

Comparison of two split-window methods for retrieving land surface temperature from MODIS data

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Land surface temperature (LST) is a key parameter in environment and earth science study, especially for monitoring drought. The objective of this work is a comparison of two split-window methods: Mao method and Sobrino method, for retrieving LST using MODIS (Moderate-resolution Imaging Spectroradiometer) data in North China Plain. The results show that the max, min and mean errors of Mao method are 1.33 K, 1.54 K and 0.13 K lower than the standard LST product respectively; while those of Sobrino method are 0.73 K, 1.46 K and 1.50 K higher than the standard respectively. Validation of the two methods using LST product based on weather stations shows a good agreement between the standard and Sobrino method, with RMSE of 1.17 K, whereas RMSE of Mao method is 1.85 K. Finally, the study introduces the Sobmao method, which is based on Sobrino method but simplifies the estimation of atmospheric water vapour content using Mao method. The Sobmao method has almost the same accuracy with Sobrino method. With high accuracy and simplification of water vapour content estimation, the Sobmao method is recommendable in LST inversion for good application in Ningxia region, the northwest China, with mean error of 0.33 K and the RMSE value of 0.91 K.

1. Introduction

Land surface temperature (LST) is a good indicator of energy and water balance on the interface between the atmosphere and land. It has attracted much attention in recent decades owing to a large scale temperature information requirement in environmental and earth sciences, for example, in drought monitoring. One of the most important potential applications of LST retrieved from satellite data is in the validation and improvement of global meteorological prediction models after proper aggregation and parameterization (Price 1982; Diak and Whipple 1993). The inversion of LST from satellite data requires correction for atmosphere-induced effects, mainly the absorption

and emission of atmospheric water vapour and surface emissivity, which can be significantly lower than unity and varies spatially with surface cover and cover type (Coll *et al* 2005). As for MODIS data, LST retrieval is performed mainly through the application of split-window technique. Several split-window algorithms have been developed on the basis of variation and effect of the atmosphere and emitting surface (Becker and Li 1990a; Sobrino *et al* 1996, 2003; Mao *et al* 2005).

It is widely documented that atmospheric transmittance, water vapour and surface emissivity generate significant impact on LST retrieval accuracy. Atmospheric transmittance describes the magnitude of attenuation of a radiance passing through the atmosphere. It is affected by a range

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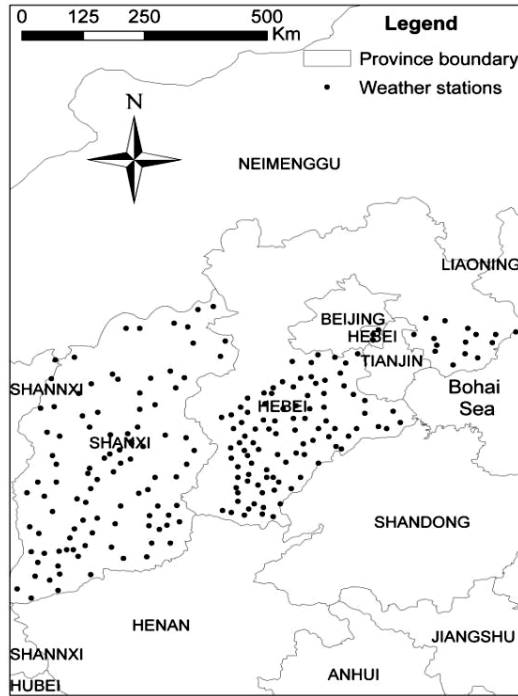


Figure 1. Location map of the study area.

of atmospheric constituents, including carbon dioxide, nitrogen oxide, ozone oxide, methane and other gases that are generally assumed fairly constant, as opposite to the highly variable water vapour content. Therefore variations in atmospheric transmittance strongly depend on the dynamics of water vapour content in the profile, especially for thermal channels. Among the 36 MODIS channels, channels 2 ($0.875 \mu\text{m}$) and 5 ($1.24 \mu\text{m}$) are atmosphere window bands, while channels 17 ($0.905 \mu\text{m}$), 18 ($0.936 \mu\text{m}$) and 19 ($0.940 \mu\text{m}$) are absorption bands. Thus, based on the characteristics of the channels, water vapour content of the atmosphere can be estimated directly from MODIS image, and transmittance will be further estimated. Considerable research work (Chesters *et al* 1983; Fraser and Kaufman 1985; Grant 1990; Kaufman and Gao 1992; King *et al* 1992; Czajkowski *et al* 2002) has been done in this regard.

Surface emissivity is a measure of inherent efficiency of the surface in converting heat energy into radiant energy above the surface (Sobrino *et al* 2001). It is critical for determining land surface thermal radiation (Caselles *et al* 1995), thereby, also a key parameter affecting LST retrieval accuracy through split-window algorithm. Already, many efforts have been made on surface emissivity estimation (Becker and Li 1990b; Li and Becker 1993; Van De Griend and Owe 1993; Valor and Caselles 1996; Wan and Li 1997; Gillespie *et al* 1998; Sobrino and Raissouni 2000; Sobrino *et al* 2001; Momeni and Saradjian 2007) using different

techniques. Emissivity is often either assumed constant or estimated with empirical methods in split-window algorithms.

In this work, we have two objectives:

- to find out the effectiveness of two latest split-window methods for retrieving LST from Aqua-MODIS data by comparing their performance with LST product (as a standard), and
- to develop a simplified method from the two methods for LST estimation.

2. Study area and data

2.1 Study area

The study area covers mainly Hebei and Shanxi regions (figure 1), a representative area in North China Plain, which is a vital food production base of China. Each region contains agricultural weather stations with 113 and 101 station sites randomly distributed in Hebei and Shanxi regions respectively.

2.2 MODIS data

In this work, version 5 of Aqua-MODIS Level 1B products of daytime (MYD02 1km), Land Surface Temperature and Emissivity (LST/E)-Daily L3 Global 1 km product (MYD11A1) on dates of 28/03, 9/10 and 14/11 in 2006 were chosen randomly for little or no cloud atmosphere conditions. LST products downloaded with SIN projection in HDF format were then reprojected to Albers equal area projection with GeoTIFF format using MRT (MODIS Reprojection Tool), which is downloadable from 'http://lpdaac.usgs.gov/landdaac/tools/modis/index.asp' website. LST products provide per-pixel temperature values with 1K accuracy (Wan *et al* 2002).

3. Methodology

3.1 Sobrino *et al* (2003) algorithm

3.1.1 Land surface temperature

A quadratic algorithm for LST estimation is given as follows (Sobrino *et al* 2003):

$$T_s = T_{31} + a_1 + a_2(T_{31} - T_{32}) + a_3(T_{31} - T_{32})^2 + (a_4 + a_5W)(1 - \varepsilon) + (a_6 + a_7W)\Delta\varepsilon, \quad (1)$$

where T_s is land surface temperature; T_{31} and T_{32} represent brightness temperature of bands 31 and

32; $a_1, a_2, a_3, a_4, a_5, a_6$ and a_7 are split-window coefficients acquired through simulation with values of 1.02, 1.79, 1.20, 34.83, -0.68 , -73.27 and -5.19 respectively (Sobrino *et al* 2003); water vapour content of the atmosphere; ε [$\varepsilon = (\varepsilon_{31} + \varepsilon_{32})/2$] is the mean effective emissivity of MODIS channels 31 and 32; and $\Delta\varepsilon$ ($\Delta\varepsilon = \varepsilon_{31} - \varepsilon_{32}$) is the spectral emissivity difference.

3.1.2 Estimation of surface emissivity

In the estimation of surface emissivity, NDVI (Normalized Difference Vegetation Index) threshold method (Sobrino *et al* 2001) is applied. Current soil characteristics in each pixel are taken into consideration according to the following procedures:

- *Bare soil pixels*: Values of NDVI lower than 0.2 are considered as bare soil (with vegetation proportion P_v taken as zero, see below), which may include sparse vegetation or bare soil. According to MODIS channel 1 reflectivity (ρ_1), ε and $\Delta\varepsilon$ are calculated as:

$$\text{NDVI} = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}, \quad (2)$$

$$\varepsilon = 0.9832 - 0.058\rho_1, \quad (3a)$$

$$\Delta\varepsilon = 0.0018 - 0.060\rho_1, \quad (3b)$$

where ρ_1 and ρ_2 represent the reflectance value of MODIS bands 1 (RED) and 2 (NIR).

- *Mixed pixels*: When values of NDVI are between 0.2 and 0.5, ε and $\Delta\varepsilon$ are obtained as:

$$\varepsilon = 0.971 + 0.018P_v, \quad (4a)$$

$$\Delta\varepsilon = -0.006(1 - P_v), \quad (4b)$$

where P_v is the vegetation fraction which can be derived according to Carlson and Ripley (1997), using NDVI image equation (5) below:

$$P_v = \frac{(\text{NDVI} - \text{NDVI}_{\min})^2}{(\text{NDVI}_{\max} - \text{NDVI}_{\min})^2}. \quad (5)$$

- *Vegetation pixels*: Pixels with NDVI value higher than 0.05 are regarded as fully vegetated ($P_v = 1$) and thus ε and $\Delta\varepsilon$ are restated as:

$$\varepsilon = 0.985 + d\varepsilon, \quad (6a)$$

$$\Delta\varepsilon = 0, \quad (6b)$$

with $d\varepsilon = 0.005$.

3.1.3 Estimation of water vapour content

A 2-channel ratio of an absorption channel with a window channel is used to derive atmospheric transmittance of the absorption channel, and then total atmospheric water vapour content. With this method, as earlier mentioned in the introduction section, MODIS bands 2 and 5 are window channels and 17, 18 and 19 are absorption channels. However, the three absorption bands have different water vapour sensitivities under the same atmospheric condition. The strong absorption band 18 is most sensitive under dry conditions, while the weak absorption channel 17 is most sensitive under humid conditions (Kauman and Gao 1992). Therefore, the mean water vapour value W can be obtained by the function described as (Sobrino *et al* 2003):

$$W = 0.192W_{17} + 0.453W_{18} + 0.355W_{19}, \quad (7)$$

where W is the total water content; W_i ($i = 17, 18$, and 19) is the water vapour value for MODIS channels 17, 18 and 19.

$$w_{17} = 26.314 - 54.434G_{17} + 28.449G_{17}^2, \quad (8a)$$

$$W_{18} = 5.012 - 23.017G_{18} + 27.844G_{18}^2, \quad (8b)$$

$$W_{19} = 9.446 - 26.887G_{19} + 19.914G_{19}^2, \quad (8c)$$

G_i ($i = 17, 18$, and 19) are ratios based on L_i radiances, which are defined as:

$$G_i = \frac{L_i}{L_2}. \quad (9)$$

For extreme conditions, the accuracy of this method gives a standard deviation of 0.17 g cm^{-2} for wet atmospheres (3.32 g cm^{-2}) to 0.06 g cm^{-2} for dry atmospheres (0.33 g cm^{-2}).

3.2 Mao *et al* (2005) algorithm

3.2.1 Land surface temperature

Mao *et al* (2005) introduced a split-window algorithm to retrieve LST from MODIS data. In their algorithm, land surface temperature T_s is obtained from equation (10) as follows:

$$T_s = \frac{(C_{32}(B_{31} + D_{31}) - C_{31}(B_{32} + D_{32}))}{C_{32}A_{31} - C_{31}A_{32}}, \quad (10)$$

where A_{31} , B_{31} , C_{31} , D_{31} and A_{32} , B_{32} , C_{32} , D_{32} are functions of brightness temperature, emissivity or transmittance (also see Mao *et al* 2005). From the above equation, it appears difficult to find the relationship between LST and brightness temperature. In order to understand this relation further, equation (10) is simplified as follows:

$$T_s = A_0 + A_1 T_{31} + A_2 T_{32}, \quad (11)$$

A_0 , A_1 and A_2 can then be calculated using the following formulas:

$$A_0 = \frac{[0.09741 \cdot b_{31} b_{32} + 229.61319 \cdot b_{32} (a_{31} - 1) + 223.6506 \cdot b_{31} (a_{32} - 1)]}{a_{31} b_{32} - a_{32} b_{31}} \quad (12a)$$

$$A_1 = \frac{b_{32}}{a_{31} b_{32} - a_{32} b_{31}} \quad (12b)$$

$$A_2 = \frac{b_{31}}{a_{31} b_{32} - a_{32} b_{31}} \quad (12c)$$

$$a_i = \varepsilon_i \tau_i \quad (12d)$$

$$b_i = (1 - \tau_i)(1 + (1 - \varepsilon_i)\tau_i) \quad (12e)$$

where T_i , ε_i , τ_i , ($i =$ bands 31, 32) are brightness temperature, emissivity and transmittance of band i respectively, which can be calculated from the following sections. a_i and b_i ($i =$ bands 31, 32) are intermediate variables defined in equations (12d) and (12e).

Based on the simulation between water vapour content and the transmittance of bands 31 and 32, the equations for MODIS 31/32 are as follows (Mao *et al* 2005):

$$\tau_{31} = 2.89798 - 1.88366e^{-(w/-21.22704)}, \quad (13a)$$

$$\tau_{32} = -3.59289 + 4.60414e^{w/-32.70639}. \quad (13b)$$

3.2.2 Estimation of ground emissivity

Emissivity is mainly dependent on land surface structure and the range of spectral band used. The average emissivity of three representative terrestrial land types is adopted. For band 31, the values of water, bare soil and vegetation are approximately 0.992, 0.986 and 0.972, and for band 32, the values are 0.988, 0.991 and 0.976, respectively (Mao *et al* 2005). As far as mixed pixels,

which normally constitute two or three components, estimation of ground emissivity is done as follows:

$$\varepsilon = P_v R_v \varepsilon_v + (1 - P_v - P_w) R_s \varepsilon_s, \quad (14)$$

$$P_v = \frac{\text{NDVI} - \text{NDVI}_s}{\text{NDVI}_v - \text{NDVI}_s}, \quad (15)$$

where P_v and P_w represent vegetation and water fraction respectively, P_v is estimated from equation (15) according to Kerr *et al* (1992); for P_w calculation, if the pixel is water, then $P_w = 1$, for the bank of ocean, $P_w = \text{QDN}/\text{DNI}$, QDN represents the reflectance of the pixel and DNI represents the least reflectance of the land pixel, which is attained by samples obtained from the image. R_v and R_s represent the radiance ratio of vegetation and soil, and are given as 0.966158 and 1.04359 respectively; NDVI_v and NDVI_s represent the NDVI of vegetation and bare soil, generally taken as 0.65 and 0.05 (Kerr *et al* 1992).

3.2.3 Estimation of water content

Because the atmospheric transmittance strongly depends on water vapour dynamics of the profile, and even more for thermal bands, it is retrieved based on water content using band ratio functions. In this work, bands 2 and 19 ratio was used and the relationship between the used ratio and transmittance obtained using Kauman and Gao (1992), τ_w (transmittance) can be calculated from MODIS image, then water vapour content can be calculated from:

$$W = \left(\frac{0.02 - \ln \tau_w}{0.651} \right)^2, \quad (16)$$

$$\tau_w \left(\frac{19}{2} \right) = \frac{\rho_{19}}{\rho_2}, \quad (17)$$

where ρ_2 , ρ_{19} represent reflectance of bands 2 and 19, respectively.

Kauman and Gao (1992) performed lots of experiments and analysis for different conditions and concluded that the accuracy of this method is within 13% in the cloud-free conditions.

3.3 Calculation of brightness temperature

For the inversion of LST with the two methods mentioned above, calculation of brightness temperature for MODIS bands 31 and 32 is required. In this work, brightness temperature was obtained

from Planck radiation function according to Qin *et al* (2001):

$$T_i = \frac{c_2}{\lambda \ln[1 + (c_1/\lambda^5 B_\lambda(T_i))]}, \quad (18)$$

where T_i ($i =$ bands 31, 32) is brightness temperature; λ is wavelength in meter; c_1 and c_2 are constants with $c_1 = 5.95522012 \times 10^{-17} \text{ W m}^{-2}$ and $c_2 = 1.43876869 \times 10^{-2} \text{ m k}$; $B_\lambda(T_i)$ is the spectral radiance, which can be acquired from MODIS L1B image.

4. Results and discussion

4.1 Comparison of the two methods

Preprocessing of the Aqua-MODIS L1B data for three days was performed, including the geolocations, bow-tie effect removal, image mosaicking, cloud masking, etc., with no topographic correction due to the location of the study area (plain landscape). The LST retrieval methods of Mao *et al* (2005) and Sobrino *et al* (2003) were then used to acquire LST maps of Hebei and Shanxi regions (figure 2). Due to difficulties in obtaining ground-truth measurements at the time of the satellite pass and the high accuracy of MODIS LST product, which has been proven to be within 1K (Wan *et al* 2002), MODIS LST product was adopted as the standard for validation in place of ground-truth data. The evaluation of the methods was implemented in two steps:

- 1) comparison of statistical characteristics between retrieved LST maps and LST products, results of which are listed in table 1; and
- 2) verification by the standard LST product based on data from weather station sites.

In table 1, the max, min and mean values of estimated LST from the Mao method on the three dates are easily spotted as they are 1.33 K, 1.54 K and 0.13 K lower than the standard respectively. This is consistent with the findings of Mao *et al* (2005). On the contrary, the three indices of the Sobrino method are all higher than the standard, with average values of max error, min error and mean error of 0.73 K, 1.46 K and 1.50 K, respectively. Through the comparison of the indices of two methods, it was noted that the absolute average values of max error and min error of the Sobrino method are less than those of the Mao method, whereas the average mean error of the Sobrino method is greater than that of the Mao method. It, however, appears difficult to evaluate which method is superior over the other for LST inversion only from the maps and table values;

hence another statistical means was adopted for this purpose.

4.2 Validation of the two methods

In order to determine which method is better, the RMSE (Root Mean Square Error) was used to evaluate the accuracy of the two methods,

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (O_i - R_i)^2}{n}}, \quad (19)$$

where O_i and R_i are observed and retrieved variables respectively and n is the data number.

The validation results, based on LST products on the corresponding day of inversion LST, are shown in figure 3. It needs to be mentioned that the number of weather stations for validation on each day differs (84, 104 and 96 for three Julian dates, respectively), since sites with cloud effects were excluded in the validation and comparison analysis.

From the figure, it can be observed that two methods have little biases as can be found in the error bars. LST retrieved from Mao's method is generally lower than standard LST product, with a mean RMSE of 1.85 K, whereas the Sobrino retrieved LST shows a good agreement with the standard, with a mean RMSE of 1.17 K. The accuracy obtained from the current study is generally lower than that reported by Mao *et al* (2005) and Sobrino *et al* (2003), a probable short-fall of the use of LST product in place of measured ground truth data. In table 1, although the average mean error of the Sobrino method is higher than that of the Mao's, it is simply inadequate for a critical evaluation of the two methods. However, the analysis of RMSE and R^2 coefficients in figure 3 shows that the Sobrino method is superior over the Mao method for LST inversion.

4.3 Sobrino methods

Despite its higher accuracy of LST retrieval, the estimation of atmospheric water vapour content in the Sobrino method is generally complex, whereas the Mao algorithm is relatively simple. Water vapour estimation in the latter method needs only MODIS reflectance band 2 and absorption band 19, while the former needs reflectance band 2 and absorption bands 17, 18 and 19 and, of course, more equations. Because the water vapour absorption ability of channel 19 is intervenient between the strong absorption channel 18 and the weak absorption channel 17, which are most sensitive to the dry and humid conditions, respectively, the band ratio of 19 to 2 can be applied over a wide range

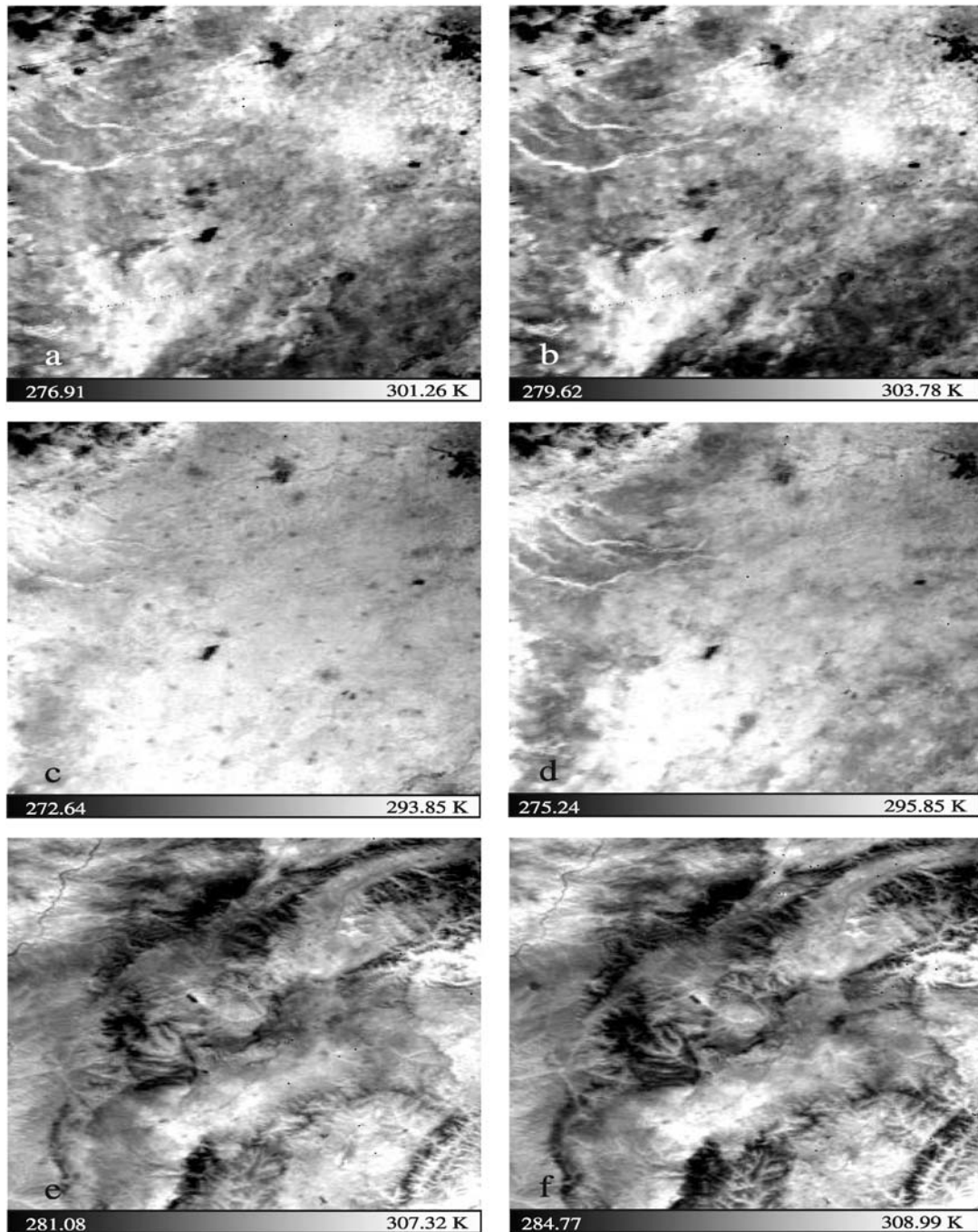


Figure 2. Map of retrieved LST on March 28, 2006 (a, b) and November 14, 2006 (c, d) in Hebei region; and October 9, 2006 (e, f) in Shanxi region (a, c and e for Mao method and b, d and f for Sobrino method).

of atmospheric conditions. For North China Plain, the annual average value of water vapour content is about 1.6 g cm^{-2} , which is similar to the calculated result on date of October 9, 2006. Thereby it can be viewed as a combined use of the LST and emissivity estimation in the Sobrino method, and the water vapour content estimation in the Mao method, this method is code-named Sobmao, with an LST retrieval value hardly different from that of the Sobrino method. In other words, the statistical

characteristics, inversion map of LST distribution and validation RMSE are almost the same as the Sobrino method. Its max, min and mean statistical values of inversion map of LST are listed also in table 1, while the validation results are plotted in figure 3. Being that it has the same accuracy and a much simplified water vapour content estimation, Sobmao method is recommended for retrieval of LST. Since Sobrino and Sobmao have different methods for estimation of water vapour

Table 1. Statistical characteristics of retrieval LST (Mao and Sobrino method) and LST product.

Date (dd/mm/yy)	Method	Max (K)	Error (K)	Min (K)	Error (K)	Mean (K)	Error (K)
28/03/06 (in Hebei)	LST	302.84	–	277.90	–	295.02	–
	Mao	301.26	–1.58	276.91	–0.99	294.95	–0.07
	Sobrino	303.78	0.94	279.62	1.72	296.91	1.89
	Sobmao	303.79	0.95	279.63	1.73	296.91	1.89
14/11/06 (in Hebei)	LST	295.54	–	274.68	–	289.19	–
	Mao	293.85	–1.69	272.64	–2.04	289.03	–0.16
	Sobrino	295.85	0.31	275.24	0.56	290.49	1.30
	Sobmao	295.86	0.32	275.26	0.58	290.49	1.31
09/10/06 (in Shanxi)	LST	308.04	–	282.67	–	297.46	–
	Mao	307.32	–0.72	281.08	–1.59	297.3	–0.16
	Sobrino	308.99	0.95	284.77	2.1	298.78	1.32
	Sobmao	308.99	0.95	284.78	2.2	298.79	1.33

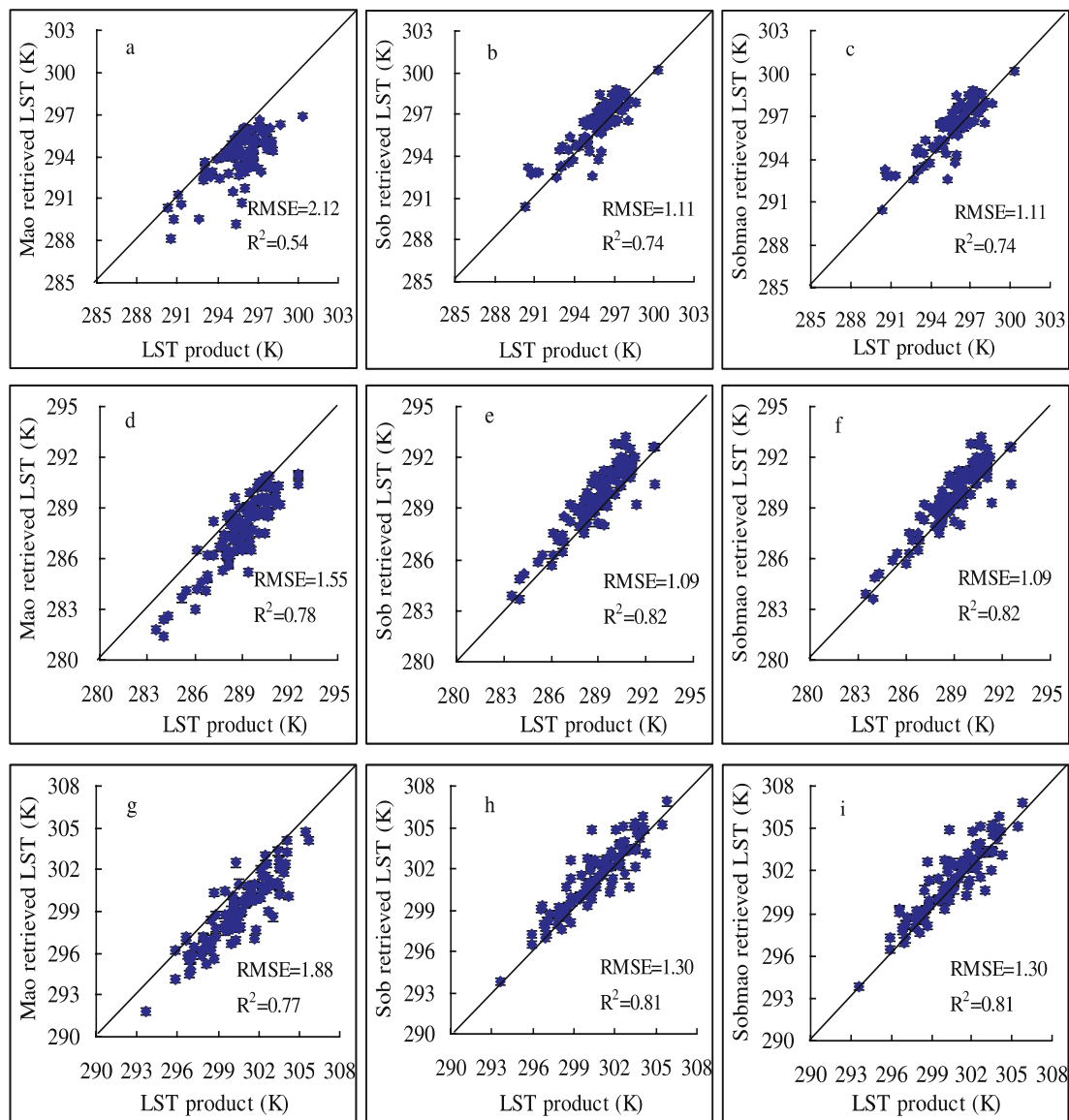


Figure 3. Match between retrieved and LST product for March 28, 2006 (a, b, c) and November 14, 2006 (d, e, f) in Hebei region and October 9, 2006 (g, h, i) in Shanxi region.

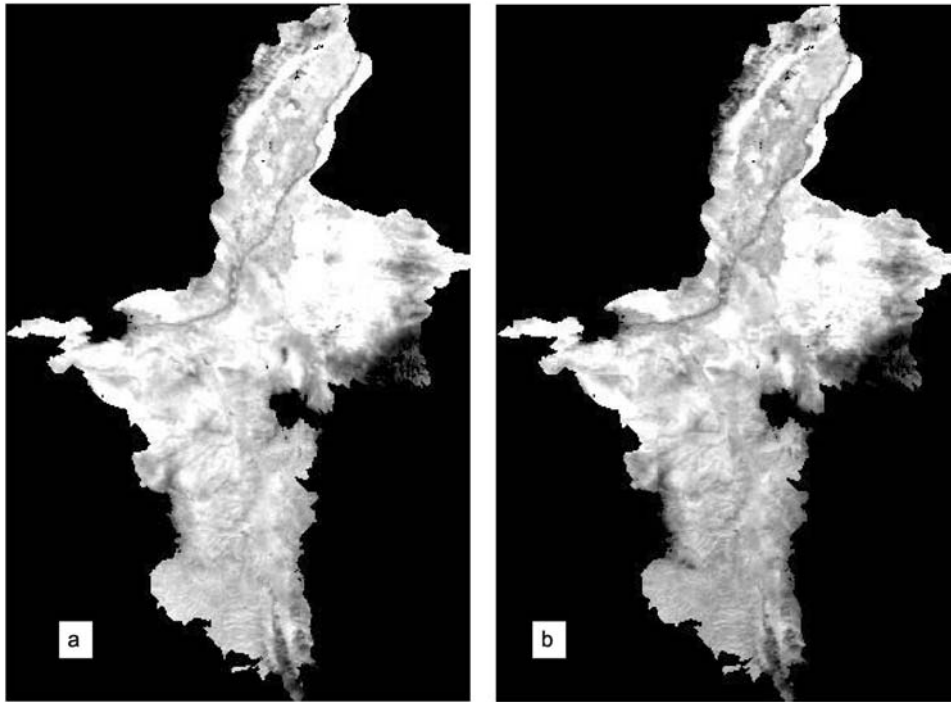


Figure 4. LST maps of (a) Sobmao method and (b) LST product on September 30, 2008 in Ningxia region.

content but same accuracy of LST, it is suggested that water vapour content is not sensitive to the split-window algorithm, which can be derived from the split-window equation. This is also consistent with Mao *et al* (2008).

In order to test the reliability, Sobmao method is applied in a different region, Ningxia Huizu Autonomous Region in northwest China. Data used include version 5 of Terra-MODIS Level 1B products of daytime (MOD02 1 km) and Land Surface Temperature and Emissivity (LST/E)-Daily L3 Global 1 km product (MOD11A1) on date of 30/09/2008. Image is preprocessed similar with the description in section 4.1, and two maps of the Sobmao retrieved LST and the MODIS standard LST product are shown in figure 4. The results of two LST maps are very similar, and the Sobmao method's LST values of max, min and mean are 304.21 K, 283.93 K and 296.13 K respectively, the LST product's values of max, min and mean are 304.54 K, 285.43 K and 295.80 K respectively. Thus, the differences between Sobmao method's LST values of max, min and mean and the LST product's are only 0.33 K, 1.50 K and 0.33 K respectively. Using the LST product as standard, RMSE of Sobmao is calculated. An RMSE value of 0.91 K indicates the reliability of the newly developed Sobmao method. It should be noted that the application of LST retrieval approach is better in arid northwest China region than in semi-humid north China. Therefore, this method may be more applicable in arid regions.

Conclusions

Mao *et al* (2005) and Sobrino *et al* (2003) methods were used to retrieve LST from MODIS data (on three different dates) in Hebei and Shanxi regions. Through comparing the results of the two methods with MODIS LST product, the Sobrino method has been proved to be more accurate for retrieving LST, with RMSE of 1.17 K, irrespective of a higher-than-standard average mean error compared with the Mao method. Finally, the Sobmao method is recommended for retrieving LST because of its high accuracy, simplified estimation of atmospheric water vapour content, and its reliability for application in Ningxia region, the arid northwest China, with the mean error of 0.33 K and the RMSE value of 0.91 K.

Although MODIS data for several cloud-free days are selected randomly, it is still hard to conclude that the results can represent the whole year. More reliable comparison with much longer time series data shall be necessary.

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