ESTIMATION OF ATMOSPHERIC COLUMN AND NEAR SURFACE WATER VAPOR CONTENT USING THE RADIANCE VALUES OF MODIS

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KEY WORDS: MODIS**,** Column water vapor, Near surface MMR water vapour, AIRS, Ratio technique, Transmissivity.

ABSTRACT:

One of the most important parameters in all surface-atmosphere interactions (*e.g.* energy fluxes between the ground and the atmosphere) is atmospheric water vapor. It is also an indicator among others to modeling the energy balance at the Earth's surface. Total atmospheric water vapor content is an important parameter in some remote sensing applications especially land surface temperature (LST) estimation. As such, total atmospheric water vapor content and LST are used as key parameters for a variety of environmental studies and agricultural ecological applications. Estimation of an accurate LST requires the atmospheric water vapor content estimation. This study is concerned with retrieving total atmospheric water vapor content (W) using Moderate Resolution Imaging Spectrometer (MODIS). We have used a ratio technique to estimate the column water vapor based on MODIS data. However Atmospheric Infrared Sounder (AIRS) column water vapor and AIRS MMR near surface water vapor have been taken into account to calculate coefficients of the equation in the ratio technique. Then the accuracy of the results was examined using independent data set. It is concluded in this study that MODIS data is appropriate in mapping water vapor content as a suitable alternative to meteorological stations measurement data.

1. INTRODUCTION

Meteorological solution to obtain atmospheric water vapor content consists of using radiosonde observations. Radiosonde observations are balloon based observation which cover a single profile from the land surface to about 30 km above the surface. The synoptic properties of the weather stations (which are the official for radiosonde measurements) and the point wise measurements of radiosonde data limit the applications.

Remote sensing methods that allow us to estimate the atmospheric water vapor content have been developed in recent years. Studies in retrieving total atmospheric water vapor content (W) has been carried out using sensors such as the Along-Track Scanning Radiometer (ATSR), the Advanced Very High Resolution Radiometer (AVHRR), and the Moderate Resolution Imaging Spectrometer (MODIS).

There are two main approaches for estimation of total atmospheric water vapor content using remote sensing data (Schroedter-Homscheidt and Drews, 2007). The first approach uses some regression based statistical relations which are based on brightness temperature of remote sensing thermal image pixels (Schroedter –Homscheidt and Drews, 2007).

The second approach uses direct radiative transfer equation which has total atmospheric water vapor content implicitly. The radiative transfer equation gives the remote sensing sensor radiance as an addition of terms so that the total atmospheric water vapor content is implicit parameter in them (Schoroedter and Homscheidt, 2007). It is well studied that the second approach can reach to better accuracies because of its physical inheritances. However, the approach needs the knowledge of LST and surface thermal emissivity (Schroedter-Homscheidt and Drews, 2007).

In this paper, an existing operational algorithm is used to retrieve total atmospheric water vapor content from MODIS data using an LST independent approach. This paper offers a radiance based algorithm for retrieving total atmospheric water vapor content (W) using MODIS radiance data. As a new approach, AIRS data are taken as the reference data to calculate the coefficients of the equation of the method. AIRS is a facility instrument whose goal is to support climate research and improved weather forecasting. The AIRS instrument measures the distribution of water vapor in the atmosphere in three dimensional, globally, every day.

The radiance data have been split into two data sets. The first three data sets have been used to estimate the coefficient of equations and the fourth one has been used to test the coefficient.

Validation of the total atmospheric water vapor has been done using a field data set. The data set contain near surface water vapor measured by weather stations.
Also, since clouds are white and cooler than land surface, in this study, a simple method to detect cloudy pixels is using NDVI. In this method if $NDVI < 0$, the pixel is cloudy and is eliminated (Ackerman, 1996).

2. DETERMINATION OF WATER VAPOR WITH MODIS DATA

There are many approaches to estimate the water vapor from MODIS observations. They are, for example, the split-window difference of the thermal bands, the ratio technique, the regression slope, a look up table derived from radiative transfer model output (Kaufman and Gao 1992).

Although these techniques were primarily developed to determine total column precipitable water vapor, they can be used to estimate near-surface water vapor, within a few meters of surface (Kaufman and Gao 1992).

The ratio technique was used by Sobrino and El Kharraz to estimate the column water vapor because of low sensibility of the technique to 1) the noise due to the statistical errors of the bands, 2) the variability of the other components of the atmosphere, and 3) the variability of the characteristics of the surfaces (Sobrino and El Kharraz, 2003).

2.1 Ratio technique

The ratio technique uses ratio of two bands (i.e. a water vapor absorption band and a non-absorption band) to derive atmospheric transmittance of the absorption band. The total column water vapor amount can be derived from a comparison between the reflected solar radiation in the absorption band, and the reflected solar radiation in non-absorbing bands. Table 1 represents suitable bands of MODIS (bands 17, 18 and 19 as absorption bands and band 2 as non-absorbing band) which are used to derive the total water vapor column amount.

Band number	Band center (μm)	Band width (μm)
2	0.865	0.04
17	0.905	0.03
18	0.936	0.01
19	0.940	0.05

Table 1: Spectral properties of MODIS near IR bands used in water vapor retrieval algorithms.

According to the ratio technique (Sobrino and El Kharraz, 2003), the ratios G_{17}, G_{18}, G_{19} are defined as:

$$G_{17} = \frac{L_{17}}{L_2} \quad (1)$$

$$G_{18} = \frac{L_{18}}{L_2} \quad (2)$$

$$G_{19} = \frac{L_{19}}{L_2} \quad (3)$$

where L_i are radiances obtained by MODIS bands 2, 17, 18 and 19. Then water vapor values are calculated using:

$$W_{17} = a_1 + b_1 G_{17} + c_1 G_{17}^2 \quad (4)$$

$$W_{18} = a_2 + b_2 G_{18} + c_2 G_{18}^2 \quad (5)$$

$$W_{19} = a_3 + b_3 G_{19} + c_3 G_{19}^2 \quad (6)$$

where W_{17}, W_{18} and W_{19} are the water vapor values for MODIS bands 17, 18 and 19, respectively.

2.1.1 Retrieve weight of each band： Atmospheric water vapor has different absorption coefficients over MODIS bands 17, 18 and 19. These three bands have different water vapor sensitivity therefore a weighted average of water vapor must be calculated according to the following equation (Sobrino and El Kharraz, 2003):

$$W = f_{17} W_{17} + f_{18} W_{18} + f_{19} W_{19} \quad (7)$$

where f_{17}, f_{18} and f_{19} are weighting functions defined according to:

$$f_i = \frac{\eta_i}{\sum \eta_i} \quad (8)$$

with $\eta_i = \frac{|\Delta \tau_i|}{|\Delta W|}$, (i=17,18 and 19).

where ΔW is the difference between the maximum and minimum water vapor content. The numerical value of ΔW has been obtained from AIRS data. $\Delta \tau_i$ corresponds to the difference between the transmissivities in maximum and minimum atmospheric water vapor content obtained in band i (Kaufman and Gao, 1992).

The f_i of bands 17, 18 and 19 have been simulated and estimated using MODTRAN 4.5 radiative transfer calculation code. Transmissivities have been simulated using mid-latitude summer standard atmosphere (Sobrino and El Kharraz, 2003) and maximum and minimum water vapor content (obtained from AIRS data (max=5.4, min=0.092 (gm/m^2)). The results are shown in Table 2.

τ_{17} min	τ_{17} max	τ_{18} min	τ_{18} max	τ_{19} min	τ_{19} max
0.85	0.678	0.6	0.056	0.78	0.273

Table 2: Transmissivity in minimum and maximum water vapor content for bands 17, 18 and 19, obtained by interpolation.

Therefore, the strongest absorption band is band 18 and the weakest is band 17. The values obtained for f_i are: $f_{17} = 0.141$, $f_{19} = 0.415$ and $f_{18} = 0.444$. So equation (7) can be written as:

$$W = 0.141 W_{17} + 0.444 W_{18} + 0.415 W_{19} \quad (9)$$

Equation (9), is the general method that has been proposed to obtain the total water vapor from MODIS images.

3. DATASETS AND RESULTS

3.1 Polynomial coefficients estimation according to AIRS column water vapor

In this study, four data sets in different days were considered. For each data set, there is a series of AIRS data and for 4th data set also there is a ground metrological station data available (Table 3). In order to estimate polynomial coefficients for each data set, 11500 pixels of MODIS data have been used. Cloudy pixels have been removed from each dataset using NDVI threshold method.

	MODIS data	AIRS data	ground metrological station data
Data Set 1	2007/11/02	2007/11/02	-
Data Set 2	2007/11/26	2007/11/26	-
Data Set 3	2007/11/30	2007/11/30	-
Data Set 4	2005/11/23	2005/11/23	2005/11/23

Table 3: Information about datasets

The column atmospheric water vapor amounts can be derived from AIRS sensor data. Coefficients of equations (4), (5) and (6) are calculated using regression on MODIS band ratios G_{17}, G_{18} and G_{19} and column water vapor derived from AIRS data. Then, the mean of coefficients that were derived from the first three data sets, were calculated (Tables 4 and 5).

	Data set 1	Data set 2	Data set 3
a_1	21.215	14.207	18.233
b_1	-1655.135	-645.297	-933.297
c_1	1156.887	380.433	548.658
a_2	66.977	44.851	57.564
b_2	-153.648	29.313	-25.422
c_2	351.292	-28.239	23.661
a_3	62.536	41.878	53.747
b_3	452.421	-17.521	73.061
c_3	-618.567	5.609	-62.305

Table 4: Coefficients of equations (4), (5) and (6) according to column water vapor obtained from the first three data sets

a_1	17.885
b_1	-1077.91
c_1	695.326
a_2	56.464
b_2	-49.919
c_2	115.571
a_3	52.720
b_3	169.320
c_3	-225.087

Table 5: Mean Coefficients of equations (4), (5) and (6) according to column water vapor, obtained from mean of coefficients in the first three data sets.

3.2 Polynomial coefficients estimation according to AIRS near surface MMR water vapor

Similar to previous stage, the first three data sets were used to estimate coefficients of equations (4), (5) and (6) according to AIRS near surface water vapor. The near surface water vapor amounts can be derived easily from a file of AIRS data. Water vapor in 14 vertical layers of atmosphere was provided in the AIRS processed data. The data unit is water vapor Mass Mixing Ratio (MMR) that is mass of water vapor in determined volume of air as compared with the mass of dry air in the same air volume (Alizadeh, 2003). Therefore, MMR in 14 layers has the unit of gm/kg. The AIRS data have been taken to calculate the coefficients of equations (4), (5) and (6). Then, the mean of the coefficients that were derived from the first three data sets, were calculated (Tables 6 and 7).

	Data set 1	Data set 2	Data set 3
a_1	21.372	86.173	84.977
b_1	-2157.074	-4757.652	-3768.222
c_1	1490.870	3139.424	2418.422
a_2	67.470	272.047	268.271
b_2	-443.937	111.225	186.478
c_2	890.846	110.383	-206.701
a_3	62.997	254.011	250.484
b_3	1019.378	223.133	-316.427
c_3	-1307.746	-484.64	221.704

Table 6: Coefficients of equations (4), (5) and (6) according to near surface MMR obtained from the first three data sets.

a_1	53.174
b_1	-2962.648
c_1	1954.646
a_2	167.870
b_2	-128.729
c_2	342.072
a_3	156.741
b_3	351.475
c_3	-543.021

Table 7: Mean coefficients of equations (4), (5) and (6) according to near surface MMR obtained from mean of coefficients in the first three data sets.

3.3 Estimation of column water vapor accuracy

To estimate the accuracy, coefficients of the equations 4, 5 and 6 are calculated based on the first three data sets. Then MODIS bands ratios which come from the first three datasets is taken to calculate water vapor using equation 9. Then the calculated water vapor is compared with water vapor reported in AIRS data. Therefore, the coefficients that are determined by each data set are tested in other independent data sets. The results are represented in table 8. The Root Mean Squares Error (RMSE) on all the pixels are presented in the table.

	Data set 1	Data set 2	Data set 3
Data set 1		-0.06332	-0.43406
Data set 2	0.67577		-0.23084
Data set 3	0.62161	-0.03501	

Table 8: Accuracy of total column water vapor {gm/cm^2} as compared with AIRS column water vapor data. The coefficients that were determined by each data set tested in other data sets.

Finally, the mean coefficients were tested in all data sets particularly on the fourth one. Therefore, the first three data sets participated in estimation of coefficients and the last one was used as the check data (Table 9).

	Accuracy(RMSE)
Data set 1	0.441258
Data set 2	-0.05748
Data set 3	-0.26885
Data set 4	-0.126649

Table 9: Accuracy of estimated column water vapor by the ratio method as compared with AIRS column water vapor (gm/cm2) data by using the mean coefficients.

According to the results, the accuracy of the mean coefficients to retrieve column water vapor using participated data sets and non-participated data set (i.e. the fourth one) are almost the same and accordingly acceptable. The accuracies obtained from the second data set is highest probably due to the low variations of water vapor in the data set. Also, the maximum and minimum difference in the data set is as low as $4.3 gm/cm^2$. Thus accuracy of this method to retrieve atmospheric column water vapor as compared with AIRS column water vapor data which was calculated based on least squares of accuracies mentioned in Table 9 is almost $0.28 gm/cm^2$ and the accuracy of AIRS column water vapor data is approximately $1 gm/cm^2$ based on AIRS documentations. Therefore, the lowest accuracy of the ratio method to retrieve column water vapor applied in this study is almost $1.28\ gm/cm^2$.

3.4 Estimation of near surface MMR water vapor accuracy

In this stage, such as previous stage, after calculation of polynomial coefficients according AIRS near surface water vapor, accuracy of near surface water vapor retrieved by the ratio method was estimated. The coefficients that were determined by each data set tested in other data sets. The results are shown in table 10. The RMSE for all the pixels is represented in the table.

	Data set1	Data set2	Data set 3
Data set1		-1.51265	-2.14210
Dataset 2	1.76320		-1.11923
Dataset 3	1.02895	0.34761	

Table 10: The accuracy of near surface MMR water vapor as compared with AIRS near surface MMR water vapor data using the coefficients that were determined by each data set tested on other data sets.

Finally, it is necessary to test the accuracy of the mean coefficients in all four data sets. Similar to the stage of column water vapor estimation, only the first three data sets were participated in the calculations (Table 11).

	Accuracy(RMSE)
Data set 1	0.66263
Data set 2	-0.33573
Data set 3	-1.10436
Data set 4	-1.33726

Table 11: The accuracy of retrieved near surface MMR water vapor by the ratio method as compared with AIRS near surface MMR water vapor data by using the mean coefficients.

The accuracy of the mean coefficients to retrieve column water vapor using participated and non-participated data sets show that the accuracy of data set 2 is highest and that for data set 4 is lowest although acceptable.
The accuracy of the ratio method to retrieve near surface MMR water vapor as compared to AIRS near surface MMR water vapor data is almost 0.93 gm/kg and the accuracy of AIRS near surface MMR water vapor data is approximately 0.8gm/km. Therefore, the lowest accuracy of this method to retrieve near surface MMR water vapor is almost 1.73gm/kg. In order to assess this accuracy, the polynomial coefficients were used to obtain near surface MMR water vapor. Then the results were compared with in situ data in some meteorological stations in IRAN. The obtained accuracy of the method to retrieve near surface MMR water vapor as compared with meteorological data is 0.81gm/kg.

4. CONCLUSION

In this study, an efficient algorithm to retrieve atmospheric column and near surface water vapor from MODIS data has been proposed. It was shown that, near surface water vapor can be obtained with a relative error of 22% and with RMSE of 0.81gm/kg from validation with meteorological observations and MODIS product data. Also, atmospheric column water vapor can be obtained with a relative error of 22% and with RMSE $1.28\ gm/cm^2$ from validation with AIRS observations and MODIS product data. Because of the long distances between meteorological stations (i.e. about 60 Km), the only way to retrieve atmospheric water vapor in regions which do not have stations, is to apply interpolation. According to calculations made in this study, the accuracy of a weighting interpolation to retrieve near surface MMR water vapor from meteorological data is approximately 25% with RMSE of 0.93 gm/kg. Therefore, it has been shown the usefulness, accuracy and efficiency of the ratio method applied in this study to estimate relevant polynomial coefficients and to retrieve water vapor amount in the atmosphere.

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