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A physics-based statistical algorithm for retrieving land surface temperature from AMSR-E passive microwave data

MAO KeBiao[1,2,3†], SHI JianCheng[2], LI ZhaoLiang[4], QIN ZhiHao[1,5], LI ManChun[4] & XU Bin[1]

[1] Key Laboratory of Resources Remote Sensing and Digital Agriculture, MOA, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China;
[2] State Key Laboratory of Remote Sensing Science, Jointly Sponsored by the Institute of Remote Sensing Applications of Chinese Academy of Sciences and Beijing Normal University, Beijing 100101, China.
[3] Graduate University of Chinese Academy of Sciences, Beijing 100049, China;
[4] Institute of Geographical Science and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China;
[5] International Institute for Earth System Science, Nanjing University, Nanjing 210093, China

AMSR-E and MODIS are two EOS (Earth Observing System) instruments on board the Aqua satellite. A regression analysis between the brightness of all AMSR-E bands and the MODIS land surface temperature product indicated that the 89 GHz vertical polarization is the best single band to retrieve land surface temperature. According to simulation analysis with AIEM, the difference of different frequencies can eliminate the influence of water in soil and atmosphere, and also the surface roughness partly. The analysis results indicate that the radiation mechanism of surface covered snow is different from others. In order to retrieve land surface temperature more accurately, the land surface should be at least classified into three types: water covered surface, snow covered surface, and non-water and non-snow covered land surface. In order to improve the practicality and accuracy of the algorithm, we built different equations for different ranges of temperature. The average land surface temperature error is about 2－3℃ relative to the MODIS LST product.

brightness temperature, LST, AMSR-E, MODIS, AIEM

1 Introduction

The extensive requirement of temperature information on a large scale for environmental studies and management activities of the Earth's sources has made the remote sensing of land-surface temperature (LST) an important issue in recent decades. Many studies have shown that land surface temperature is a key parameter in numerical weather-prediction model that leads to significant forecasting improvement in the physics of land surface processes on regional and global scales, combining the results of all surface-atmosphere interactions and energy fluxes between atmosphere and the ground.

Many efforts have been devoted to the establishment of methodology for retrieving LST from remote sensing data. There are many algorithms[1－15] have been proposed to retrieve sea and land-surface temperature from thermal data, (MODIS, NOAA/AVHRR datas etc.) in the last twenty years. But the thermal remote sensing is influenced much by cloud, atmospheric water content and falling rain. Over 60% areas in MODIS LST product are influenced by weather, epically cloud. But the microwave remote sensing has advantage in these aspects because it can overcome these shortcomings of thermal remote sensing.

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†Corresponding author (email: maokebiao@126.com)
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The retrieval algorithm of land surface temperature from passive microwave is very little in the development of application of passive microwave radiometry. No physical algorithm (not including iterative algorithm) retrieving land surface temperature from AMSR-E data has been published. The main reason is that the major complicating factor for land surface temperature retrieval in the field of radiometers view is variable. Water in any form in the atmosphere, on the land surface, or in soil changes the emissivity, absorptivity and scattering. On the other hand, it is very difficult to get *in situ* land surface data because of the limitation of passive microwave data resolution at the satellite pass. McFarland et al.[16] made some research for passive microwave SSM/I data to retrieve LST and obtained some useful conclusions: The surface water has some influence because the high dielectric constant of water decreases the emissivity at 19 GHz, depresses the brightness temperatures and increases the polarization difference. Thus, the term 19 GHz can compensate for the influence of surface water. The difference between 37 GHz and 22 GHz can be utilized to correct for the influence of atmospheric water vapor content on the emission.

AMSR-E and MODIS are two EOS (Earth Observing System) sensor instruments in Aqua satellite. AMSR-E is passive microwave radiometer and influenced little by atmosphere and cloud. MODIS is thermal radiometer and influenced much by atmosphere and cloud. The resolution of MODIS is higher than AMSR-E data, however, the land surface temperature retrieval algorithm is mature relative to passive microwave[10,13,15]. The two instruments can make up for each other in their own predominance. Passive microwave brightness temperature can be used to retrieve land surface temperature. Therefore, AMSR-E data have more advantages in this aspect. So how to utilize the multiple instrument characteristics is an important methodology in remote sensing.

2 Theoretical basis for passive microwave remote sensing of retrieving LST

The theoretical basis for passive microwave of LST retrieval is based on the thermal radiance of the ground and its transfer from the ground through the atmosphere to the remote sensor. Generally speaking, the ground is not a blackbody. Thus ground emissivity has to be considered for computing the passive microwave radiance emitted by the ground. Atmosphere has important effects on the received radiance at remote sensor level. Considering all these impacts, the general radiance transfer equation for passive microwave remote sensing of LST can be formulated as

$$B_f(T_f) = \tau_f(\theta)\varepsilon_f B_f(T_s) + [1-\tau_f(\theta)](1-\varepsilon_f)\tau_f(\theta)B_f(T_a^{\downarrow}) + [1-\tau_i(\theta)]B_f(T_a^{\uparrow}), \tag{1}$$

where T_s is the LST, T_a is average atmosphere temperature, T_f is the brightness temperature in frequency f, $\tau_f(\theta)$ is the atmospheric transmittance in frequency f at viewing direction θ (zenith angle from nadir), and ε_f is the ground emissivity. $B_f(T_s)$ is the ground radiance, and $B_f(T_a^{\downarrow})$ and $B_f(T_a^{\uparrow})$ are the downwelling and upwelling path radiances, respectively. Every term of radiance transfer equation owes the Planck function. Planck function is a bridge between spectral radiance emitted by a blackbody at a given frequency and temperature. The expression is

$$B_f(T) = \frac{2hf^3}{c^2(\mathrm{e}^{hf/kT}-1)}, \tag{2}$$

where $B_f(T)$ is the spectral radiance of the blackbody, the unit is $\mathrm{Wm^{-2}sr^{-1}Hz^{-1}}$, h is Planck constant with h=6.63×10^{-34}J, f is frequency and unit is Hz, k is Boltzman constant with k=$1.380658\times10^{-23}I$, T is temperature in Kelvin, and c is the light speed with c=$2.992458\times10^{8}\mathrm{ms^{-1}}$, Because the wavelength of passive wave is longer than VIR and TIR, according to Ralleigh-Jeans approximation, expression (2) can be simplified as

$$B_f(T) = \frac{2kT}{\lambda^2}. \tag{3}$$

Thus, eq. (1) can be written as

$$T_f = \tau_f\varepsilon_f T_s + (1-\tau_f)\tau_f(1-\varepsilon_f)T_a^{\downarrow} + (1-\tau_f)T_a^{\uparrow}. \tag{4}$$

Seen from eq. (4), the LST can be retrieved through building the linear relationship between brightness temperatures.

3 The algorithm for retrieving LST from AMSR-E data

In this research, we will find the best single band to retrieve land surface temperature by regression analysis between MODIS LST product and brightness temperature of AMSR-E, and then find the best method to eliminate the influence of soil water and atmosphere water by simulation of AIEM model.

3.1 Regression analysis of MODIS LST and brightness temperature of AMSR-E data

Because it is very difficult to obtain the *in situ* ground truth measurement of LST matching the pixel scale (25 km×25 km at nadir) AMSR-E data at the satellite pass. Generally speaking, LST varies from point to point on the ground, and ground measurement is generally point measurement. On the other hand, precisely locating the pixel of the measured ground in AMSR-E data especially night images is also a problem, so the algorithm for retrieving LST is very few. McFarland (1990) overcame many difficulties and made some research, but just for local regions because the limitation of condition. AMSR-E and MODIS are two EOS (Earth Observing System) instruments in Aqua satellite, so the product of MODIS LST provides chance for us to develop algorithm. However, Wan et al.[17,18] overcame many of these difficulties and managed to get a data set between 2000－2001 to evaluate the MODIS LST product. The conclusion indicated that the accuracy of MODIS LST product is under 1℃.

We made the MODIS LST product as *in situ* ground

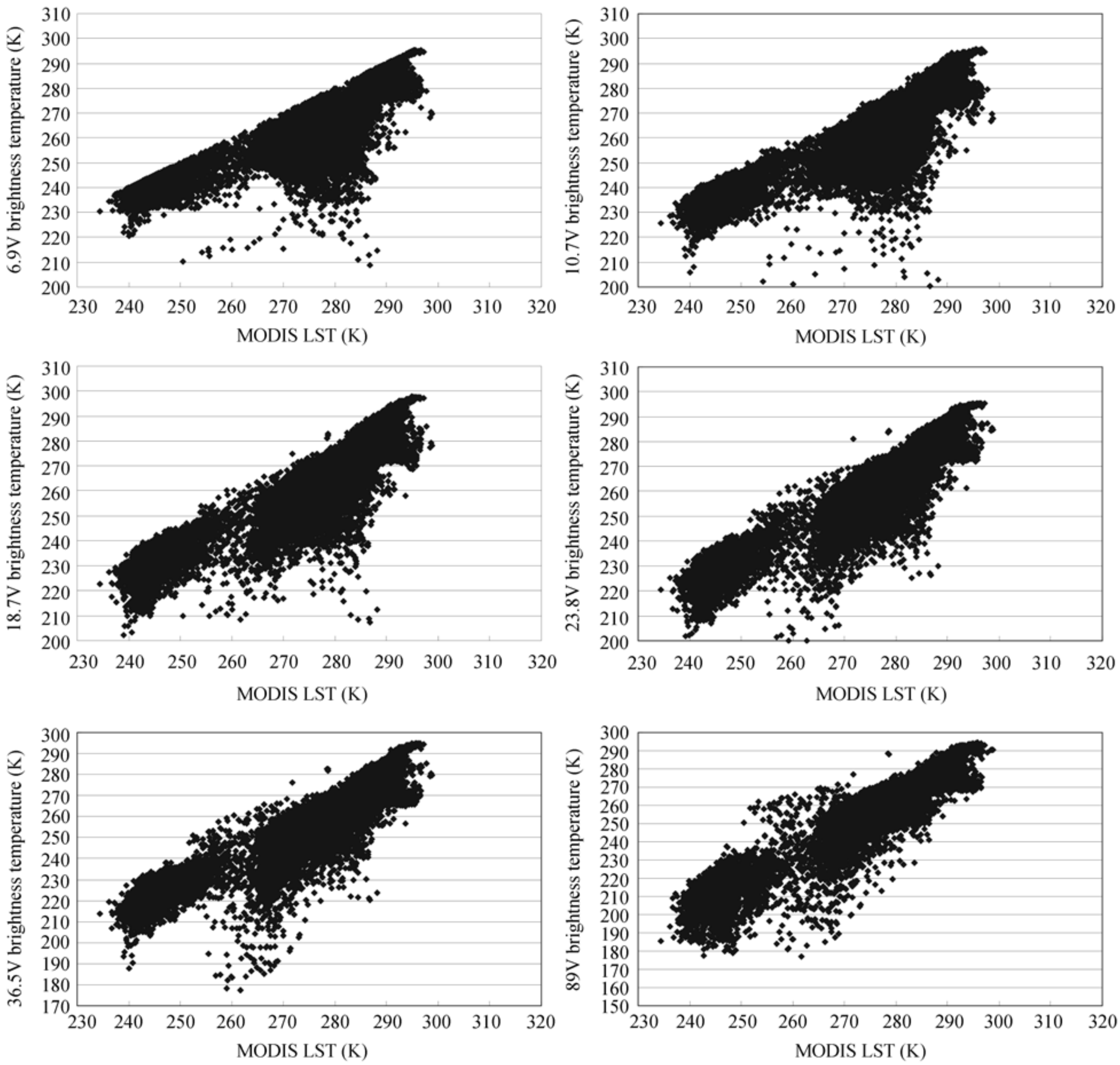

Figure 1 The relationship between MODIS LST product and AMSR-E brightness temperature.

truth measurement to regress with the lightness temperature of AMSR-E data. The Tibet region is selected as main research site (location latitude: 24°—40°; longitude: 75°—100°; date: 2004-2-2—9 and 2004-8-1—15). The number of pixels is about 20799.

We made some analysis for brightness V and H polarizations and found that the V polarization data are more sensitive and steady than H polarization data. So the V polarization is more suitable to retrieving land surface temperature. We made a regression analysis for Figure 1 (just part of data) and got Table 1.

Seen from Table 1, we can find that the accuracy increases with increasing frequency for single frequency (band). Seen from the coefficient of brightness temperature, we know the influence of atmosphere increase with the increasing of frequency. In order to improve retrieval accuracy, we need to eliminate the influence of the soil water and atmosphere. Seen from Figure 1, we find that the radiation mechanism is different when the land surface temperature is lower than about 273 K. The reason maybe is that the radiation situation of soil changes much when the temperature of soil is under 273 K.

3.2 Simulation analysis of AIEM and LST retrieval algorithm

Microwave observation is sensitive to soil moisture through the effects of moisture on the dielectric constant and hence emissivity of the soil, thus the microwave remote sensing is an important method for retrieving soil moisture[19]. AIEM is one of best models to simulate the emission characteristic of rough surface which overcomes the shortcoming of other models (GO, SPM, POM)[20−23]. AIEM have demonstrated a wider application range for surface roughness than the conventional model such as small perturbation model, physical model and geometrical optical model[21] which is extended and advanced by Chen et al.[23] on the basis of the integral equation mode (IEM).

In this study, we use AIEM model to simulate the relationship between soil moisture and difference of different frequency (under AMSR-E sensor: 6.9, 10.7, 18.7, 23.8, 36.5, 89 GHz, $\theta = 55°$) emissivity. In order to analyze conveniently, we just give some part of simulation results under different given conditions. Figure 2 shows the relationship between soil moisture and emissivity under given roughness (sig=2; cl=5.5) . Seen from Figure 2(a), there is an approximately linear relationship between soil moisture and emissivity for vertical polarization, and it is the same for horizontal polarization. The lower frequency is, the more sensitivity for soil moisture is.

We just give some part of simulation results. Seen from Figure 2(b), the change of soil moisture is not a simple linear relationship with the change of difference of different frequency emissivity. McFarland et al.[16] use difference of different frequency brightness temperatures to eliminate the influence of soil moisture.

Table 1 The Relationship between MODIS LST and AMSR-E brightness temperature

Frequency (GHz)	Number of pixels	Equation	LST error (℃)	R^2
6.9V	20799	LST=49.013+0.8529$T_{6.9V}$	5.71	0.704
10.7V	20799	LST=63.677+0.80471$T_{10.7V}$	5.34	0.734
18.7V	20799	LST=76.399+0.75911$T_{18.7V}$	4.61	0.805
23.8V	20799	LST=83.633+0.73353$T_{23.8V}$	4.04	0.847
36.5V	20799	LST=96.7131+0.69397$T_{36.5V}$	4.17	0.832
89V	20799	LST=121.63+0.59712T_{89V}	3.7	0.876

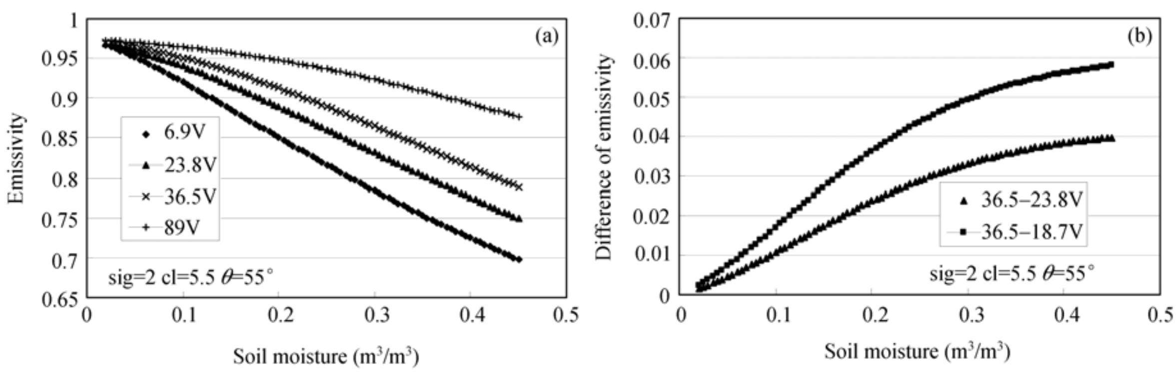

Figure 2 The relationship between soil moisture and difference of different frequency emissivity.

Table 2 Retrieval method in different ranges of temperature

Date	Range of temperature (K)	Number of pixels	Retrieval equation	Relative MODIS LST error (℃)
2004-2-2 —2004-8-15	<279	15563	LST=0.63291×89V−1.93891×(36.5V−23.V) +0.02922×(36.5V−23.V)^2+0.52654×(36.5V−18.7V) −0.00835×(36.5V−18.7V)^2+106.395	2.78
	>270	12520	LST=0.50898×89V+0.31302×(36.5V−23.V) +0.02095×(36.5V−23.V)^2−0.87117×(36.5V−18.7V)+ 0.00576×(36.5V−18.7V)^2+142.6452	2.61

Now it can be seen that we can get more accuracy if we use second-order approximate relationship between soil moisture and difference of different frequency brightness temperatures. So we can utilize the difference of different frequency brightness temperatures. However, according to the regression analysis between MODIS LST product and AMSR-E brightness temperature, the land surface temperature can be depicted as Figure 3. 89V is the main channel to retrieve LST, the difference of 36.5V and 18.7V and 23.8V can be used to eliminate the influence of soil water and atmosphere. First, we get LST through 89V by utilizing the expression in section 3.1; second, we improve the accuracy through Figure 3. After regression analysis, we obtain the retrieval method as in Table 2. The average accuracy is under 3℃.

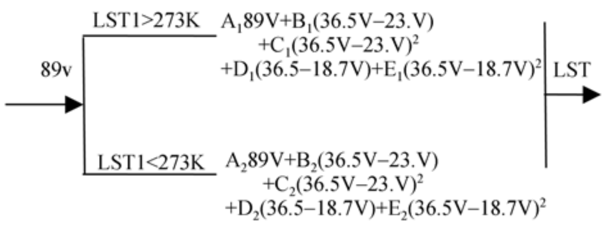

Figure 3 Land surface temperature retrieval frame.

4 Validation and application of LST retrieval algorithm

It is very difficult to obtain the measured LST to validate the land surface temperature retrieval algorithm. For thermal remote sensing, the standard atmosphere simulation was often used to validate the retrieval algorithm, but there has been no good method to use for microwave remote sensing. Fortunately, the MODIS LST product provides a chance to evaluate our algorithm which overcomes the difficulty of the *in situ* measurement. In this research, we utilize MODIS LST product provided by NASA in the Tibet region to validate our algorithm. The analysis result is as in Table 3. The average land surface temperature error is about 2.69℃ when land surface temperature is under 273 K and the average land surface temperature error is about 1.89℃ when land surface temperature is larger than 273 K relative to the MODIS LST product. On the other hand, we have to show that we endeavor to eliminate the mixed pixel influence and get the evaluation. The main reason is that the value of some pixel is 0 and the other reason is cloud influence.

Table 3 Validation sample information

Date	Range of temperature (K)	Number of pixels	Range of change (℃)	Relative MODIS LST error (℃)
2004-3-1	<273	10407	0—8.38	2.69
2004-6-4	>273	9702	0—17.5	1.89

In order to analyze the difference of radiation mechanism between microwave and thermal remote sensing, we retrieve land surface temperature from some AMSR-E images which includes Tibet, and parts of Qinghai, Gansu and Xinjiang. The distribution of temperature is like block which cannot be indicated in TM image because of the low resolution of AMSR-E images (25 km×25 km) (Figure 4). This is an advantage to analyze the difference of distribution of the temperature from continental and global scale.

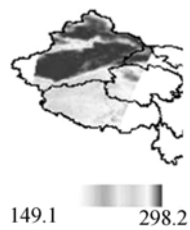

Figure 4 The retrieval of land surface temperature.

On the other hand, we retrieve the land surface temperature for the east of China and find that the retrieval land surface temperature is very high on the verge of land, which is not accuracy. The reason is that the algorithm is different between water surface and land surface. The second terms in the algorithm will make large error when there is water in the pixel. The resolution of passive microwave data is very low, so there exist many mixed pixels on the verge of land and the retrieval LST error is maybe very large. We have to improve the retrieval method on the verge of seashore. A suggestion is that retrieval algorithm should be built based on the different retrieval equations according to the types of ground and different ranges of land surface temperature.

5 Conclusion

On the basis of analyzing the characteristics of multiple-instruments in Aqua satellite, we build land surface temperature retrieval algorithm by utilizing the MODIS LST product and different brightness temperatures of AMSR-E, which overcomes the difficulty of *in situ* data at the satellite pass. This provides a good example for using multiple instruments from application and theory. From the analysis of regression coefficient, the radiation mechanism of different terra is different. The land surface should be at least classified into three types: water-covered surface, snow-covered surface, and non-water and non-snow-covered land surface. The average land surface temperature retrieval error for our algorithm is about 2—3℃ relative to the MODIS LST product. In order to improve the practical and accuracy of the algorithm, we have to make further research for cloud-covered land surface and mixed pixel.

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