Snow Information Abstraction Based on Remote Sensing Data: Taking the North of Xinjiang for Example

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Abstract  This paper proposes an applicable approach for snow information abstraction in northern Xinjiang Basin using MODIS data. Linear spectral mixture analysis (LSMA) was used to calculate snow cover fractions (SF) within a pixel, which was used to establish a regression function with NDSI. In addition, 80 snow depths samples were collected in the study region. The correlation between image spectra reflectance and snow depth as well as the comparison between measured snow spectra and image spectra was analyzed. An algorithm was developed for snow depth inversion on the basis of the correlation between snow depth and snow spectra in the region. The results indicated that the model of SF had a high accuracy with the mean absolute error 0.06 tested by 26 true measured values and the validation for snow depth model using another dataset with 50 sampling sites showed an RMSE of 1.63. Our study showed that MODIS data provide an alternative method for snow information abstraction through development of algorithms suitable for local application.

Keywords  snow information; MODIS satellite data; snow cover; snow fraction; snow depth

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Introduction

Snow is an important resource of fresh water. Various techniques for surveying the snow coverage on regional and global scales exist. Meteorological observations and regular manual surveys of snow depth and snow density are traditional methods to estimate the snowmelt water amount and to follow the evolution of the snow cover. Contrary to the mentioned techniques, satellite images provide continuous spatial measurements, acquired globally at regular intervals. Different classification techniques have been developed for snow-cover abstraction by optical remote sensing data. Examples of approaches include conventional unsupervised and supervised classification, linear interpolation techniques[1,2], spectral ratios combined with thresholds and spectral unmixing[3]. Presently, global snow maps are produced regularly from MODIS images based on the normalized difference snow index (NDSI)[4]. However, it takes each pixel as the pure one and can only divide a pixel into snow or non-snow, so when a pixel includes several land cover types, the accuracy of NDSI will decrease.

Snow fraction has been developed through several studies[5,6]. Recently, Kaufman et al.[7] and Barton et al.[8] have described some methods for estimating subpixel snow cover using MODIS observations. Kaufman’s approach is essentially a variation of a
“tie-point” algorithm using the 0.645 μm band (band 1) and the 2.1 μm band (band 7) of the MODIS instrument. Barton’s method is a multivariate polynomial regression approach using the NDSI and MODIS observations. In this paper, a spectral unmixing approach was applied to estimate the fraction of snow cover in the pixel, and then the value of snow fraction and the NDSI were used to build the regression equation to examine whether the NDSI can be used to obtain subpixel estimates of snow cover. We also developed an applicable approach for snow depth inversion based on MODIS data. Finally, the snow distribution in northern Xinjiang was studied by the two methods.

1 Methodology

1.1 The study region

The northern Xinjiang is a typical arid area, which is located in the northwest of China and the north of Tianshan Mountain with an area of 0.58 million km$^2$ and a population of 9.4 million (Fig.1). It has a continental climate pattern in temperate zone. The annual average precipitation in northern Xinjiang is only 254 mm, which is only 39% of the China-averaged precipitation but with the evaporation as high as 1 500 mm. Dry climate with water resource shortages is a basic characteristic in the region.

[Fig.1 The location of the study area]

Xinjiang consists of six regions: Aletai, Bole, Yili, Tacheng, Changji and Urumqi. Snow is the main supply source for water in northern Xinjiang, but in recent years, environmental problems have been more and more serious for the lack of water resource. Frequent snow disasters also brought serious impacts on local people’s living and production. Accurate snow monitoring is urgently needed which can provide scientific basis for water resource management.

1.2 Data and field campaigns

MODIS images from Nov.2004 to Mar.2005 were obtained for the study. All the images were corrected to remove the atmospheric effects and were registered to a 250 m grid in a UTM projection. Eighty samples of snow depth were collected from hydrologic stations for snow depth inversion and the geographical coordinates of the sampling sites were also recorded by using a GPS device to match the geographical coordinates of the image. True measured snow depth and snow fraction value were obtained for result testing. A county boundary file was obtained and land use/cover documents were also collected. DEM was collected for classifying the elevation.

From Nov. 2005 to Mar. 2006, field campaigns were conducted to measure the snow fraction in the south of Urumqi(43°32′21.7″ ~ 43°43′10.2″N, 87°19′20.3″~ 87°32′21.7″E) and Changji (43°32′21.7″~43°43′10.2″N, 87°19′20.3″ ~ 87°32′21.7″E). Twenty-six samples of 250 m grids were chosen and a GPS device was used to record the geographical coordinates in order to match the MODIS images of the study region. Then manual measurements combined with visual measurements were applied to get the true ground snow fraction. At the same time, 50 samples of snow depths were measured by measuring stick in Urumqi and Changji. The geographical coordinates of each sample were recorded by GPS. ASD was also used to measure snow spectra in different depth levels. Except for the measured value, field observations were conducted in the mountainous area, forest area and at different slopes in Yili, Tacheng, Bole in Apr 2005.

1.3 Linear spectral mixture analysis for snow cover abstraction

Several approaches had been proposed for snow cover abstraction. We use linear spectral mixture analysis (LSMA$^{[9]}$). Physically, LSMA is based on image processing with the assumption that spectra measured by a sensor is a linear combination of the spectra of all components within the pixel. Therefore, we have
\[ R_i = \sum_{k=1}^{n} f_k R_{ik} + ER_i \]  

where \( i=1,\cdots,m \) (the number of spectral bands); \( k=1,\cdots,n \) (the number of endmembers); \( R_i \) is the spectral reflectance of band \( i \) which contains one or more endmembers; \( f_k \) is the proportion of endmember \( k \) within the pixel; \( R_{ik} \) is the known spectral reflectance on band \( i \) of endmember \( k \) within the pixel; and \( ER_i \) is the error for band \( i \). Root mean square error was used to measure the accuracy of the solution:

\[ \text{RMSE} = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (ER_i^2)} / m \]

The smaller \( \text{RMSE} \) is, the more accurate it will be. A constrained inverse least squares deconvolution model was used in this research, assuming that the following two conditions are satisfied simultaneously:

\[ \sum_{k=1}^{n} f_k = 1 \quad \text{and} \quad 0 \leq f_k \leq 1 \]

This will restrict each endmember fraction between 0 and 1; all the summation is equal to 1, which can avoid any fraction larger than 1 or less than 0. \( f_k \) is the parameter we need. When snow endmember is extracted, the snow fraction in each pixel can be obtained. Consequently, the snow cover map can be made.

Selecting suitable endmembers is the key to determine the overall accuracy during the unmixing process. Many studies\(^{10,11}\) concluded that the MNF transformation can reduce the correlation between bands and can concentrate most information on the first several components, which can improve the accuracy of LSMA. First, we conducted an MNF transformation. Then pixel purity index (PPI)\(^{12}\) was used to find the most “spectrally pure” pixels in images.

### 1.4 Snow depth inversion

To reverse snow depth from MODIS, the suitable bands for snow depth inversion should be selected. First, the correlation between each MODIS band spectra value and the measured snow depth for 80 sampling sites was analyzed to select the highest correlation bands with snow depth. Then we compared true measured snow spectra with MODIS snow spectra for band 1 to band 15, and selected the bands which can truly reflect that snow spectra. Finally, an algorithm was developed for snow depth inversion on the basis of the 80 snow depth samplings and its correlation with MODIS snow reflectance of the corresponding bands we selected in the region.

## 2 Results and analysis

### 2.1 Endmembers in study area

The MODIS data we used to extract endmembers was acquired on Jan 16, 2005, because the image quality was quite good and the snow cover rate was high on that day. Fig.2 shows the endmembers scattering plot in \( n \)-dimensional visualizer of ENVI after PPI calculation. Because the endmembers always present themselves at the corner of a triangle, we can see that there are five endmembers in the study area, and the land cover map also shows that there are five types of land cover: forest, plowland, water, rock and snow. Through continuous filtration, we selected 100 dots for each endmember, and the average reflectance of endmembers is shown in Fig.3.

### 2.2 LSMA results

After extracting endmembers spectra, LSMA can be used to get the snow fraction. We calculated the...
NDSI using band 4 and band 6, then drew a scattering plot of the NDSI and snow fraction (Fig. 4). A MODIS land/water mask was employed to exclude lakes, etc. An ordinary least-squares regression approach was then used to derive the linear relationships between the snow fraction and NDSI corresponding to the 250 m grid cells (Eq. 4). The correlation coefficient was 0.88, indicating the good correlation.

\[
SF = 0.94 \text{NDSI} + 0.21, \quad R = 0.88 \quad (4)
\]

The model accuracy needs to be tested by using measured data. We calculated the snow fraction by Eq. (4) from MODIS according to the corresponding time and geographic position of the snow fraction we measured, and compared the calculated value with the measured value. The results show that when the NDSI value was between 0.4 ~ 0.75, the calculated value was close to the measured one, but when NDSI was higher or lower than these two values, there would be some errors. The mean absolute error was 0.06, indicating that NDSI can be used to estimate snow fraction.

### 2.3 Snow depth inversion

Fig. 5 shows the result of correlation analysis between spectra values from MODIS image and the measured snow depth. We can see that the correlation curve between snow depth and spectra in three months tends to be consistent. The correlation between visible, near infrared band (band 1~9) reflectance and snow depth was positive, but the correlation was negative between thermal infrared and snow depth. Among all the bands, band 1 and band 3 were the highest correlation with the snow depth.

Fig. 6 and Fig. 7 are the true measured snow spectra and snow spectra of MODIS in the same day. We can see that the snow reflectances of band 1 and band 3 were close to the true measured spectra with the value about 0.7, and they were suitable for snow depth inversion.

Through the analysis above, band 1 and band 3 were chosen to build the snow inversion model. Li and Sun\cite{13} indicated that when the snow depth is between 10~20 cm, the snow reflectance change slightly. Therefore, we built the bilinear regression equation according to different snow levels (Table 1).

We tested the model using the other 50 snow depth data measured in the south of Urumqi and Changji. The average absolute error was 1.63 cm, and the average relative error was 11.62%. The precision of snow depth between 10~20 cm was relatively high with the absolute error lower than 2 cm, but when snow depth was over 20 cm, the precision was low.
3 Conclusion

This article is mainly about searching for an applicable approach for snow information abstraction in northern Xinjiang using MODIS. Linear spectral unmixing approach was used to abstract snow cover. We built a regression model between NDSI and snow cover fraction. Then we conducted field campaigns to test the model. The results showed that the mean absolute error for 26 true measured snow fraction samples is 0.06. In addition, we collected the snow depth data at 80 sampling sites from 35 hydrology stations and analyzed the correlation between the image spectra value and the measured snow depth for the 80 sampling sites. Band 1 and band 3 were selected to build the snow depth inversion model and an algorithm was developed on the basis of the correlation between image spectra value and the measured snow depth. Another dataset with 50 sampling sites were used to validate the model and it showed that the RMSE was 1.63. The multispectral characteristics of MODIS data can be widely used to abstract snow information. This study is very meaningful for snow disaster monitoring as well as snow melt runoff simulation and forecast.

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