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Examination of Total Precipitable Water using MODIS measurements and Comparison with Radiosonde and GPS Data

S.Mahdi, Pourbagher kordi*[1], Maryam Kazemi[2]
[1]*Faculty Member, Department of GIS and physical Geography, Payame Noor University.Iran*
2Department of Biology, College of Basic Sciences, Hanedan Branch, Islamic Azad University, Hanedan, Iran

ABSTRACT: *In this research, precipitable water vapor, as the most effective character in the production of biomass is estimated using remote sensing techniques. Total Precipitable Water (TPW) was estimated using measurements in the Near Infrared bands of the MODIS. To examine the level of confidence in TPW deriving, a simultaneous in situ measurement by Radiosonde and ground-based Global Positioning System (GPS) was carried out. The TPW as results in Radiosonde and GPS was accomplished using the relevant physical equations and base on wet delay troposphere, respectively. Results showed a high correlation among the values of TPW derived from MODIS banding ratio, Radiosonde and GPS data at the Mehrabad station. Also, Using the ratio of the apparent reflectance in the water vapor absorption band to reflectance in non-absorbing band, the atmospheric water vapor transparency was mapped, that the maps showed a high correlation between apparent reflectance and TPW MODIS as their statistical results showed an inverse negative relationship(R^2= -0.97).*

KEYWORDS: *GPS, Mehrabad, MODIS, Radiosonde, Total Precipitable water*

I. INTRODUCTION

The amount of atmospheric water vapor is useful for biomass production and its capacity to drive energy exchanges between the oceans, the atmosphere by releasing latent heat which is the principal motivation for this research. The most important applications of precipitable water air content is in the agricultural meteorology, physical meteorology, flood warning systems, hydrology and many other environmental sciences [1], for example, in synoptic meteorology, the onset and withdrawal of the monsoon is related to changes in wind circulation patterns in the upper atmosphere and associated changes in precipitable water content of air in the lower layers [2]. Preparation of fields for sowing and the sowing of a crop with adequate availability of seed-zone soil moisture requires copious rains [3]. The total amount of water vapor in an atmospheric column is often called the total precipitable water and traditional units used in the scientific literature are centimeters or millimeters of liquid water equivalent [4]. The conversion to SI units makes 1 cm of TPW equivalent to 10 kg/m2 of water vapor [5]. There are many approaches to estimate the water vapor from MODIS observations. They are, for example, the split-window difference of the thermal bands [6] and [7] the ratio technique that is used a water vapor absorption band and a non-absorption band to derive atmospheric TPW [8]; [9];[10]; [11]; [12] or similar techniques that is used for example two water vapor absorption bands and a non-absorption band [13]. Band ratio techniques are more common than other methods in extracting TPW, because of low sensibility of the technique to the noise due to the statistical errors of the bands and the variability of the other components of the atmosphere and the variability of the characteristics of the surfaces [14]. Other various studies of deriving Total column precipitable water have been reported in the macro scale. Some scientistestimated TPW using Japanese Geostationary Meteorology Satellite (GMS) over ocean tropical surfaces that concluded GMS data were appropriate in mapping water vapor content [15]. It is clearly that estimation of water vapor over oceans is easier where emissivity and temperature of objects is relatively constant [16].Since 1992, a several scientists investigated the use of GPS for the determination of total precipitable water vapor [17]. There are many literature studies on the air water vapor, but a little work has been conducted on the processing of atmospheric classification and discrimination of types of retrieval water vapor.

This research will show the capabilities of the MODIS spatial resolution in moisture measurements on the local scale for the Mehrabad station in Iran. The objective is to examine the assimilation MODIS NIR TPW by comparing them with independent observations from ground-based GPS in the Tehran network and from

**Corresponding author: S.Mahdi, Pourbagher kordi( )*
Institute for Remote Sensing and GIS Sciences,
PNU University, TEL: +989124547153, MahdiPourbagher@gmail.com, IRAN

Radiosonde soundings in the same location simultaneously. TPW derived from MODIS near infrared absorbing and non- absorbing water vapor bands has concurrently compared with Radiosonde and GPS techniques.

II.MATERIALS & METHODS

In this research, three type data were used to knowledge of atmospheric water vapor:

2.1. Radiosonde data for calculating TPW in the Mehrabadstation

Radiosonde is a telemetric weather balloon that can measure physical atmospheric parameters such as air temperature, pressure and humidity as it ascends through the air [18]. Then this system transmits the collected data to the ground station.

To calculate TPW using Radiosonde data the following steps were used by prior known thermodynamic equations:

Step 1: calculation of water vapor partial pressure:

Calculate water vapor partial pressure (e_s) which is equal to the saturated partial pressure at dew point temperature, it is used to measure the dew point temperature and (1) offered by Rogers and Yau[19]:

$$e_s(T_d) = 6.11 Exp\left[\frac{L_v}{R_V}\left(\frac{1}{273.15} - \frac{1}{T_d}\right)\right] \tag{1}$$

Where; T_d , L_v and R_v are dew point temperature ($\circ k$), latent heat of evaporation (2.5×106 j kg-1) and universal gas constant (461.5 j k-1 kg-1) respectively.

Step2: Specific humidity; that can be calculated using (2) offered by Hurly et al. [20]:

$$q = q(T_d) = \frac{0.622 e_s(T_d)}{[P - 0.378 e_s(T_d)]} \tag{2}$$

Where; q is specific humidity ($gr.kg^{-1}$) and P is air pressure (mbar). Other parameters are introduced in step1.

Step3: calculation of total water vapor; the TPW was worked out using all calculated q values at different level with pressure P and (3) offered by Carlson et al. [21]:

$$TPW = -\frac{1}{\rho_w g_m}\int_{P_0}^{P} q.dP \tag{3}$$

Where;

TPW is total column precipitable water (mm) and ρ_w is water density (1000 $kg.m^{-3}$), q is specified humidity ($gr.kg^{-1}$)and g_m is mean acceleration due to gravity ($m.s^{-2}$) which varies with latitude and height.

The values of TPW vary between 10 to 50 millimetres for geographical middle latitudes [22].

2.2 MODIS satellite data for derivation TPW using near-IR bands

Our techniques is based remote sensing of water vapor on a ratio of absorbing to non-absorbing channels like a ratio of the measured radiation at 0.94μm to that of 0.86 μm, that were presented firstly by Kaufman and Gao (1992). We selected three channels of MODIS specifically designed for absorption of water vapor and one channel non-absorption over the land in cloud-free conditions, that shown in Table I. The technique is based ondetection of the absorption of solar radiation by water vapor as it is transmits down to the surface and up to the sensor through the atmosphere. [23] and[24].

Table I. Mean amount of TPW derived from MODIS, Radiosonde and GPS (to millimeters) in the series times

Satellite passing date	2004/09/17	2002/09/15	2002/05/26	2003/05/26	2000/08/25	2002/06/16	2003/07/05	2005/09/03	2001/06/10	2008/07/03
$TPW_{Radioso}$	13.48	5.37	9.78	7.27	16.10	15.80	17.20	9.20	15.30	13.20
$TPW_{b17/b2}$	5.51	4.95	0.56	4.69	14.20	12.50	14.30	7.20	10.50	10.10
$TPW_{b18/b2}$	22.98	10.00	12.57	8.38	18.50	16.50	19.30	11.50	17.90	18.50
$TPW_{b19/b2}$	12.57	4.90	5.11	6.58	15.70	14.90	17.50	11.90	14.70	12.80
TPW_{GPS}	15.02	4.07	6.92	5.09	14.08	11.09	22.8	13.04	11.4	19.20

Eq. (4) is mathematically expanded form via Kaufman and Gao (1992) algorithm. (4) is used for normal atmospheric conditions with ratio of the number of 19 to number of 2 banding that written generally $b19 / b2$, instead of humid and dry atmospheric conditions are used banding ratios $b17 / b2$ and $b18 / b2$ in the algorithm respectively.

$$TPW = ((\alpha - \log(b_{19\,MODIS} / b_{2\,MODIS})) / \beta)^2 \times ((1/\cos(\theta \times \pi / 180)) + (1/\cos(\theta_0 \times \pi / 180)) \quad (4)$$

Where;

TPW is Total precipitable water vapor (mm)

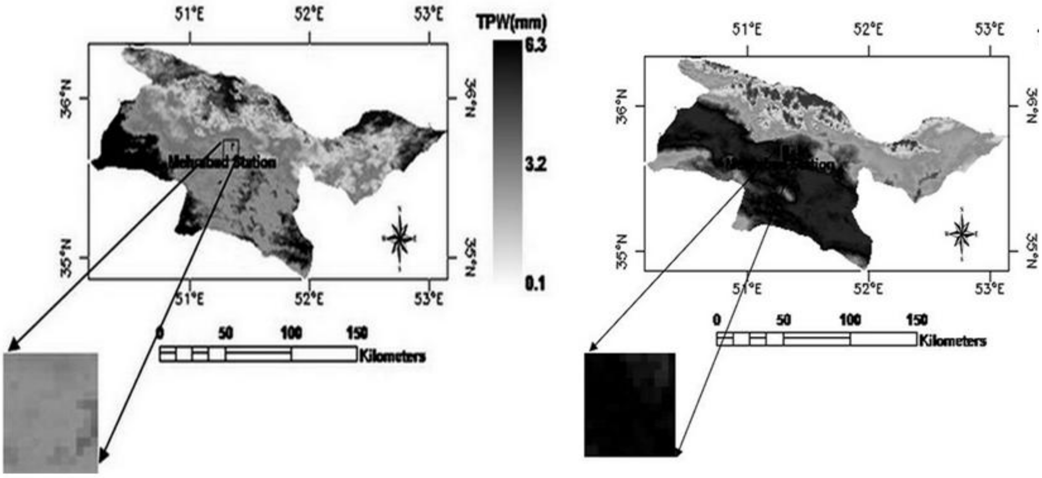
α, β are local constant coefficients that depend on reflectance surface cover

$b_{19\,MODIS} / b_{2\,MODIS}$ is the apparent reflectance for No.19 channel of the MODIS(W m-2 μm-1)

θ , θ_0 are sensor and sun zenith angle respectively (°C)

The apparent reflectance is defined as the ratio between the actual upward radiance and the radiance for a perfect lambert reflector with reflectance of 1.0 without the atmosphere [9].

In order to calculate vertical columnar of water vapor, three atmospheric conditions were assumed including 1) humid or saturated atmosphere 2) dry or unsaturated atmosphere and 3) low to moderate or normal atmosphere. The TPW is separately derived for three modes in the Mehrabad station as the case studyand in the satellite passing date (Table I). The studied area is Mehrabad international airport of Iran. Mehrabad station is located at 51° 21′ E and 35° 41′ N in southern part of Tehran, capital city of Iran, inside of Mehrabad international Airport.The mean values of the TPW were extracted by a small matrix square centralized on the Mehrabad station based on (4).The result of implementation of (4) on the MODIS imageries are shown in Fig. 1 All statistical results showed that the banding ratio of 19 to 2 is best compared to the other ratios in order to extracting TPW in the atmospheric condition of Mehrabad as the case study.



(a)

(b)

(c)

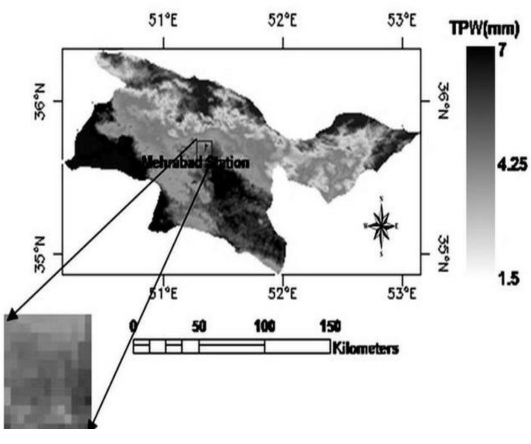


Figure1. mean of TPW results in banding ratio 17 to 2 (a), band 18 to 2 (b) and band 19 to 2(c) for the satellite passing data of 17 Sep 2004.

2.3. GPS data for water vapor measurements

The Global Positioning System (GPS) is a satellite-based navigation system made up of a network of approximately 24 satellites placed into orbit by the U.S. Department of Defense. As the GPS signals propagate from the GPS satellites to the receivers on the ground, they are delayed by the atmosphere [25].The tropospheric delay is directly to the refractive index or refractivity and can be expressed as a function of atmospheric temperature, pressure, humidity as well as the transmitter and receiver antennas location. It can be computed through the integration along the signal path through the troposphere using (5) and (6)the fallowing expression [26]:

$$d_{trop} = \int_{path} (n-1)\,ds \tag{5}$$

$$d_{trop} = 10^{-6} \int_{path} N ds \tag{6}$$

Where; d_{trop} shows delay troposphere, n and N are refractive index of air and refractivity, respectively, which N is function of pressure, temperature and humidity. The refractive index is more conveniently expressed by the term refractivity (N) in (7):

N=10-6(n-1) (7)

The tropospheric delay has dry delay and wet delay components. The dry delay is due to the total mass of the atmosphere and the wet delay is caused by the total amount of Precipitable Water Vapor (PWV) along the GPS signal path .Furthermore the Eq. (4) and Eq. (5) indicate tropospheric delay in the straight line path between a ground GPS receiver and a GPS satellite (line of sight). We can project the tropospheric delay to Zenith Tropospheric Delay (ZTD) via a mapping function. Amount of PWV (mm) can be derived in Zenith direction from Zenith Wet Delay (ZWD). Thus ZWD is result in directly subtract between ZTD and ZWD. We can get ZTD and ZHD (Zenith Hydrostatic Delay) from surface pressure. So ZWD is obtained Zenith direction by fallowingrelationship (8):

ZWD=ZTD-ZHD (8)

Then ZWD can be converting to PWV using in (9):

PWV=Π™×ZWD (9)

Where; Π™ is a dimensionless conversion factor approximately equal to 0.15 [27].

This relationship is basis of GPS Meteorology Technique. Factor Π™ is function of various physical constant of the mean temperature of the water vapor in the atmosphere and can be estimated by (10).[27]:

$$\Pi = \frac{10^{6}}{\rho R_{V}\,[k_{3}/T_{m}) + k'_{2}]} \tag{10}$$

Where; ρ is liquid water density (mm), R_V is gases constant (461.5 j k-1 kg-1), k_3 , k'_2 are physical constants. T_m is the mean vapor pressure weighted temperature ($^\circ k$) can be derived from surface temperature measurement or Numerical Weather Models (NWM) using(11). [17]:

$$T_{m} = \frac{\int (P_{v}/T)\,dz}{\int (P_{v}/T^{2})\,dz} \tag{11}$$

In Eq. (11), P_v is the pressure of water vapor in the atmosphere (mbar) and T is surface temperature ($^\circ k$). The accuracy of GPS derived ZWD estimate is dependent upon the accuracy to of T_m .

In this research the GPS receiving data in the time series has been processed by GAMIT/GLOBK software for deriving zenith tropospheric delay. The result of the GPS data processing has been showed in Table I.

III.RESULTS & DISCUSSION

Providing local to global mapping of atmosphere water vapor is an important objective of the global energy and water cycle between biosphere and atmosphere. The sparse location of ground monitoring stations, especially in arid areas, merits the need for an accurate remote sensing technique that can provide water vapor information on a daily basis with an adequate spatial resolution(e.g., 0.5 -1 km from MODIS). A comparison between the reflected solar radiation in the absorbing bands and the reflected solar radiation in non-absorbing bands can quantify the total vertical amount of water vapor. The main uncertainty in the determination of Water vapor comes from cloudy and the turbulent atmosphere[28]. Thus, firstly, the MODIS images were selected without any cloudy and secondary, the general condition atmosphere were investigated by thermodynamic curve that shown Fig. 2.

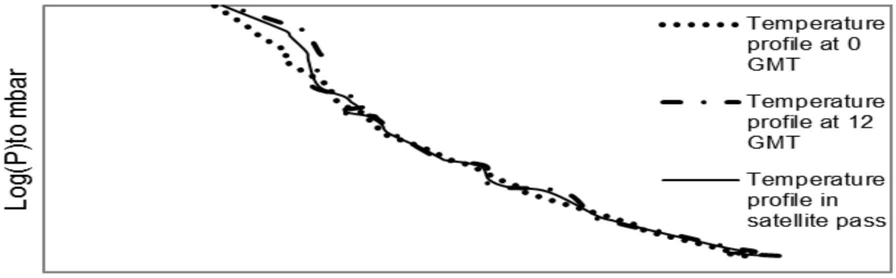


Fig. 2. Temperature profiles at Radiosonde sounding times and satellite passing date (26 May 2002).

As seen in Fig. 2, the atmosphere condition was similar as point of temperature profile and there was no any turbulent flow. Another important subject that should be considered is classification of atmosphere from the standpoint of water vapor contents. Three different banding ratios can be used to precipitable water vapor in three modes of atmospheric water vapor contents:

1. Dry atmosphere or unsaturated water vapor: in this case, the reflectance ratio of channel 18 to 2 as a function of the amount of water vapor is recommended. In the case of very small water vapor content (TPW < 0.5 cm), the main error in the remote sensing technique may result from uncertainty in the spectral surface reflectance [29]. To minimize this effect, a ratio of the narrow channel of 18 to the wide channel 19 can be used [30]. Then TPW can be found from(12):

$$TPW = ((\alpha - \log(b_{0.931-0.941} / b_{0.915-0.965})) / \beta)^2 \times ((1/\cos(\theta \times \pi/180)) + (1/\cos(\theta_0 \times \pi/180)) \quad (12)$$

2. Normal atmosphere or low to moderate water vapor: For TPW of around 2 cm in nadir or even less than 2 cm in off-nadir viewing angle, ratio of channel 19 to channel 2 is suggested by (13)

$$TPW = ((\alpha - \log(b_{0.915-0.965} / b_{0.841-0.876})) / \beta)^2 \times ((1/\cos(\theta \times \pi/180)) + (1/\cos(\theta_0 \times \pi/180)) \quad (13)$$

3. Saturated water vapor or Humid atmosphere: for total precipitable water vapor amount larger than 4 cm in nadir view condition or even less than this value but for slant view and illumination conditions, the strong absorption in the proposed 0.915-0.965 µm channel may partially saturate, resulting in lower sensitivity to water vapor, Table II shows the particulars of three water vapor absorption MODIS channel numbers of 17, 18 and 19.

Table II: Classification of atmosphere, in generally and application of the absorption bands.

Classes and bands application	Wavelength(µm)	Band No.
Very humid and saturated atmosphere: Weak water vapor absorption	0.920-0.890	17
Dry atmosphere: strong water vapor absorption	0.941-0.931	18
No clouds, ordinary atmosphere: Moderate water vapor absorption	0.965-0.915	19

In this case, a water vapor absorption band in a spectral range corresponding to lower absorption like 0.890-0.920 µm for remote sensing of water vapor in humid conditions is preferred by (14).

$$TPW = ((\alpha - \log(b_{0.890-0.920} / b_{0.841-0.876})) / \beta)^2 \times ((1/\cos(\theta \times \pi/180)) + (1/\cos(\theta_0 \times \pi/180)) \quad (14)$$

Applying (1)-(3) to Radiosonde data and (12)-(14) to MODIS thermal data and (5)-(11) to GPS tropospheric delay, in TPWs which are shown in Table I. As can be seen this table, TPW values derived from the ratio of 19 to 2 MODIS bands are closer and more similar to the values obtained TPW Radiosonde and GPS data compared to other band ratios. Indeed, the results are valid for Mehrabad airport Station's atmosphere and similar atmospheres that belong to second class in the mentioned classification. Mehrabad station has a low to moderate water vapor and unsaturated water vapor atmosphere.

As can be observed in Fig. 3(a), there was a high correlation between the TPW Radiosonde values and the retrieved TPW from the near-IR MODIS algorithm using the band 19 to band 2 ratios, that it could be as an ordinary and cloud free atmosphere in the stable conditions.

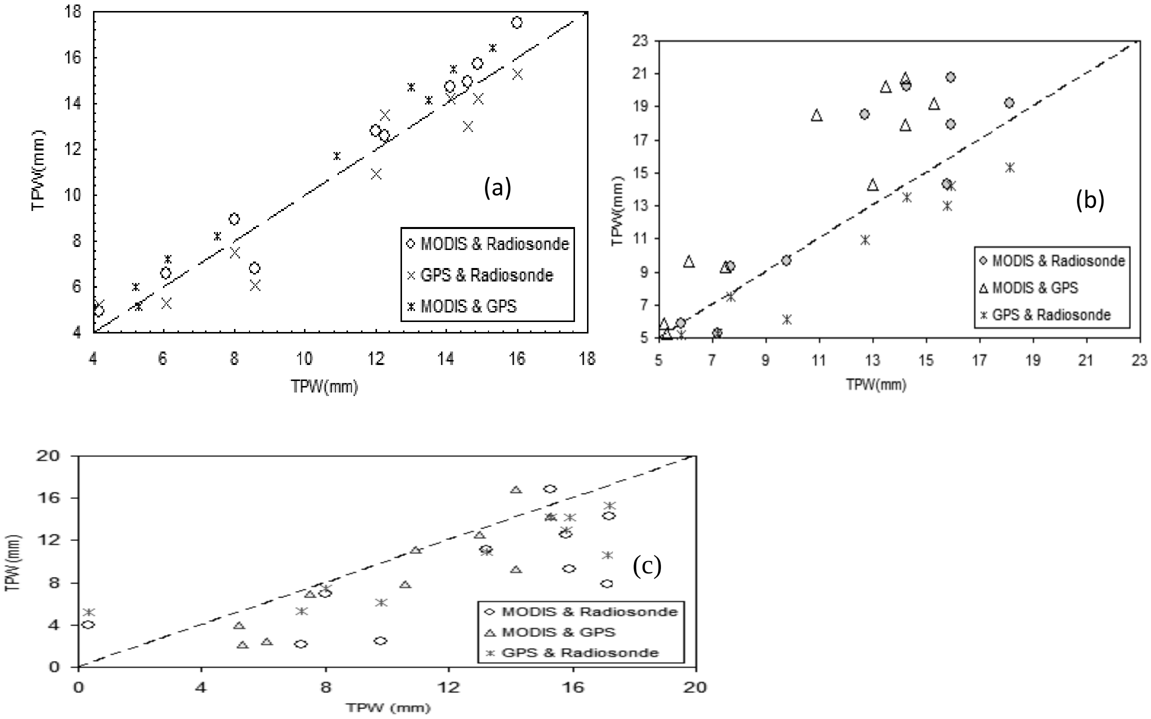


Figure3. The correlation between Radiosonde and Near-IR TPW for band ratios (a): 19 to 2, (b): 18 to 2 (c): 17 to 2.

Since the width of channel 18 is narrower than that of channel 19, it is more readily saturated by water vapor; therefore the accuracy of the TPW estimates from the ratio of band 18 to band 2 is often compromised, see Fig.3 (b). The band 17 to band 2 ratios shows lower correlation, see Fig. 3(c); this ratio is the most inconsistent with meteorological conditions at the Mehrabad station. The ratio of band 18 to band 2 is almost consistently moister than the Radiosonde values. Therefore for simulation of TPW for the studied station, we suggest using the band 19 to band 2 ratios in the algorithm; it shows the best agreement with Radiosonde and GPS wet delay atmosphere(Pourbagher kordi et al., 2008), see Fig. 3(a).This paper shows to investigate physical water vapor bands of MODIS imageries is appropriate technology for any purpose in biomass production and drive energy exchanges between the oceans and the atmosphere by releasing latent heat, and this research shows how satellite remote sensing technology is used in studies of the physical characteristics of the biosphere such as water vapor which affect strongly in agriculture. Calm atmosphere clear sky MODIS near infrared determinations of TPW (using band ratio 19 to 2), when tuned to the surface conditions at the Mehrabad station, show good agreement with Radiosonde and GPS determinations as well as MODIS infrared TPW[31].This research has showed that the mean of TPW values derived from MODIS band 19 to band 2 ratio water vapor absorbing band is consistent with Radiosonde and GPS determinations at the Mehrabad station.

The statistical analyses between reflectance and TPW parameters have shown in Table III. This Table suggests an inverse negative relationship between reflectance and TPW, (R^2 = - 0.97), that this fact is also shown in Fig. 4.

Table III. Correlation coefficients derived from correlation matrix

Selected dates	**Banding ratios**	**Correlation coefficients derived from correlation matrix**
2002/9/15	18/2	- 0.925
2003/5/26	18/2	-0.954
2004/9/17	18/2	-0.965
2003/5/26	19/2	-0.977
2002/9/15	19/2	-0.983
2004/9/17	19/2	-0.992
2004/9/17	17/2	-0.987
2002/9/15	17/2	-0.988
2003/5/26	17/2	-0.993

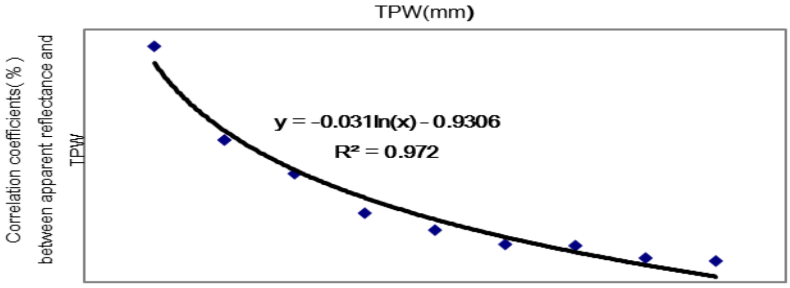


Figure4. negative and inverse correlation between apparent reflectance (%) and TPW (mm)

This work demonstrates that adaptation of the MODIS TPW algorithm using near infrared measurements to unique local characteristics enables direct broadcast users to achieve improved performance in real time.

IV. CONCLUSION

1-Since water vapor has a high spatial and temporal variability; therefore, a revisiting time of 2 to 3 days make MODIS products ideal for the study of the biosphere-atmosphere interaction, its relation to water agricultural production.

2- MODIS satellite imageries due to their absorption bands of water vapor are able to monitor the distribution of water vapor important for agricultural produces.

3- MODIS satellite imageries, unlike the Radiosonde weather balloon, provide important physical information in larger areas, such as wide land surface and other impassable areas.

4- The MODIS near IR algorithm for the retrieval of water vapor can be used only in cloud free and calm atmosphere conditions thus, for cloudy and the turbulent atmosphere requires more studies in the future.

5- Among three water vapor thermal bands in MODIS sensor, the band number of 19 MODIS compared with bands 17 and 18 has the highest agreement with Radiosonde and GPS data (see Fig. 3) as the error is about 2.5 mm and increases with the water vapor content.

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