Retrieving Snow Surface Temperature Based on MODIS Data

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Abstract  On the basis of simplification of the Planck function in a low temperature range, this paper revises the practical split-window algorithm and presents a method for retrieving snow surface temperature (Ts) based on MODIS data in the middle-latitude region. The application of this method in Qinghai Lake region reveals that it is feasible for the retrieval of Ts. Results of correlation analysis indicate that there was strong negative relationship between Ts and altitude. By analyzing three typical areas in which land cover was relatively homogenous, this paper discusses the relationship between Ts and normalized difference snow index (NDSI) and then presents a new concept named “NDSI-Ts space”.

Keywords  snow surface temperature; normalized difference snow index; altitude; MODIS

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Introduction

The temporal and spatial distribution of snow surface temperature (Ts) is important to the melting and transformation processes of snow and energy exchange between land surface and atmosphere. Therefore, the retrieval and dynamic monitoring of snow surface temperature based on remote sensing are crucial issues. So far, most of the related researches are focused on the Polar Regions and a lot of achievements have been obtained[1-6]. However, domestic researches are lacking. At present, the studies in the mid-latitude regions are rare, except for Oesch et al.[7] which analyzed the temporal and spatial distribution of snow surface temperature and its relationship with the spectral mixture of the Alps. The research advances the process of remote sensing of snow surface temperature.

1 Methodology

This paper proposes a method for retrieving snow surface temperature based on the modification of the practical split-window algorithm for retrieving land surface temperature from MODIS data[8]. The flow-chart of this method is shown in Fig.1.

1.1 Calibration of MODIS data

The digital number (DN) of reflective solar bands of MODIS image was converted to reflectance at the top of atmosphere (TOA) following this formula:

\[ \rho_{\text{TOA}} = \text{reflec \_scales}_{i} \times (DN - \text{reflec \_offsets}_{i} \cos \theta_{0}) \]  

where \( \rho_{\text{TOA}} \) is the reflectance at TOA at band \( i \); \( \text{reflectance \_scales}_{i} \) and \( \text{reflectance \_offsets}_{i} \) are the scale and offset parameters at band \( i \) and can be derived.
from the HDF file; $\theta_0$ is the solar altitude angle.

For thermal bands, the radiance was calculated as:
\[ I_i = \text{radiance}_\text{scales}_i \times (\text{DN} - \text{radiance}_\text{offsets}_i) \]  
where $I_i$ is the radiance at band $i$; $\text{radiance}_\text{scales}_i$ and $\text{radiance}_\text{offsets}_i$ are the scale and offset parameters, respectively.

Then the brightness temperature was computed as:
\[ T_i = \frac{2hc}{\lambda^2} \ln(1 + \frac{hc^2}{\lambda I_i}) \]  
where $h$ is Planck constant ($6.626 \times 10^{-34}$ J·s); $k$ is the Bolztmann constant ($1.380 \times 10^{-23}$ J·K$^{-1}$); $c$ is the velocity of light ($2.998 \times 10^8$ m·s$^{-1}$); $\lambda$ is the wavelength (m); $T$ is the brightness temperature (K).

1.2 Mapping of the snow cover

For non-densely forested regions, the reflectance at bands 2 and 4 and NDSI (normalized difference of snow index) were combined to map the snow cover[9]. NDSI was estimated by:
\[ \text{NDSI} = (\rho_4 - \rho_2) / (\rho_4 + \rho_2) \]  
The following three criteria were used to identify the snow pixels: ① $\text{NDSI} \geq 0.40$; ② $\rho_2 > 0.11$; ③ $\rho_4 \geq 0.10$.

1.3 Linearization of Planck equation

It is necessary to simplify the Planck equation because the relationship between temperature $T$ and the radiance $B(T)$ is complicated when establishing the split-window algorithm. Mao et al. (2005) proposed

the linearized Planck equations in the range of $273$–$322$K[8]. However, these equations are not appropriate for snow cover because of its low temperature range.

For $243$K–$283$K, the radiance calculated by the spectral response function of band 31 and band 32 of MODIS was regressed with the temperature $T$, and the linear equations for snow cover were proposed as follows:
\[ B_{31}(T) = 0.049 \text{DN} T_{31} - 10.273, R^2 = 0.996 \]  
\[ B_{32}(T) = 0.044 \text{DN} T_{32} - 9.070, R^2 = 0.997 \]  

1.4 Estimation of atmospheric transmittance

According to Kaufman & Gao (1992), atmospheric transmittance at 0.940 $\mu$m can be calculated according to Eq.(7) or Eq.(8)[10-11]:
\[ \tau_w(0.940 \mu m) = \rho^*(0.940 \mu m) / \rho^*(0.865 \mu m) \]  
\[ \tau_w(0.940 \mu m) = \rho^*(0.940 \mu m) / (c_1 \rho^*(0.865 \mu m) + c_2 \rho^*(1.240 \mu m)) \]  
where $\rho^*$ is reflectance; $c_1=0.80$, $c_2=0.20$. Kaufman & Gao simulated the relationship between the two-band ratio and water content based on LOWTRAN and proposed the following model[10]:
\[ \tau_w(0.940 \mu m / 0.865 \mu m) = \exp(\alpha - \beta \sqrt{w}), R^2 = 0.999 \]  
where $\alpha=0.02$ and $\beta=0.651$ for complex land surface. In Eq.(7), Eq.(8) and Eq.(9), 0.865 $\mu$m, 1.240 $\mu$m and 0.940$\mu$m denote bands 2, 5 and 19 of MODIS, respectively.

Then, water content $w$ was calculated as:
\[ w = \left[(\alpha - \ln \tau_w) / \beta\right]^2 \]  

Mao et al. (2005) simulated the relationship between water content and transmittance of bands 31 and 32 based on LOWTRAN[8]:
\[ \tau_{31} = 2.897 \times 10^{19} - 1.83 \times 10^{13} e^{(w/21.227)}, R^2 = 0.997 \]  
\[ \tau_{32} = -3.592 \times 10^{19} + 4.604 \times 10^{13} e^{(w/32.706)}, R^2 = 0.996 \]  

1.5 Determination of the emissivity

Emissivity is determined by the components, surface conditions, physical properties and so on, and it changes with wavelength and viewing angle[12]. In this paper, we assume emissivity of snow are $0.982$ at
1.6 Retrieval of snow surface temperature

For details of the practical split-window algorithm, readers are encouraged to refer to [8]. Based on Eq.(5), Eq.(6) and this algorithm, snow surface temperature $T_s$ is expressed as:

$$T_s = \frac{C_{32}(B_{31} + D_{31}) - C_{31}(D_{32} + B_{32})}{C_{32}A_{31} - C_{31}A_{32}}$$  

(13)

where $A_{31} = 0.049\ 00\varepsilon_{31}\tau_{31}$,
$B_{31} = 0.049\ 00T_{31}^{r} + 10.273\tau_{r31} - 10.273$,
$C_{31} = 0.049\ 00(1 - \tau_{31})(1 + (1 - \varepsilon_{31})\tau_{31})$,
$D_{31} = 10.273(1 - \tau_{31})(1 + (1 - \varepsilon_{31})\tau_{31})$,
$A_{32} = 0.044\ 22\tau_{32}$,
$B_{32} = 0.044\ 22T_{32}^{r} + 9.070\tau_{r32}\varepsilon_{32} - 9.070$,
$C_{32} = 0.044\ 22(1 - \tau_{32})(1 + (1 - \varepsilon_{32})\tau_{32})$,
$D_{32} = 9.070(1 - \tau_{32})(1 + (1 - \varepsilon_{32})\tau_{32})$, $\varepsilon_i$ and $\tau_i$ are emissivity of snow and atmospheric transmittance at band $i$ ($i=31, 32$), respectively.

2 Application

2.1 Study area and data

The Qinghai Lake region has been chosen as the study area, and its extent is 95°14′~103°40′E and 34°45′~39°50′N, covering 16 counties of Qinghai province and 2 counties of Gansu Province. The terrain of the study area is complex, with the highest altitude about 5 700 m and the lowest 1 600 m, and the average is 3 600 m. According to LULC data of China in 2000, the eastern, northern and southern parts of the study area are homogeneous with grassland or pasture. Lakes are scattered in the study area.

MODIS image with 1km spatial resolution dated on November 20, 2002 was used in this research. The geometric rectified image of the study area is shown in Fig.2, which is synthesized with bands 6, 3 and 1.

2.2 Spatial distribution of snow surface temperature

The snow cover is shown in Fig.3, which is denoted by NDSI and layered with the vector data of the study area. The comparison of the snow cover with the original MODIS image reveals that most of the snow pixels have been identified.

Snow surface temperature ($T_s$) of the study area is shown in Fig.4. The highest temperature is 275.68K, the lowest is 250.55K, and the average is 264.61K. Fig.4 shows that the pixels with high temperature were mainly located at the edge of the snow cover, and a number of pixels with high temperature about 267.0K were located in the east of Qinghai Lake. The lowest value was distributed in Delingha City, with about three cold centers, while there was a cold region located in the eastern part of Dulan County.

2.3 Snow surface temperature and altitude

Previous researches indicate that heat absorbed by land surface and the partition of energy change with
altitude, thereby the temperature\(^{[14]}\). In order to analyze the relationship between \(T_s\) and altitude, two transects (\(AB\) and \(CD\), see Fig.2) were selected. Transect \(AB\) covered the snow cover in the east of Qinghai Lake, with complex thermal patterns and different altitudes; while transect \(CD\) covered the snow cover in the east of Dulan County, which contained cold regions.

The 1:250 000 DEM was resampled and then layered with \(T_s\) image, and \(T_s\) and altitude of \(AB\) and \(CD\) are shown in Fig.5. It is obvious that the snow surface temperature and the altitude change to the opposite directions, that is higher altitude value corresponds to lower temperature. The correlation analysis of \(T_s\) with altitude indicated that there was significant negative relationship between \(T_s\) and altitude. The correlation coefficient of \(AB\) is \(-0.543\), while that of \(CD\) is \(-0.610\) at 0.01 level. It suggests that the distribution of \(T_s\) may be influenced by altitude, which is consistent with Stroeve & Steffen\(^{[6]}\).

![Fig. 5 Distribution of \(T_s\) and altitude](image)

### 2.4 Snow surface temperature and NDSI

Because different land cover types obtain different properties, it is important to consider the snow-covered land surfaces when analyzing the relationships between \(T_s\) and NDSI. In order to quantify their relationships, Datong County, Delingha City and Dulan County were selected as samples (see Fig.4) according to LULC data of China. Datong was vegetated densely with grasslands and pastures; Dulan had homogenous snow-covered land surfaces, mainly with grasslands and pastures; Delingha was homogenous with bare surfaces, except for little vegetation covered by snow. Correlation analysis indicated that there was strong negative correlation between \(T_s\) and NDSI for the samples above. All correlation coefficients were smaller than \(-0.7\) at 0.01 level (see Table.1). Fig.6 shows the feature space of NDSI-\(T_s\) of Datong.

![Fig.6 NDSI-Ts space of Datong](image)

This interesting phenomenon can be explained by snow fraction and thermal properties of the pixels mixed by snow and other land surfaces. Salomonson & Appel (2004) suggested that NDSI derived from MODIS image is correlated with snow fraction positively, and they proposed a model to estimate snow fraction based on NDSI\(^{[15]}\). On the other hand, snow has different radiative properties from other surfaces, i.e. it absorbs less shortwave solar radiation than other surfaces because of higher albedo, while its effective radiation is greater under the same temperature condition because of its greater longwave radiation. As a result, snow obtains lower surface temperature than other surfaces. Snow surface tempera-
ture reaches 273.16K when melting. However, there were some pixels that obtained temperatures higher than 273.16K. This can also be explained by spectral mixture of snow and other surfaces.

3 Conclusion

This paper establishes the linear equations to simplify the Planck equation for cold environment, and proposes a model to retrieve snow surface temperature based on the practical split-window algorithm. Because in situ measurements were lacking, the validation of this model was impossible. However, the results seemed to be applicable and feasible. The negative relationship between snow surface temperature and altitude was examined in this paper. On the other hand, the relationship between $T_s$ and NDSI was also investigated and a new concept “NDSI-$T_s$” feature space is proposed. This feature space was further explained from the point of spectral mixture. This work may be useful for mining the theories of snow fraction, snow surface temperature and NDIS-T$_s$ space and their scale effects.

As a key parameter, the emissivity of snow may be influenced by many factors. In order to retrieve snow surface temperature with higher accuracy, it is important to quantify the emissivity of snow based on remote sensing. On the other hand, MODIS image seems to be too coarse to grasp the details of land surfaces, so it is necessary to analyze the influences caused by land cover types and snow fraction with higher resolution satellite images. This is important to mine the NDSI-$T_s$ feature space and its scale effect. Additionally, the validations of snow surface temperature and NDSI-$T_s$ feature space derived from MODIS with ASTER that is also onboard the Terra satellite are critical issues. These works will be carried out in the future.

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