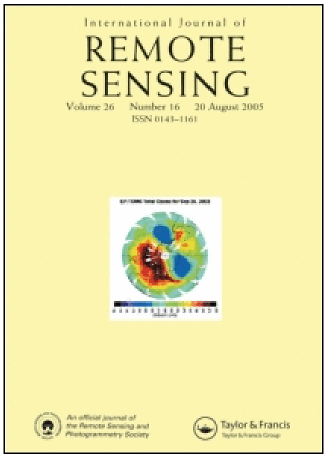

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A practical split-window algorithm for retrieving land-surface temperature from MODIS data

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This paper presents a practical split-window algorithm utilized to retrieve land-surface temperature (LST) from Moderate-resolution Imaging Spectroradiometer (MODIS) data, which involves two essential parameters (transmittance and emissivity), and a new method to simplify Planck function has been proposed. The method for linearization of Planck function, how to obtain atmosphere transmittance from MODIS near-infrared (NIR) bands and the method for estimating of emissivity of ground are discussed with details. Sensitivity analysis of the algorithm has been performed for the evaluation of probable LST estimation error due to the possible errors in water content and emissivity. Analysis indicates that the algorithm is not sensitive to these two parameters. Especially, the average LST error is changed between 0.19–1.1°C when the water content error in the simulation standard atmosphere changes between −80 and 130%. We confirm the conclusion by retrieving LST from MODIS image data through changing retrieval water content error. Two methods have been used to validate the proposed algorithm. Results from validation and comparison using the standard atmospheric simulation and the comparison with the MODIS LST product demonstrate the applicability of the algorithm. Validation with standard atmospheric simulation indicates that this algorithm can achieve the average accuracy of this algorithm is about 0.32°C in LST retrieval for the case without error in both transmittance and emissivity estimations. The accuracy of this algorithm is about 0.37°C and 0.49°C respectively when the transmittance is computed from the simulation water content by exponent fit and linear fit respectively.

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 efforts have been devoted to the establishment of methodology for retrieving LST from remote sensing data.

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A variety of split-window methods have been developed to retrieve sea-surface temperature and land-surface temperature from National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR) data. The split-window LST method utilizes the differential absorption in adjacent thermal band to correct the atmospheric effects (Price 1984, Wan *et al.* 1989, Becker and Li 1990a, Sobrino and Coll 1991, Vidal 1991, Kerr 1992, Otlle and Stoll 1992, Prata 1994, Wan and Dozier 1996, Qin *et al.* 2001). The form of these algorithms is the same as the general one, but the calculation of parameters is different. Price (1984) assumed the ground surface as a blackbody in his derivation. Several modifications to the algorithm of Price have been proposed. Coll *et al.* (1994) consider the satellite zenith observation θ and surface emissivity ε of band i into the radiation transfer equation and modify this algorithm into a new form accordingly. Except for the transmittance and ground emissivity, this algorithm requires the prior knowledge of atmosphere. Sobrino *et al.* (1991) developed a methodology for atmospheric and emissivity correction. Ground emissivity, atmospheric transmittance and two further parameters (water content of atmosphere and parameter stating atmospheric absorption) are involved in their algorithm. Through a complicated radiation transfer equation, França and Cracknell (1994) established two atmospheric correction models for retrieving LST. The water content and an atmospheric parameter are also needed in this algorithm. Li and Becker (1993) propose a method to estimate both land-surface emissivity and LST using pairs of day/night co-registered AVHRR images, which need atmosphere profile information. Wan *et al.* (1996) propose a general split-window algorithm; this algorithm considers the viewing angle and gets high accuracy of LST retrieval, which still needs the prior knowledge of the water content of atmosphere. Wan and Li (1997) propose a multi-band algorithm to retrieve land-surface emissivity and LST from Earth Observation System/Moderate-resolution Imaging Spectroradiometer (EOS/MODIS), which is only influenced by the surface optical properties and the ranges of atmospheric condition. The accuracy of these two algorithms is under 1°C (Wan *et al.* 2002, 2004). Gillespie and Matsunaga (1998) propose an algorithm to retrieve temperature and emissivity from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The accuracy of this algorithm output temperature and emissivity images are dependent on the empirical relationship between emissivity values and spectral contrast, compensation for reflected sky irradiance, and ASTER's precision, calibration, and atmospheric compensate.

The accuracy of most algorithms is very high but they still need to make some assumptions regarding prior knowledge of atmosphere (especially water content). Owing to different considerations of the atmospheric effect on the radiation transfer through the air, the prior knowledge required is different. Qin *et al.* (2001) make some reasonable simplifications for the radiation transfer equation and propose a split-window algorithm, which needs only two parameters (emissivity and transmittance) and the accuracy of retrieval LST is under 2°C. Qin *et al.* (2001) develop a method to compute the transmittance from water content of atmosphere, but it still needs the prior knowledge of water content, which often is got from the meteorology station.

Harris *et al.* (1992) and Sobrino *et al.* (1993) conclude that including column water vapour in the split-window algorithms can improve sea-surface temperature (SST) accuracy. Barton (1991) explored the possibility to derive water vapour absorption coefficients from satellite thermal infrared (TIR) data.

MODIS is an EOS instrument that has 36 bands. MODIS is particularly useful because of its global coverage, radiometric resolution and dynamic ranges, and accurate calibration in multiple thermal infrared bands designed for retrievals of SST, LST and atmospheric properties. Nowadays, only two algorithms proposed by Wan *et al.* (1996, 1997) have been published and some applications use the split-window developed for NOAA/AVHRR to retrieve the LST. In order to fully utilize the advantage of band characters which develop for the monitoring of land, sea and air, we propose a practical split-window to retrieve LST from MODIS data based on the algorithm proposed by Qin *et al.* (2001) to retrieve the LST from AVHRR data. The main advantage of our algorithm is that we get the transmittance from retrieval water content by near-infrared (NIR) bands of MODIS and make the computation of transmittance accurate for every pixel. However, we find that our algorithm is not sensitive to the water content of atmosphere.

2. The approach of research

The frame method and routine of this research can be described as figure 1. At first, we analyse the current algorithms, and select an algorithm proposed by Qin (2001) as the base of an algorithm improved by us and therefore suitable to retrieve LST from MODIS data. Then we utilize a method to simplify the Planck function, not by Taylor expansion.

Second, according to the character of the MODIS data, we propose a method to estimate the parameters (transmittance and emissivity). Atmospheric transmittance is an essential parameter for the retrieval of LST, which influences the accuracy of the retrieval of LST. The knowledge of temperature and humidity profiles is needed in atmospheric transmittance calculations. These profiles can be estimated with the

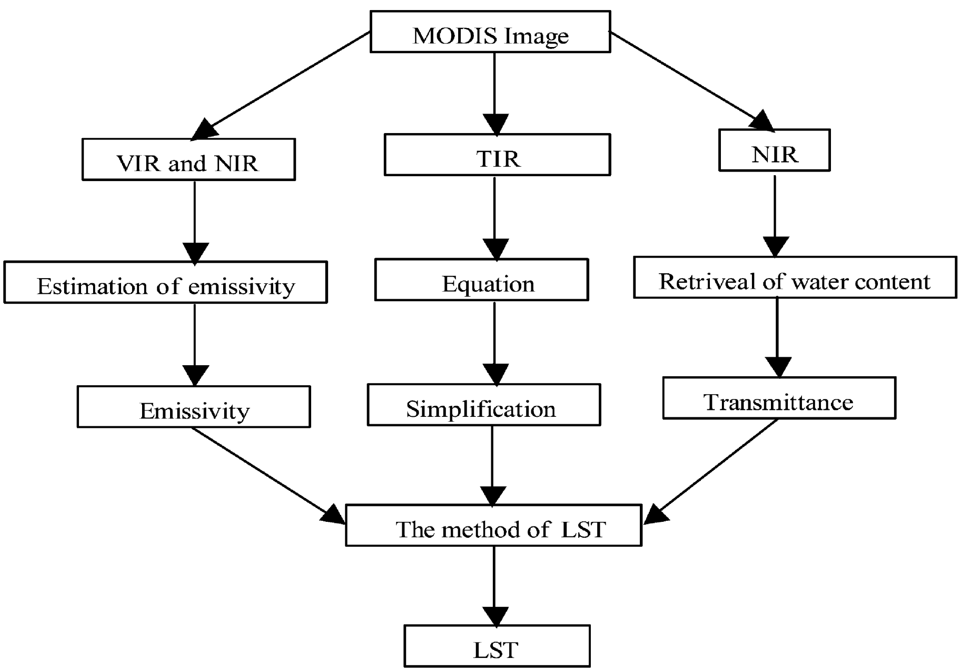

Figure 1. Map of retrieving LST by MODIS.

use of radiosonde data. However, radiosonde measurements are performed only at upper atmosphere stations (radiosonde stations) and not in every meteorological station. Studies based on these data usually suffer from data deficiency and reliability that comes from the sparse existing radiosonde stations network. However, the data of atmosphere and the MODIS image are not obtained simultaneously, so it may produce some error and influence the accuracy of the retrieval. According to the character of NIR band sensitivity in relation to the water content of atmosphere, we retrieve the water content of atmosphere from the MODIS image and furthermore estimate the transmittance of every pixel of image by the water content of atmosphere, which overcomes the problem of only one transmittance in an image in many split-window algorithms. This estimation is more suitable to the real world. For the other parameter (emissivity), we think the pixel is mainly composed of three components (vegetation, soil, water) under the 1 km scale of the thermal band at nadir. After analysing the method of emissivity of land surface, we think we can make the accuracy estimation of emissivity further to sub-pixel. Of course, this estimation method of emissivity is not very suitable for artificial surfaces, for example, urban. Finally, we utilize standard atmosphere simulation and MODIS LST product to validate our algorithm and make some sensitivity of the parameters, especially for water content.

3. The simplification of Planck function, estimation of transmittance and emissivity

The radiance transfer equation is the base of thermal remote sensing and LST retrieval. Planck function is the kernel part of the radiance transfer equation. Because of the complication of the Planck function, the simplification of the Planck function is the precondition of LST retrieval. In this paper, we simulate the relationship between radiance of MODIS31/32 and the temperature and propose a method to simplify the Planck function. The transmittance of atmosphere and emissivity of land surface are the two key parameters of LST retrieval. Transmittance is often attained from the simulation of atmosphere software (6S, LOWTRAN, MODTRAN, etc.). In this paper, we utilize the sensitivity of NIR in relation to the water content of atmosphere, calculate the water content of atmosphere, then compute the transmittance furthermore. The emissivity of land surface is estimated from visible and infrared (VIR) and NIR band of MODIS data.

3.1 *The simplification of Planck function*

The derivation of the algorithm for 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 thermal 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 (Ottle and Stoll 1993) for remote sensing of LST can be formulated as follows:

$$B_i(T_i) = \tau_i(\theta)\left[\varepsilon_i B_i(T_s) + (1-\varepsilon_i)I_i^{\downarrow}\right] + I_i^{\uparrow} \tag{1}$$

where T_s is the LST, T_i is the brightness temperature in channel i, $\tau_i(\theta)$ is the atmospheric transmittance in band i at viewing direction θ (zenith angle from nadir), and ε_i is the ground emissivity. $B_i(T_s)$ is the ground radiance, and $I_i{}^{\uparrow}$ and $Ii^{\downarrow}$ are the downwelling and upwelling path radiances, respectively. Every term of radiance transfer equation owes the Planck function. From equation (1), we can see that we need to simplify the radiance transfer equation if we need to solve the equation. This is very important for the mono-window algorithm and split-window algorithm. Price (1984), França and Cracknell (1994), Coll *et al.* (1994) and Qin *et al.* (2001) make a tailor extension. The product of LST usually utilize the look-up table (LUT) which utilize the linear interpolate to simplify the Planck function. In fact, we think the essence of these two methods is the same and that the Planck function can be simplified in linear equation (2):

$$B_i = a_i + b_i T_i \tag{2}$$

We compute the radiance by Planck function between 273 and 322 K in temperature for the effect wavelength of MODIS31/32. For MODIS31/32 figure 2 is the scatter plot. Figure 2 indicates that the radiance and temperature are satisfied with an approximate linear relationship. We make a linear fit for MODIS31/32.

$$\text{For band 31}: B_{31}(T) = 0.13787 T_{31} - 31.65677,\ R^2 = 0.9971 \tag{3a}$$

$$\text{For band 32}: B_{32}(T) = 0.11849 T_{32} - 26.50036,\ R^2 = 0.9978 \tag{3b}$$

See from figure 2 and the squared correlation coefficients (R^2), the accuracy of approximative methods is very high. Of course, we can make a higher linear approximate by separating through a greater range of temperatures.

3.2 *Determination of atmospheric transmittance*

Atmospheric transmittance is a critical parameter that affects the accuracy of LST retrieval using the split-window algorithm. The thermal radiance is attenuated on its way to the remote sensor. Transmittance depicts the magnitude of the attenuation of the radiance transfer through the atmosphere. It varies with wavelength and viewing angle. Many atmospheric constituents such as carbon dioxide, nitrogen oxide, ozone oxide, methane, carbon monoxide, and other gases having impacts can be assumed as constant and simulated by standard atmospheric profiles. On the contrary, water content is highly variable. Thus the variation of

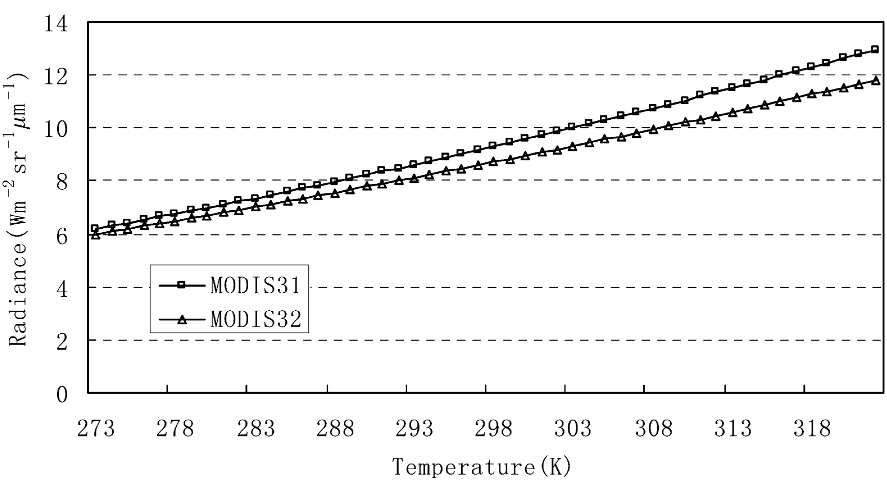

Figure 2. Relationship of temperature and radiance for MODIS bands 31 and 32.

atmospheric transmittance strongly depends on the dynamics of water content in the profile, especial for thermal bands. Consequently, many split-window algorithms relate the determination of atmospheric transmittance to the change of water content while assuming other impacts as constant (Sobrino *et al.* 1991, Coll *et al.* 1994, Franca *et al.* 1994).

Because of many technical difficulties, atmospheric transmittance is usually not available at *in situ* satellite passes; the most practical way to determine the atmospheric transmittance is through simulation with local atmospheric conditions, especially water vapour content. Qin *et al.* (2001) give a statistical linear fit expression of transmittance with the change of water vapour content in mid-latitude through the simulation by LOWTRAN. Because it is very difficult to get water vapour content at *in situ* satellite passes, we often use the water vapour measured by the meteorology station instead. These meteorology stations are distributed sparsely and the number is limited, so the accuracy of this simulation is sometimes not guaranteed and it contains the application of the statistical expression of transmittance with the change of water vapour content. Due to the character of the MODIS bands, we can retrieve the water vapour of atmosphere from the NIR bands of MODIS and compute the transmittance of every pixel thereafter.

3.2.1 The retrieval method of water content through MODIS data. In order to improve the accuracy of the estimation of water content in the atmosphere, Chesters *et al.* (1983), Fraser and Kaufman (1985), Grant (1990), Kaufman and Gao (1992), King *et al.* (1992) and Czajkowski *et al.* (2002) do many jobs for the retrieval of water content of atmosphere. They often use TIR to retrieve water content of atmosphere, but the result of retrieval depends on the initial temperature and the selection of humidity profiles. Among the 36 bands of MODIS, five of them are NIR bands: 2 (0.865 μm), 5 (1.24 μm), 17 (0.905 μm), 18 (0.936 μm) and 19 (0.940 μm). Bands 17, 18 and 19 are three absorption bands, but bands 2 and 5 are atmosphere window bands. The purpose of devise is in order to retrieve the water content of atmosphere from the MODIS image. In this paper, we retrieve directly the water content of atmosphere from the MODIS image, and estimate further the transmittance, which improves the accuracy and the timely estimation of transmittance.

Kaufman *et al.* (1994) do many experiments and conclude that the retrieval of water content by ratio is available. The details can refer to the Kaufman and Gao (1992). Five bands in MODIS are devised to retrieve water content according to this principle. Bands 17, 18 and 19 are band absorption. Bands 2 and 5 are window bands of atmosphere. The two and three band ratio approaches to retrieve the water content of the atmosphere. The equations are as follows:

$$\tau_w(i) = \rho(i)/\rho(2) \tag{4}$$

$$\tau_w(i) = \rho(i)/[\mathrm{C1}\cdot\rho(2) + \mathrm{C2}\cdot\rho(5)] \tag{5}$$

$\rho(i)$ (i=17, 18, 19), $\rho(2)$ and $\rho(2)$ represent the reflectance of bands i, 2, 5 respectively, τ_w represents the transmittance of i, C1 and C2 are coefficients. For band 18, C1 equals 0.8. C2 equals 0.2 (C1 and C2 are computed according to the linear approximate between three bands reflectance at the ground). The two approaches retrieve the water content of atmosphere by utilizing the same principles that use the relationship between water content and the ratio of absorption band and the window band of atmosphere. For the relationship of water content and transmittance of atmosphere, we can utilize the LOWTRAN, MODTRAN, etc. to simulate and secure the statistical expression. Kaufman and Gao (1992) give the expression as equation (6):

$$\tau_w(19/2) = \exp\left(\alpha - \beta\sqrt{w}\right) \quad R^2 = 0.999 \tag{6}$$

For complex ground, α=0.02, β=0.651 (Kaufman and Gao 1992 give a description of the details). τ_w (transmittance) can be computed from the image, so we can get the water content of the atmosphere through equation (7).

$$w = \left(\frac{\alpha - \ln\tau_w}{\beta}\right)^2 \tag{7}$$

Kaufman and Gao (1992) make a lot of experiments and analysis for different conditions and conclude that the accuracy of retrieval water by MODIS instrument is −13% to 13% in the cloud-free conditions. The accuracy will be higher if we use additional MODIS channels to decrease the effect of uncertainty in the spectral reflectance of surface, sub-pixel clouds, haze and temperature profile, etc.

3.2.2 The simulating computation of transmittance from water vapour content. The transmittance of atmosphere can be estimated by MODTRAN, LOWTRAN. The estimation of simulation needs atmosphere profiles as an input parameter, but it is very difficult to get timely atmosphere profiles. We often use standard atmosphere instead and revise it according to the real world. Because the situation of weather is variable, the accuracy of simulation is sometimes not very high. Qin *et al.* (2001) propose a method to estimate the transmittance of atmosphere; that is, estimating the water content of atmosphere through the statistical expression that is attained by the simulation of LOWTRAN. We also simulate the range of band by LOWTRAN suitable for MODIS31/32. From simulation data, we know the transmittances of MODIS31/32 are prominently different at the same water content. With the increase of water content of atmosphere, this difference of transmittance also increases and the transmittance is also the function of temperature, although the temperature influences little relative to the water content. Of course, the transmittance is also the function of other gases, although we usually omit that. With the increase of the water content of atmosphere, the transmittance of MODIS31/32 decreases. After analysing the influence of aerosol content and other atmospheric constituents, we find that the transmittance of aerosol content and atmospheric constituents is almost above 0.95 in the region of 8–14 μm through simulation by MODTRAN. So we mainly consider the water content in the expression of water content and transmittance. We make the scatter plot of water content of atmosphere and transmittance of MODS31/32. The results are described as figure 3. The transmittance of MODIS31/32 and water content of atmosphere are approximately satisfied as a linear relationship.

In this paper, we make some analysis for these simulated data and the relationship of transmittance with the change of water vapour content and conclude that the accuracy will be higher if we use exponent fit.

We make exponent fit for these data. The equation for MODIS31/32 is as follows.

$$\text{For band 31}: \tau_{31} = 2.89798 - 1.88366e^{-(w/-21.22704)},\ R^2 = 0.99748 \tag{8a}$$

$$\text{For band 32}: \tau_{32} = -3.59289 + 4.60414e^{w/-32.70639},\ R^2 = 0.99685 \tag{8b}$$

The squared correlation coefficients (R^2) of exponent fit is higher than the linear fit

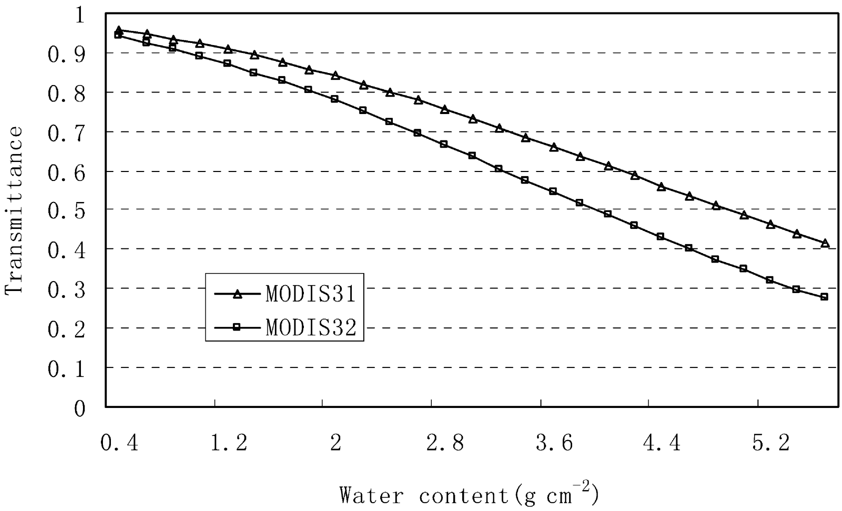

Figure 3. Relationship of atmospheric transmittance and water vapour content for MODIS bands 31 and 32 under mid-latitude atmosphere.

that Qin *et al.* (2001) give, so we can more accurately guage the transmittance of MODIS31/32 through the water content of atmosphere. We will give some analysis for these two fit expressions that influence the accuracy of retrieval of LST, because we can compute the water content of atmosphere of every pixel from MODIS and then make the estimation of transmittance of MODIS31/32 accurate to every pixel.

3.3 *Determination of emissivity of ground*

Emissivity of surface ground is also a critical parameter that affects the accuracy of retrieval LST using split-window algorithm. Many researches have been done on this aspect (Becker 1987, Becker and Li 1990b, Kerr and Lagouarde 1992, Griend and Owe 1993, Li and Becker 1993, Göita and Royer 1997, Wan and Li 1997, Sobrino *et al.* 2001). Especially Becker and Li (1993) utilized the Temperature-independent Spectral Indices (TISI) method to retrieve emissivity and get high accuracy. Emissivity is often assumed as constant or estimated with empirical knowledge for split-window algorithms. In this paper, we assume the pixel of MODIS is composed of three components (vegetation, soil, water) under 1 km scale of the thermal band at nadir, which enables us to use empirical knowledge for emissivity estimation.

3.3.1 The method of estimation of emissivity of ground. The emissivity is mainly determined by the structure of ground surface and the range of spectral band considered. The emissivity of ground is altered with the change of the wavelength. Labed *et al.* (1991), Salisbury *et al.* (1992) and Sobrino *et al.* (2001) analysed the emissivity of terrestrial materials in the 8–14 μm and concluded that the emissivity of most terrestrial materials changes little in the range of 8–14 μm. Using the ASTER spectral database (URL: http://speclib.jpl.nasa.gov), we find that most terrestrial materials have an emissivity higher than 0.97 with small changes in the ranges of MODIS31/32 (10.780–11.280 μm and 11.770–12.270 μm). Although the ground surface is very complex in composition structure, three main components (vegetation, soil, water) can be distinguished. Generally speaking, the pixels of MODIS can be classified into two groups in most cases: (1) water pixels, and (2) land pixels mainly composed of various fractions of vegetation and soil. For water pixels, we can directly use the spectral emissivity of water in the two MODIS thermal bands for its LST retrieval. For the land pixels, we can estimate its emissivity according to the relationship between emission and vegetation fraction, using the following formula:

$$\varepsilon B(T) = P_v \varepsilon_{\mathrm{v}} B(T_v) + (1 - P_v)\varepsilon_s B(T_s) \tag{9a}$$

$$\varepsilon = P_v R_v \varepsilon_{\mathrm{v}} + (1 - P_w - P_v) R_s \varepsilon_{\mathrm{s}} \tag{9b}$$

where ε is the average emissivity of the mixed pixel. T is the average temperature of the pixel and T_i (i=v, s) is the component temperature. P_v represents the vegetation fraction. ε_{v} and ε_{s} denote the emissivity of vegetation and soil, respectively. R_v and R_s are the radiance ratio, defined as

$$R_i = B(T_i)/B(T) \tag{10}$$

where i denotes vegetation (i=v) and soil (i=s). This ratio is roughly viewed as 1. Qin *et al.* (2004) presented an elaborate determination of the ratio for accurate LST retrieval from Landsat Thematic Mapper (TM) 6 data, using a simulation procedure with various combinations of soil–vegetation temperatures and vegetation fraction. According to their ground temperature measurements in Israeli desert, Qin *et al.* (2005) found that the vegetation temperature was generally about 10–12°C lower than bare ground at very high temperature conditions such as 50°C over bare ground. However, the temperature difference between vegetation and bare ground tends to be little at low temperature conditions such as about 15°C over bare ground. Using the relationship, we can assume the simultaneous change of vegetation and soil temperatures (T_v and T_s) in the range of 0–50°C. Then we can use equation (9*a*) to estimate the average pixel temperature (T) for various vegetation cover fractions (0–1.0). Finally, we are able to approximate the radiance ratio with equation (10). Though the ratio may vary with temperature and vegetation fraction, Qin *et al.* (2004) gave the following accurate estimation of the ratio from vegetation fraction of the pixel:

$$R_v = 0.9332 + 0.0585 P_v \tag{11a}$$

$$R_s = 0.9902 + 0.1068 P_v \tag{11b}$$

A rough estimation may be enough for pixel emissivity determination. According to Qin *et al.* (2004), we average its changes with vegetation fraction to give R_v=0.966158 and R_s=1.04359 for land pixels.

In order to estimate the emissivity of MODIS31/32, we need to estimate the ratio of components in a pixel. In fact, it is difficult to estimate the ratio of components in a pixel. In this paper, we think we may utilize P_v index to approximately estimate the ratio of vegetation, water and soil in a pixel under 1 km scale. Due to the strong absorption of water in VIR band, especially in red band, the reflectance ratio is often under 5%. Of course, an NIR band would be much better when there is vegetation. So the digital number (DN) value is lower than the land surface. If there were plenty of water in the image, we can extract many pixels of water, and make it compare with the DN value of land. If the DN value of a pixel is smaller than the largest DN of a water pixel, we regard it as water and make P_w=1. For the pixel of the bank of ocean, we may use equation (12) to approximately estimate the ratio of water.

$$P_w = \mathrm{QDN}/\mathrm{DNI} \tag{12}$$

QDN represents reflectance of the pixel. DNl represents the least reflectance of land pixel, which is attained by samples obtained from the image. For the pixel of land surface, we may use equation (13) to estimate the ratio of vegetation through NDVI:

$$\mathrm{NDVI} = (\mathrm{B2} - \mathrm{B1})/(\mathrm{B2} + \mathrm{B1}) \tag{13}$$

B2 and B1 represent the reflectance value of bands 2(NIR) and 1(RED) of MODIS2/1. Then we can use equation (14) (Kerr and Lagouarde 1992) to estimate P_v, the ratio of vegetation in a pixel.

$$P_v = (\mathrm{NDVI} - \mathrm{NDVI}_s)/(\mathrm{NDVI}_v - \mathrm{NDVI}_s) \tag{14}$$

NDVI_v and NDVI_s represent the NDVI of vegetation and soil. We approximately take NDVI_v=0.65 and NDVI_s=0.05 (Kerr *et al.* 1992). The P_v can also be estimated (Carlson *et al.* 1997) by equation (15)

$$P_v = [(\mathrm{NDVI} - \mathrm{NDVI}_s)/(\mathrm{NDVI}_v - \mathrm{NDVI}_s)]^2 \tag{15}$$

For the emissivity of vegetation, soil, water, we may use the equation (16) (Wan and Li 1997) to estimate the average emissivity of two or three components

$$\bar{\varepsilon}_i = \frac{\int_{\lambda(i,\,lower)}^{\lambda(i,\,upper)} \psi_i(\lambda)\varepsilon_i(\lambda)\mathrm{d}\lambda}{\int_{\lambda(i,\,lower)}^{\lambda(i,\,upper)} \psi_i(\lambda)\mathrm{d}\lambda} \tag{16}$$

where ε_i is average emissivity, $\psi_i(\lambda)$ is the spectral response function of the sensor in band i, $\varepsilon_i(\lambda)$ is the emissivity function with the change of spectral wavelength. We get the emissivity function from the spectral database of the ground supplied by ASTER. We get the curve of emissivity and, through analysis, and find that the emissivity of most terrestrial materials is higher than 0.97 and changes very little in the ranges of MODIS31/32 (10.780–11.280 μm and 11.770–12.270 μm). Considering the scale of the MODIS image character, we utilize the average of emissivity of three representative terrestrial materials to compute. For band 31, the values of the vegetation, soil and water are approximately 0.972, 0.986, 0.992, respectively; for band 32, the values of the vegetation, soil and water are approximately 0.976, 0.991, 0.988, respectively.

4. Split-window algorithm

Split-window algorithm is previously proposed to retrieve LST for NOAA/AVHRR 4/5. This technology used to retrieve SST and the accuracy of the retrieval is about 0.77k. The retrieval of SST is the base of retrieval of LST. There are many influence factors, such as; the selection of radiance transfer method, absorption coefficient of gas (especially water) and the scatter coefficient are variable. In the previous algorithm of SST and LST, we often use LOWTRAN, 6S, MODTRAN to computer the parameters of atmosphere. So it has some difficulties to rectify the radiance of atmosphere and land surface and the accuracy of retrieval of LST often cannot be guaranteed.

So far, at least 18 split-window algorithms have been published. The general algorithm of split-window can be depicted as follows:

$$T_s = T_4 + A(T_4 - T_5) + B \tag{17}$$

T_s represents LST. A and B are parameters. T_4 and T_5 are brightness temperatures of AVHRR 4/5, respectively. The unit of T_s, T_4, T_5 is K.

In this paper, the derivation of our split-window algorithm of retrieving LST is based on the split-window algorithm proposed by Qin *et al.* (2001). This algorithm requires only two parameters (transmittance and emissivity) and the accuracy of this algorithm is very high.

4.1 *The derivation of split-window algorithm for MODIS data*

The derivation of split-window algorithm is based on radiance transfer equation (1). Qin *et al.* (2001) identify a detailed derivation for the $I_i^{\uparrow}$ and $I_i^{\downarrow}$, which can be depicted as follows:

$$I_i^{\uparrow} = (1 - \tau_i(\theta'))B_i(T_a) \tag{18}$$

$$I_i^{\downarrow} = (1 - \tau_i(\theta'))B_i\left(T_a^{\downarrow}\right) \tag{19}$$

T_a is the average temperature of upward radiance of atmosphere. $T_a^{\downarrow}$ is the average temperature of the downward radiance of atmosphere. Using $I_i^{\uparrow}$ and $I_i^{\downarrow}$ represent equation (1),

$$B_i(T_i) = \tau_i(\theta)\left[\varepsilon_i B_i(T_s) + (1-\varepsilon_i)(1-\tau_i(\theta))B_i\left(T_a^{\downarrow}\right)\right] + (1-\tau_i(\theta'))B_i(T_a) \tag{20}$$

In order to simplify the equation, Qin *et al.* (2001) make some reasonable simplifications and analysis; they conclude that it has not much influence if using T_a instead $T_a^{\downarrow}$, so the equation can be depicted as equation (21)

$$B_i(T_i) = \tau_i(\theta)\varepsilon_i B_i(T_s) + [1-\tau_i(\theta)][1 + (1-\varepsilon_i)\tau_i(\theta)]B_i(T_a) \tag{21}$$

For MODIS31/32, the equation can be depicted as follows:

$$B_{31}(T_{31}) = \tau_{31}(\theta)\varepsilon_{31}B_{31}(T_s) + [1-\tau_{31}(\theta)][1 + (1-\varepsilon_{31})\tau_{31}(\theta)]B_{31}(T_a) \tag{22a}$$

$$B_{32}(T_{32}) = \tau_{32}(\theta)\varepsilon_{32}B_{32}(T_s) + [1-\tau_{32}(\theta)][1 + (1-\varepsilon_{32})\tau_{32}(\theta)]B_{32}(T_a) \tag{22b}$$

In equation (22), the Planck function makes the equation complicated. So, we should simplify the equation before solving the equation. In the previous research, researchers often use Taylor extension to Planck function. In this paper, we use the method proposed by us to simplify the Planck function. We use $B_{31}(T)$=0.13787T_{31} − 31.65677 and $B_{32}(T)$=0.11849T_{32} − 26.50036 instead of Planck function of (22), then:

$$\begin{aligned} 0.13787\varepsilon_{31}\tau_{31}T_s = {} & 0.13787T_{31} + 31.65677\varepsilon_{31}\tau_{31} - (1-\tau_{31})[1 + (1-\varepsilon_{31})\tau_{31}] \\ & (0.13787T_a - 31.65677) - 31.65677 \end{aligned} \tag{23a}$$

$$\begin{aligned} 0.11849\varepsilon_{32}\tau_{32}T_s = {} & 0.11849T_{32} + 26.50036\varepsilon_{32}\tau_{32} - (1-\tau_{32})[1 + (1-\varepsilon_{32})\tau_{32}] \\ & (0.11849T_a - 26.50036) - 26.50036 \end{aligned} \tag{23b}$$

For comparational convenience, we simplify the coefficient of equation (23) as follows:

$$A_{31} = 0.13787\varepsilon_{31}\tau_{31}$$

$$B_{31} = 0.13787T_{31} + 31.65677\tau_{31}\varepsilon_{31} - 31.65677$$

$$C_{31} = (1-\tau_{31})(1+(1-\varepsilon_{31})\tau_{31})0.13787$$

$$D_{31} = (1-\tau_{31})(1+(1-\varepsilon_{31})\tau_{31})31.65677$$

$$A_{32} = 0.11849\varepsilon_{32}\tau_{32}$$

$$B_{32} = 0.11849\, T_{32} + 26.50036\, \tau_{32}\, \varepsilon_{32} - 26.50036$$

$$C_{32} = (1-\tau_{32})(1+(1-\varepsilon_{32})\tau_{32})0.11849$$

$$D_{32} = (1-\tau_{32})(1+(1-\varepsilon_{32})\tau_{32})26.50036$$

The equation (23) can be depicted as (24)

$$A_{31}T_S = B_{31} - C_{31}T\text{a} + D_{31} \qquad (24a)$$

$$A_{32}T_S = B_{32} - C_{32}T\text{a} + D_{32} \qquad (24b)$$

Solving the equation (24), the LST can be secured through (25

$$T_s = (C_{32}(B_{31}+D_{31}) - C_{31}(D_{32}+B_{32}))/(C_{32}A_{31} - C_{31}A_{32}) \qquad (25)$$

From the equation (25), the coefficient of A_i, B_i, C_i, D_i can be computed if the transmittance and emissivity of land surface. In §3, we have solved these two parameters, so this algorithm is now available. Of course, we can also change equation (25) into equation (26)

$$T_s = T_{31} + A(T_{31} - T_{32}) + B \qquad (26)$$

5. Sensitivity analysis and validation of the algorithm

Sensitivity analysis is necessary in many applications where the knowledge about probable LST estimation due to possible errors in parameter determination is generally desired. We make some sensitivity analysis for key parameters (emissivity and transmittance), and especially make some analysis of the water content of atmosphere because it is the main influence factor of transmittance.

Validation is also important in order to know how well the retrieved LST is when we apply with the algorithm in the real world. In this paper, we use two methods to validate our algorithm: standard atmospheric simulation and compare with MODIS LST product.

5.1 *Sensitivity analysis of the split-window algorithm*

In order to evaluate the impact of parameter errors on LST retrieval, we need to perform the sensitivity analysis of our split algorithm. We commonly utilize equation (27) to compute the probable LST estimation error ΔT as follows:

$$\Delta T = |T_s(x+\Delta x) - T_s(x)| \qquad (27)$$

where x is the parameter that influences the estimation error of LST retrial, Δx is the possible parameter error. In this paper, we make a few approximations for the transfer equation, so it has some errors relative to the truth LST which is simulated by LOWTRAN even though we utilize the truth parameters. In order to evaluate the influence of the these approximations and parameter errors to retrieve LST, we make the $T_s(x+\Delta x)$ to compare with truth LST, not the $T_s(x)$ which includes some error due to the approximation. We utilize equation (28) instead

$$\Delta T = |T_s(x+\Delta x) - T_s| \tag{28}$$

For our algorithm, the water content is the main influence factor for the accuracy of LST. In this paper, we utilize the standard atmosphere simulation (the sensitivity analysis based standard atmosphere simulation data, see table 1) to analyse the sensitivity of water content. Table 2 is part of retrieval results through changing the error of the water content of atmosphere. The second line presents the increase times of water content error relative to the real water content. LST error presents the difference between the truth LST and the retrieval LST. rms presents the root mean square. We can see from table 2 that the highest accuracy of the retrieval LST is not in the real water content. It is very interesting that, we find, the less water content is relative to the real water content, the higher the accuracy of the retrieval of LST. In order to understand that clearly, we make more detailed analysis for the sensitivity of water content with transmittance computed from exponent fit. (The results are given in figure 5.) The transmittance of MODIS31/32 is computed by $\tau_{31} = 2.89798 - 1.88366e^{-(w/-21.22704)}$ and $\tau_{32} = -3.59289 + 4.60414e^{w/-32.70639}$ (w represents water content). The accuracy of retrieval LST (the average LST error is about 0.18°C, rms is about 0.26) is highest and the average transmittance error of MODIS31/32 is about 0.09 and 0.12, respectively, when the water content error is about -60% of the real water content. On the contrary, the LST error is about -0.37°C and the average transmittance 31/32 error is about 0.013 and 0.015 when we compute the transmittance from the real water content. LST error is changed between 0.18–1.1°C when the water content error change between -80% and 130% and the relative transmittance error is changed between 0.014 and 0.31. From §3.2.1 and Kaufman and Gao (1992), we know that the absolute accuracy of retrieval water content from MODIS instrument is -13% and 13% in the cloud-free conditions, so the method that computes the transmittance from the water content can improve the practicality of split window because the algorithm is not sensitive to water content. The reason is that the water content error control in the MODIS31/32 transmittance 31/32 error change trends as a relationship in the retrieval equations. From table 1 and figure 4, we can improve the retrieval accuracy if we utilize the reasonable prior knowledge. From figure 4, we know that the highest accuracy is about -60% error of water content. The reasons are caused by the simplification of the Planck function, the simplification of the radiance transfer equation and the transmittance computed from water content. In fact, the transmittance is not the only function of water content, where further contributory factors are the temperature, angle, other gases and other factors. In order to prove our conclusion, we retrieve LST from MODIS image data (see figure 9) through changing retrieval water content error. Figure 5 is the LST temperature profile retrieved by our algorithm in the different water content error retrieved by MODIS image. In order to analyse conveniently, we assumed that the retrieved water content from the MODIS image is right (no variance). From figure 5, the difference of retrieval LST is very little when the water content error changes in some range and

Table 1. The sensitivity analysis of parameters.

Water content error					LST error				
−40%	−20%	0%	20%	40%	−40%	−20%	0%	20%	40%
0.6	0.8	1	1.2	1.4	0.1242	0.09789	0.08525	0.08059	0.08135
0.6	0.8	1	1.2	1.4	0.03429	−0.0361	−0.0787	−0.106	−0.1237
0.6	0.8	1	1.2	1.4	−0.1021	−0.1975	−0.2565	−0.2955	−0.3221
0.6	0.8	1	1.2	1.4	−0.2391	−0.3489	−0.4165	−0.461	−0.4912
1.2	1.6	2	2.4	2.8	0.08701	0.05066	0.03302	0.0271	0.02962
1.2	1.6	2	2.4	2.8	−0.0203	−0.123	−0.1959	−0.2526	−0.3
1.2	1.6	2	2.4	2.8	−0.2034	−0.3361	−0.432	−0.5089	−0.575
1.2	1.6	2	2.4	2.8	−0.5626	−0.726	−0.8458	−0.9433	−1.0288
1.5	2	2.5	3	3.5	0.08398	0.0327	0.00135	−0.0182	−0.0304
1.5	2	2.5	3	3.5	0.00402	−0.1369	−0.2499	−0.3508	−0.4484
1.5	2	2.5	3	3.5	−0.1853	−0.3659	−0.5132	−0.647	−0.7783
1.5	2	2.5	3	3.5	−0.8439	−1.0781	−1.2727	−1.4527	−1.6318
Average LST error					0.2075128	0.29415781	0.36507701	0.42865414	0.48671697
rms					0.316705	0.422843	0.511533	0.59043	0.665658

Table 2. The summer simulation of atmosphere transformation in mid-altitude.

Water vapour ($g\,cm^{-2}$)	Emissivity		Transmittance		LST	Brightness temperature (K)	
	Emiss31	Emiss32	Trans31	Trans32	T_s°C	MODIS31	MODIS32
1 g	0.97	0.974	0.913	0.862	20	290.87	290.74
	0.97	0.974	0.9158	0.867	30	300.34	299.98
	0.97	0.974	0.9184	0.871	40	309.97	309.49
	0.97	0.974	0.920	0.875	50	319.68	319.14
2 g	0.97	0.974	0.817	0.722	20	290.47	290.10
	0.97	0.974	0.830	0.741	30	299.56	298.77
	0.97	0.974	0.843	0.759	40	309.06	308.07
	0.97	0.974	0.853	0.767	50	318.72	317.52
2.5 g	0.97	0.974	0.756	0.640	20	290.20	289.69
	0.97	0.974	0.774	0.665	30	299.03	298.01
	0.97	0.974	0.793	0.689	40	308.43	307.15
	0.97	0.974	0.814	0.703	50	318.14	316.53

we get the similar conclusion that our algorithm is not sensitive to water content. This further proves the practicality of our algorithm if we utilize some reasonable prior knowledge.

In order to understand the sensitivity of parameter transmittance and water content, we do some analysis for the change of transmittance. Figure 6(*a*) is LST error when we change the MODIS31/32 transmittance error at the same ratio. Figure 6(*b*) is the LST error when we change the MODIS31 error and the MODIS32 transmittance is right. Figure 6(*c*) is the LST error when we change the MODIS32 error and the MODIS31 transmittance is right. When the transmittance 31/32 changes between −0.07 and 0.08, the LST error changes between 0.11 and 0.98°C; when transmittance 31 error change between −0.01 and 0.08, the LST error change between 0.13 and 0.92°C; when transmittance 32 error change between −0.2 and

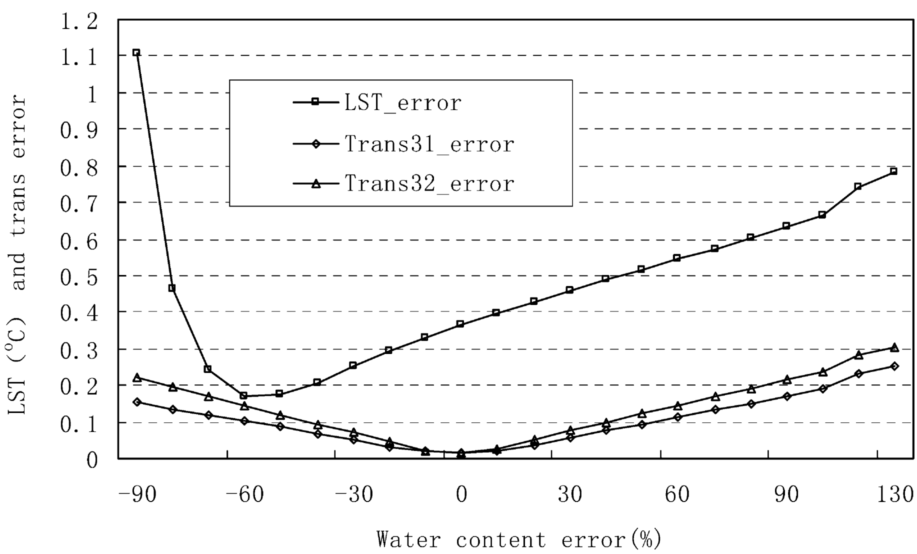

Figure 4. The change of LST and the transmittance error with the change of water content error.

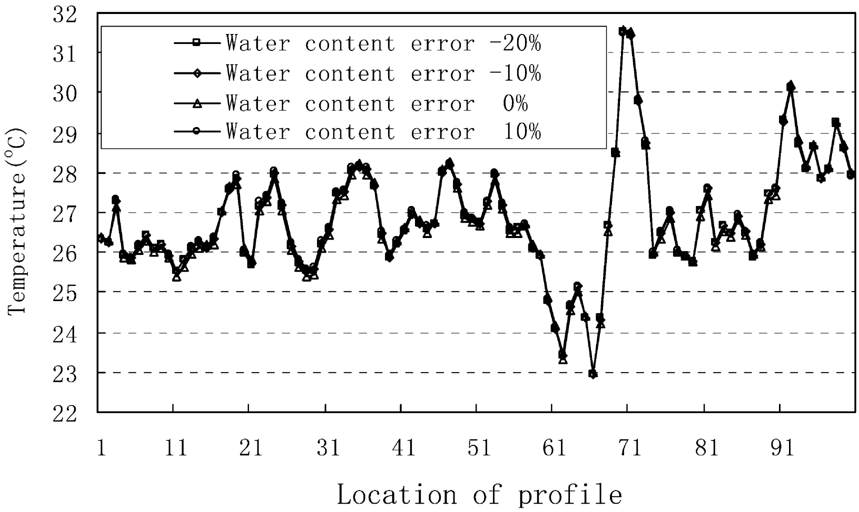

Figure 5. The retrieval temperature profile with changing of water content error (figure 9 MODIS data): (*a*) MODIS31/32 trans error; and (*b*) trans31 change but trans32 constant.

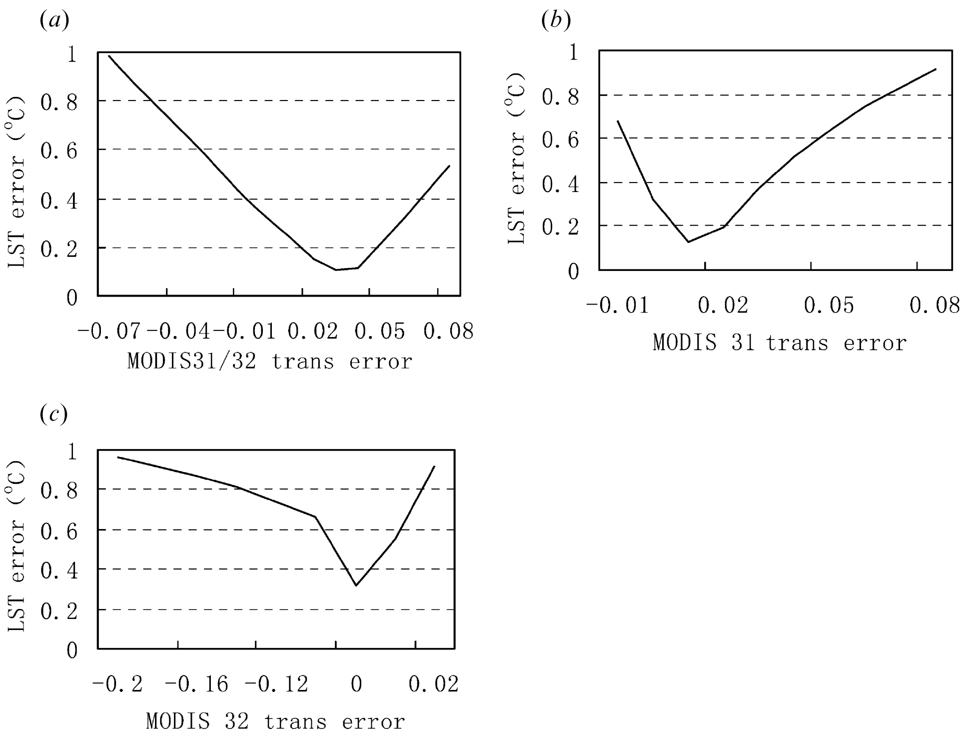

Figure 6. The change of LST error with the change of transmittance; (*a*) trans31/32 change at same ratio; (*b*) trans31 change but trans32 constant; and (*c*) trans32 change but trans31 constant.

0.02, the LST error change between 0.32 and 0.96°C. We can see from figure 6 that the parameter transmittance is sensitive for our split-window algorithm relative to the water content.

From the above analysis, the change of water content is not sensitive for our split-window algorithm. So we can make a conclusion that we can also get high retrieval accuracy of LST by our algorithm even though the retrieval water content from MODIS data is not very high. However, we can get a higher accuracy if we can utilize some prior knowledge according to figures 4 and 5.

In order to make a comprehensive evaluation of the sensitivity of the algorithm to ground emissivity, we also do some analysis for the change of emissivity error. Figure 7(*a*) is LST error when we change the MODIS31/32 emissivity at the same ratio. Figure 7(*b*) is the LST error when we change the MODIS31 emissivity error and the MODIS32 emissivity is right. Figure 7(*c*) is the LST error when we change the MODIS32 emissivity error and the MODIS31 emissivity is right. When the emissivity 31/32 changes between −0.01 and 0.02, the LST error changes between 0.168 and 1.116°C; when emissivity 31 changes between −0.004 and 0.009, the LST error change between 0.173–1.210°C; when emissivity 32 changes between −0.014 and 0.008, the LST error change between 0.204 and 1.135°C. On the other hand, we analyse the emissivity of the most terrestrial materials MODIS31/32 (10.780–11.280 μm and 11.770–12.270 μm) and find that most terrestrial material is higher than 0.97 and changes very little in the MODIS31/32. Therefore, we can conclude that our algorithm is not very sensitive to emissivity. Of course the soil fluctuates greatly with the change of environment among these three main terrestrial materials.

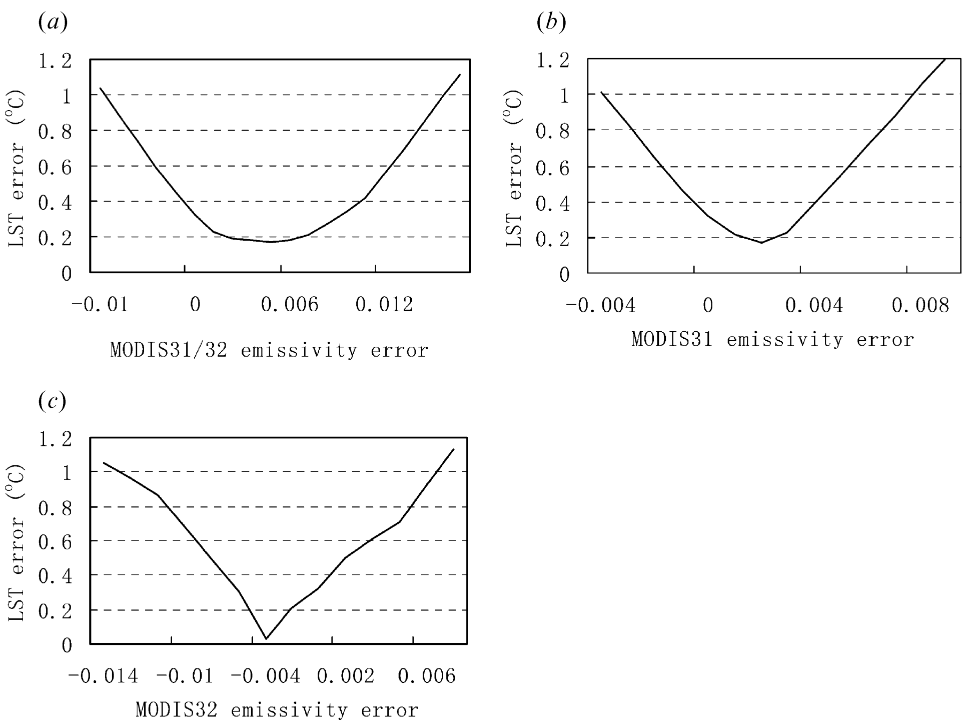

Figure 7. The change of LST error with the change of emissivity error: (*a*) emiss31/32 change at same ratio; (*b*) emiss31 change but emiss32 constant; and (*c*) emiss32 change but emiss31 constant.

5.2 *Validation of the algorithm*

Many researchers use standard atmospheric simulations with such programs as LOWTRAN, MODTRAN as an alternative way to validate split-window algorithm in remote sensing (Sobrino and Caselles 1991, Qin *et al.* 2001). In this study, we use data simulated by LOWTRAN 7 to simulate the required parameters for the validation. Since it is very difficult to conduct the *in situ* ground truth measurements at the satellite pass, we utilize the retrieval results by our algorithm to compare with the MODIS product.

5.2.1 Validation through standard atmosphere simulation. The atmospheric simulation program LOWTRAN 7 is used to simulate the thermal radiance reaching the remote sensor at the satellite level for the input profile data with the known ground thermal properties (LST and emissivity). The required atmospheric quantities such as transmittance for remote sensing of LST can also be computed from the output of the simulation with the program. The simulated total radiance is then converted into the brightness temperature for the two bands of MODIS, from which the LST can be estimated with split-window algorithm. Comparisons of the assumed LST used for the simulation with the retrieved one from the brightness temperature enable us to examine the accuracy of the split-window algorithm proposed by us.

A number of situations were designed for the validation. Four LST (20°C, 30°C, 40°C, 50°C) with four corresponding air temperatures (18°C, 23°C, 30°C, 38°C) near the surface (at 2 m height) were arbitrarily assumed for the simulation. Here we mainly present the results for the mid-latitude 45° N summer July) atmosphere with two emissivity cases (0.97 and 0.974). Table 2 gives the simulation outputs of LOWTRAN 7 for the two cases of total water content of atmosphere. Table 3 is the result of retrieval using real transmittance by our algorithm. Table 4 is the retrieval result by our algorithm with different method to the transmittance computed from total water vapour content of atmosphere. The rms error is computed as $\left[\sum (T_t - T_s)^2 \Big/ N\right]^{1/2}$ (T_t is retrieval temperature) and the average accuracy of LST is computed by $\left[\sum |T_t - T_s|/N\right]$ where N is the number of samples for the computation, table 3 indicates the average difference of the retrieved LST denoted as T_t' in table 3. Table 4: linear fit: $\tau_{31} = -0.10671w + 1.04015$;

Table 3. The retrieving results by split window (real transmittance).

A31	A32	B31	B32	C31	C32	D31	D32	T_s	T_t°C	$T_t - T_s$
0.122	0.1	36.5	30.22	0.0123	0.0166	2.823	3.7161	293.1	20	0.045
0.122	0.1	37.9	31.43	0.0119	0.0161	2.737	3.5967	303.3	30	−0.19
0.123	0.101	39.3	32.67	0.0115	0.0155	2.652	3.4773	313.6	40	−0.41
0.123	0.101	40.7	33.92	0.0113	0.015	2.589	3.3647	323.8	50	−0.63
0.109	0.083	33.5	26.52	0.0258	0.0335	5.931	7.4904	293.1	20	0.036
0.111	0.086	35.1	28.03	0.024	0.0313	5.508	6.9915	303.4	30	−0.2
0.113	0.088	36.9	29.61	0.0221	0.029	5.085	6.4941	313.6	40	−0.42
0.114	0.089	38.5	30.94	0.0207	0.028	4.758	6.2722	323.8	50	−0.62
0.101	0.074	31.6	24.35	0.0343	0.0433	7.88	9.6893	293.1	20	0.029
0.104	0.077	33.4	25.98	0.0318	0.0404	7.294	9.0298	303.4	30	−0.21
0.106	0.08	35.2	27.7	0.0292	0.0374	6.707	8.3694	313.6	40	−0.43
0.109	0.081	37.2	29.18	0.0262	0.0357	6.023	7.9898	323.8	50	−0.62
Average error			0.32							
rms			0.39							

Table 4. The retrieving results by split window (transmittance computed from water content).

Linear fit					Exponent fit				
Trans31	Trans32	T_s	T_t-T_s	R^2	Trans31′	Trans32′	T_s'	T_t-T_s'	R^2
0.93344	0.86652	293	0.194	0.037707	0.923458	0.872608	293.1	0.085	0.007268
0.93344	0.86652	303	0.17	0.028986	0.923458	0.872608	303.2	−0.08	0.006192
0.93344	0.86652	313.1	0.076	0.005802	0.923458	0.872608	313.4	−0.26	0.065787
0.93344	0.86652	323.2	−0.03	0.001007	0.923458	0.872608	323.6	−0.42	0.173484
0.82673	0.74075	293.2	−0.02	0.000275	0.828213	0.738142	293.1	0.033	0.00109
0.82673	0.74075	303.5	−0.3	0.087538	0.828213	0.738142	303.4	−0.2	0.038358
0.82673	0.74075	313.7	−0.56	0.311789	0.828213	0.738142	313.6	−0.43	0.186665
0.82673	0.74075	324.2	−1	0.998273	0.828213	0.738142	324	−0.85	0.715442
0.773375	0.677865	293.3	−0.17	0.030096	0.778881	0.672434	293.2	0.001	1.82E-06
0.773375	0.677865	303.8	−0.59	0.351327	0.778881	0.672434	303.4	−0.25	0.062461
0.773375	0.677865	314.1	−0.94	0.888787	0.778881	0.672434	313.7	−0.51	0.263383
0.773375	0.677865	325	−1.81	3.286032	0.778881	0.672434	324.4	−1.27	1.619863
Average LST error		0.49			0.37				
rms		0.71			0.51				

$\tau_{32}=-0.12577w+0.99229$ (w is the precipitable water); exponent fit: $\tau_{31}=2.89798-1.88366e^{(w/21.22704)}$, $\tau_{32}=-3.59289+4.60414e^{(w/-32.70639)}$. Table 3 contains the retrieval results extracted using standard atmosphere simulation (real transmittance and emissivity). The results indicate that the average accuracy is about 0.32°C, rms is 0.39. Table 4 also contains retrieval results using standard atmosphere simulation, but the transmittance is computed from water content. The average accuracy is about 0.37°C, rms is 0.51 when we utilize the exponent fit between water content and transmittance. The average accuracy is about 0.49°C, rms is 0.71 when we utilize the linear fit between water content and transmittance. These results indicate that the accuracy is highest when we use a real parameter, the second is exponent fit, the last is linear fit.

5.2.2 Comparison with the MODIS LST product. It is very difficult to obtain the *in situ* ground truth measurement of LST matching the pixel scale (1 km × 1 km at nadir) MODIS data at the satellite pass for the validation of algorithm. Generally speaking, LST varies from point to point on the ground, and ground measurement is generally point measurement. It is a problem to obtain the measured LST matching the pixel of MODIS data. On the other hand, MODIS observes the ground at different angles, and precisely locating the pixel of the measured ground in MODIS data especially night images is also a problem. In addition to these difficulties, ground emissivity and the *in situ* atmospheric conditions also have to be known for the validation. Since there are so many difficulties in obtaining ground truth data, validation with the use of ground truth data is quite difficult. However, Wan *et al.* (2002, 2004) overcome many of these difficulties and manage to get a dataset between 2000–2001 to evaluate the MODIS LST product. The conclusion indicates that the accuracy of MODIS LST product is under 1k. In this paper, we utilize the results retrieved by our algorithm to compare with the MODIS LST product. We select the MODIS/TERRA of Beijing region (400*400), China, 11/08/2003 which is representative because the ground is very complex. Figure 8 is the MODIS/TERRA daily L3 ISIN grid 1 km LST product and the average LST is 28.77°C. Figure 9 is

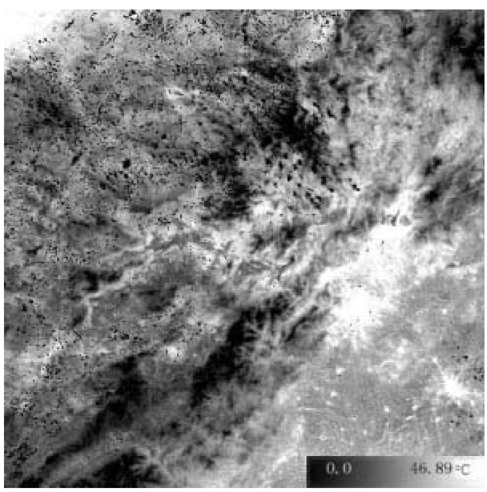

Figure 8. The MODIS LST product (provided by the National Aeronautics and Space Administration).

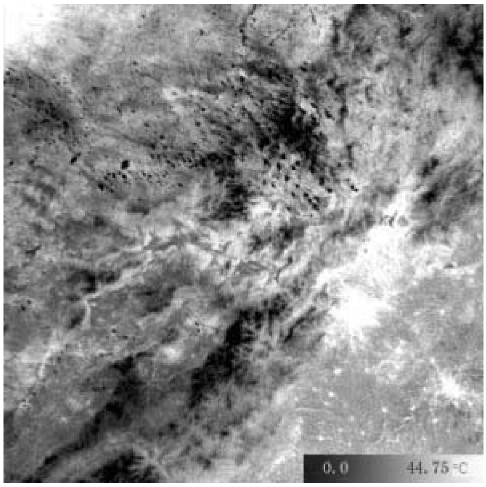

Figure 9. The LST retrieved by our algorithm.

the retrieval LST by our algorithm and the average LST is 28.70°C. The results indicate that the retrieval LST by our algorithm is very approximate with the MODIS LST. The average LST and the distribution of LST are almost the same and the average LST error is 0.07°C, although the max value MODIS LST product is about 2°C higher than the max of our retrieval results. We analysed the two results gained by different algorithm at the same region. The quality of MODIS LST is very high, but we find that some pixels change intrinsically when we make profile analysis in the image. We can also see these senses (black points) from figure 8, but figure 9 is less relative to figure 8. We think the main reason maybe is the cloud influence and have some other reasons.

6. Conclusion

According the characters of MODIS data, we propose a practical split-window algorithm. The algorithm requires two essential parameters (transmittance and emissivity) for LST retrieval. A method has been proposed in this paper to simplify the Planck function.

Methods have been proposed for estimating transmittance from water content. That is, we retrieve the water content from the MODIS NIR bands, and then compute the transmittance of MODIS31/32 through building the relationship between the water content and the transmittance. LST error is only changed between 0.18 and 1.1°C when the water content error changes between −80% and 130% and the relative transmittance error changes between 0.01 and 0.31. However, we get a similar conclusion through changing the water content retrieved from MODIS band 2 and band 19. We confirm the conclusion by retrieving LST from MODIS image data through changing retrieval water content error. So we can make a conclusion that our algorithm is not sensitive to water content and get higher accuracy if we can reasonably utilize the prior knowledge of water content. On the other hand the emissivity is not sensitive to our algorithm in MODIS31/32.

Two methods have been used to validate the algorithm: standard atmospheric simulation and MODIS LST product. Validation with standard atmospheric simulation indicates that this algorithm can achieve the average accuracy of this algorithm of 0.32°C in LST retrieval for the case without error in both transmittance and emissivity estimations. The accuracy of this algorithm is 0.37°C and 0.49°C, respectively, when the transmittance is computed from water by exponent fit and linear fit, respectively. Compared with the MODIS LST product, the results from the analysis indicate that the proposed algorithm is able to provide an accurate estimation of LST from MODIS data.

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