Estimation of Total Atmospheric Water Vapor Content
Using MODIS Channels 31 and 32

Z. Li, H. Liu, L. Xu, J. Ding, and X. Deng
Atmospheric Radiation & Satellite Remote Sensing Lab
College of Electrical Engineering/ Atmospheric Sounding Key Laboratory
Chengdu University of Information Technology, Chengdu, Sichuan 610225, China
Tel: +86-28-85576395  E-mail: xulisheng@cuit.edu.cn

KEY WORDS: Atmospheric water vapor content; MODIS; transmittance ratio; new retrieval approach.

Abstract

A new approach for retrieval of the total atmospheric water vapor content (TAWV) based on the Moderate Resolution Imaging Spectrometer (MODIS) two thermal IR (TIR) channels (ch31 and ch32) is proposed. To developing the approach, the radiative transfer calculations are carried out using MODTRAN 4.0 combined with the latest global assimilated data, and the pixels contaminated by clouds are eliminated using cloud detection techniques. Total 6757 sets of atmospheric profiles are carefully selected. The relationship between the transmittance ratio at the two TIR channels and water vapor content is set up, with a third order polynomial of the transmittance ratio. Meanwhile, the split-window covariance-variance ratio (SWCVR) method is reviewed and the error caused by the assumptions for the method is analyzed. The new approach is tested with the MODIS data in North China region, and compared with the radiosonde data and MODIS official water vapor products. Compared the TAWV results estimated by our approach with the radiosonde data, the root-mean-square error (RMSE) is 0.39 g/cm². So the proposed approach is able to provide an estimation of the TAWV.

1. Introduction

The TAWV is the total atmospheric water vapour contained in a vertical column of unit area from the earth’s surface to the top of atmosphere [1], which is highly variable in temporal and spatial in the atmosphere. However, TAWV is an important parameter for weather, climate, hydrometeorology, and radiative transfer calculation, and so on. TAWV can be input as a parameter into numerical forecasting system for improvement of forecast accuracy. Meanwhile, it is the principal contributor to the greenhouse effect, because it plays a significant role in the absorption and emission of radiative energy, and can lead to global warming. Water vapour is wildly recognized to be a critical climate variable to a variety of atmospheric processes, but the poor coverage and representativeness of conventional radiosonde data can not satisfy our need of accurate understanding of the distribution and transport of water vapour. Data
given by satellite sensors such as the Advanced Very High Resolution Radiometer (AVHRR) and MODIS have been used to overcome this limitation. In recent years, satellite remote sensing technology is widely used for monitoring of ecological environment and land cover survey. With satellite-based measurements of water vapour, remote sensing scientists can be able to improve the accuracy of the remotely sensed surface parameters.

Jedlovec [2] proposes an extension of the technique that uses the ratio of the spatial variance of the channel brightness temperatures. Sobrino [3] improve this technique by proposing the split-window covariance-variance ratio (SWCVR), based on a quadratic relationship between $w$ and the ratio of the spatial covariance and variance of brightness temperatures measured in channels 4($T_4$) and 5 ($T_5$) of AVHRR in of N neighboring pixels, assumes that the state of the atmosphere is unchanged over the neighboring points where the land surface temperature and emissivity change. The main advantage of SWCVR algorithm is that the estimated results for $w$ are insensitive to the surface emissivity, while its main shortcoming is that it should be applied over regions with a certain level of thermal heterogeneity (standard deviation of $T_4$ in the subset is larger than 0.5K) due to its mathematical structure. The standard error is 0.5 g/cm$^2$. The SWCVR technique was applied in boxes of (21×21) pixels. This size was found to be a good compromise between greater boxes, which may present higher probability of including sea and clouds in the area, and smaller boxes, in which the covariance and variance could not be statistically representative[4].

2. Theory

Starting from radiative transfer equation for a cloud-free atmosphere under local thermodynamic equilibrium, the radiance $I_i$ measured from space in channel $i$ at the zenith viewing angle $\theta$ may be written with a good approximation as [5]:

$$I_i(\theta) = B_i(T_i(\theta)) = \tau_i(\theta)\varepsilon_i(\theta)B_i(T_S) + I_i^\uparrow(\theta) + \tau_i(\theta)(1-\varepsilon_i(\theta))I_i^\downarrow(\theta)$$  \text{(1)}

where $\varepsilon_i(\theta)$ and $\tau_i(\theta)$ are the directional surface emissivity and the total atmospheric transmittance, respectively. $T_i(\theta)$ is the brightness temperature corresponding to radiance $I_i$. $T_S$ is the surface temperature, $I_i^\uparrow(\theta)$ is the path radiance at the zenith angle $\theta$ and $I_i^\downarrow(\theta)$ is the downwelling atmospheric radiance in channel $i$ divided by $\pi$. Denoting $T_{gl}$ the surface brightness temperature at ground, $B_i(T_{gl})$ can be expressed as:

$$B_i(T_{gl}) = \varepsilon_i(\theta)B_i(T_S) + (1-\varepsilon_i(\theta))I_i^\downarrow(\theta)$$  \text{(2)}

Then Equation (1) can be written as:
From Equation (1), considering Equation (5), the variation of radiance can be expressed by:

\[ B_i(T_i(\theta)) - B_i(T_{g_i}(\theta)) = \tau_i(\theta) \left[ B_i(T_{g_i,k}(\theta)) - B_i(T_{g}(\theta)) \right] \]

where the subscript \( k \) denotes pixel \( k \), \( T_i \) and \( \overline{T_g}(\theta) \) are the mean brightness temperature and the mean surface temperature at the ground level, respectively. Considering the first-order Taylor series of the Plank function \( B_i(T) \) in the form:

\[ B_i(T) \approx B_i(\overline{T}) + \frac{\partial B_i(T)}{\partial T}(T - \overline{T}) \]

Equation (4) can be expressed in terms of temperature difference as

\[ T_{i,k} - \overline{T_i} = \tau_i \left(T_{g_i,k} - \overline{T_{g_i}}\right) \]

Similarly, in channel \( j \), one has

\[ T_{j,k} - \overline{T_j} = \tau_j \left(T_{g_j,k} - \overline{T_{g_j}}\right) \]

Dividing Equation (6) by Equation (7), we obtain,

\[ \frac{\tau_j}{\tau_i} = \frac{T_{g_i,k} - \overline{T_{g_i}}}{T_{g_j,k} - \overline{T_{g_j}}} \frac{T_{j,k} - \overline{T_j}}{T_{i,k} - \overline{T_i}} \]

The emissivity ratios of both wavelengths of 11 \( \mu m \) and 12 \( \mu m \) are between 0.98 and 1.01 for soils, vegetation, snow and water, so Equation (8) can be written as

\[ \frac{\tau_j}{\tau_i} = \frac{1}{N} \sum_{k=1}^{N} \frac{(T_{i,k} - \overline{T_i})(T_{j,k} - \overline{T_j})}{(T_{i,k} - \overline{T_i})^2} \]

Many research works studied the relationship between transmittance and TAWV directly [6][7][8], without paying attention to the relationship between the ratio of the transmittance and TAWV. In this study, to obtain the accurate relationship, the radiative transfer simulation has been carried out with MODTRAN 4.0 combined with the latest global assimilated data. Firstly, the atmospheric profiles with only the data of Feb. and July from 2000 to 2007 are used, and 467 pixels for each month are selected in the global range. Then, cloud detection is performed with a threshold method proposed by [9]. Therefore, total 6757 groups of atmospheric profiles data, including geopotential height, air temperature and relative humidity profiles, are used.
for our research, which are obtained from NCEP (National Centers for Environmental Prediction). The fitting formula for the surface brightness temperatures of the two IR channels is

$$T_g = 0.9427 \times T_g + 14.66$$  \hspace{1cm} (10)

The relationship described in equation (10) is showed in Fig. 1.

![Fig. 1. The relationship of the surface brightness temperatures for the two TIR channels.](image)

The relationship between TAWV and the ratio of the transmittance with a third order polynomial is expressed by equation (11) and Fig. (2):

$$w = -6.778 \times (ratio)^3 + 19.72 \times (ratio)^2 - 9.025 \times (ratio) - 4.134$$  \hspace{1cm} (11)

![Fig. 2. The scatter plot of w and the ratio of the transmittance for the two TIR channels.](image)
3. Calculation Results

The radiosonde data coincident nearly with MODIS measurements are obtained at 0000 and 1200 GMT for several meteorological stations in the North China. It should be pointed out that the time of the radiosonde observations does not coincide precisely with the satellite overpass, which may result in some error in the analysis [4]. Since the radiosonde data are obtained routinely and easy to get the atmospheric water vapor content, they are used as the standard results in this paper. The MODIS observations also have water vapor products, which makes easy to compare and analyze the results.

The TAWV results calculated by our method for some regions in North China are presented in Table 1, with the comparison of the corresponding data measured by radiosonde [10] and the MODIS water vapor products. The result indicates that the estimations of the TAWV vary around radiosonde data slightly, the absolute maximum value and the absolute minimum of the difference between radiosonde data and our result are 0.292 and 0.027 respectively, with a RMSE of 0.39 g/cm$^2$. It is seen from Table 1 that comparing with the radiosonde observation data, some TAWV results calculated by our method are better than the MODIS water vapor products, while some results are worse.

<table>
<thead>
<tr>
<th>Data details</th>
<th>Station num.</th>
<th>Rad (gcm$^{-2}$)</th>
<th>MOD (gcm$^{-2}$)</th>
<th>w (gcm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.2009</td>
<td>54511</td>
<td>0.267</td>
<td>0.245</td>
<td>0.174</td>
</tr>
<tr>
<td></td>
<td>54135</td>
<td>0.281</td>
<td>0.302</td>
<td>0.155</td>
</tr>
<tr>
<td></td>
<td>54347</td>
<td>0.319</td>
<td>0.305</td>
<td>0.388</td>
</tr>
<tr>
<td>1st Jan.2009</td>
<td>54161</td>
<td>0.485</td>
<td>0.373</td>
<td>0.193</td>
</tr>
<tr>
<td></td>
<td>57178</td>
<td>0.286</td>
<td>0.442</td>
<td>0.240</td>
</tr>
<tr>
<td></td>
<td>58242</td>
<td>0.228</td>
<td>0.439</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td>58665</td>
<td>0.182</td>
<td>0.366</td>
<td>0.209</td>
</tr>
<tr>
<td></td>
<td>57127</td>
<td>1.315</td>
<td>0.283</td>
<td>1.125</td>
</tr>
</tbody>
</table>

4. Summary

In this study, The SWCVR method is reviewed and the error caused by the assumptions made for the method is analyzed. A new and simple approach for estimating the TAWV based on the two MODIS TIR channels has been developed. Total 6757 sets of atmospheric profiles are selected for simulating the relationship between the transmittance ratio at the two TIR channels and the TAWV, with a third order polynomial of the transmittance ratio. The new approach is tested using the MODIS data obtained in North China region and compared with the radiosonde data and MODIS official water vapor products, with a RMSE of 0.39 g/cm$^2$. The results...
indicate that comparing with the radiosonde observation data, some TAWV results calculated by our method are better than the MODIS water vapor products, while some results are worse. Obviously, further studies should be performed for wider regions and various conditions with a large number of samples.

Acknowledgment

The authors wish to express their gratitude to the University of Wyoming which provided us with access to the Radiosonde Data.

Reference