and 3*cumulative TDD. The results of the thickness retrieved by MODIS are validated by the calculated results from Lebedev and Zubov models. The statistical results show significant correlations between our estimated results and calculated ones ($R^2 = 0.864$ and 0.858). It should be noted that a few data are not well distributed against $θ$, which may be caused by fast increasing of FDD induced by fast air temperature decreasing as well as the discontinuous MODIS data cloud and snow coverage.

The estimated sea ice thickness using MODIS data was also validated with the forecasting data from the NMEFC. The close fit between our MODIS and NMEFC data indicates that the proposed method is reliable, robust, and applicable.

6. The approach we proposed in this paper is suitable for clear sky and snow-free conditions. It should be emphasized that the accuracy of our method should be further investigated. Since each pixel of MODIS images is a complex mixed pixel, representing an actual surface area of $500 \times 500 \text{ m}^2$, the heterogeneity and mixing of pixels are two very important issues for future work.

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References


