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Evaluation of MODIS Water Vapour Products over ALGERIA using Radiosonde Data

Avaliação de Produtos de Vapor de Água MODIS na ARGÉLIA usando Dados de Radiossonda

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Abstract

Remote sensing of atmospheric water vapour using GNSS and Satellite data has become an efficient tool in meteorology and climate research. Many satellite data have been increasingly used to measure the content of water vapour in the atmosphere and to characterize its temporal and spatial variations. In this paper, we have used observations from radiosonde data collected from three stations (Algiers, Bechar and Tamanrasset) in Algeria from January to December 2012 to evaluate Moderate Resolution Imaging Spectroradiometer (MODIS) total precipitable water vapour (PWV) products. Results show strong agreement between the total precipitable water contents estimated based on radiosondes observations and the ones measured by the sensor MODIS with the correlation coefficients in the range 0.69 to 0.95 and a mean bias, which does not exceed 1.5.

Keywords: Atmosphere; precipitable water; satellite data

Resumo

O sensoriamento remoto de vapor d'água atmosférico usando GNSS e dados de satélite tornou-se uma ferramenta eficiente em meteorologia e pesquisa climática. Muitos dados de satélites têm sido cada vez mais usados para medir o conteúdo de vapor dágua na atmosfera e para caracterizar suas variações temporais e espaciais. Neste artigo, utilizam-se observações de dados de radiossondagem coletados de três estações (Argel, Bechar and Tamanrasset) na Argélia de janeiro a dezembro de 2012 para avaliar produtos do espectrorradiômetro de imagem de resolução moderada (MODIS) de vapor de água precipitável total (PWV). Os resultados mostram forte concordância entre o conteúdo de água precipitável estimado com base em observações de radiossondas e em valores medidos pelo sensor MODIS.

Palavras-chave: Atmosfera; água precipitável; dados de satélite

1 Introduction

Water vapour is one of the key parameters of dynamics processes and physics of the atmosphere. It plays an important role in the development of clouds and precipitations.

The total amount of water vapour in a vertical column is also a widely used parameter in meteorology and has several names: total precipitable water (TPW), precipitable water (PW) or integrated water vapour (IWV).

Accurate and consistent measurements of water vapour in the troposphere are essential to study the corresponding spatio-temporal variability once it is an important component of the hydrological cycle. However, water vapour remains one of the greatest uncertainties in understanding the mechanism of global warming jointly with local, regional and large-scale water balance.

Most meteorological processes, namely (convection, cloud formation, and precipitation) are influenced by the local as well as large-scale variability in atmospheric water vapour. Traditional methods of collecting data on atmospheric water vapour do not offer the spatial and temporal resolution necessary for in-depth studies of weather and climate. A better understanding of climate and weather patterns requires data sets that are more comprehensive.

Radiosondes profiles have provided long-term and all-weather in situ operational measurements of atmospheric pressure, temperature, and humidity, being recognized as classical method. However, these soundings are launched twice a day. At most, sites, the measurement procedure is affected by radiosonde sensor characteristics, which is sensitive to the dynamically changing environment. The associated measurement accuracy varies considerably in time and location for different sensor types.

In recent years, the use of satellite data to retrieve water vapour measurements along the troposphere has increased. Many studies have shown that GNSS (GPS, Glonass, Beidou and Galileo) and remote sensing instruments, like MODIS (Moderate Resolution Imaging Spectroradiometer), are efficient tools to complement other techniques for measuring the water vapour content for climatological and weather forecasting applications (Guerova et al. 2003; Rocken, Hove & Ware 1997).

Furthermore, there have been several projects from several organizations on the different continents of the world to derive tropospheric zenith delay measurements from ground-based GNSS, for operational meteorological applications. Examples of such projects in Europe include the **COST Action 716** (European Cooperation in the Field of Scientific, Technical Exploitation of Ground-Based GPS for Numerical Weather Prediction Application, 1998–2004) (Van der Marel et al. 2004), and **E-GVAP** (The EUMETNET GPS Water Vapor Programme, 2004) (Bennitt & Jupp 2012). **E-GVAP** network consists of more than 1500 GNSS sites mainly in Europe; recently processing and distribution of global GNSS data have started, since many E-GVAP members run global NWP models. In North America, the **SuomiNet** (named to honor meteorological pioneer satellite Verner Suomi) network of receivers provides real-time estimates of water vapour from zenith water vapour measurements, which are mostly concentrated in the United States (Ware, Fulker & Stein 2000).

Complementarily, in Africa, the **AMMA** (African Monsoon Multidisciplinary Analysis Project, 1999–2005) (Bock & Nuret 2009; Walpersdorf et al. 2007) worked on PWV estimation and analysis in the African monsoon region. In North Africa, especially Algeria, this climate change has produced dry periods, which have caused a drop in rainfall and streamflow in the watersheds and water resources availability, and consequently the stored volumes are reduced (Meddi & Hubert 2003). Atmospheric GNSS products (tropospheric delay–ZTD, water vapour) are paramount parameters for any climate study. These different sources of water show strong variability in time and space, and a downward trend in the Mediterranean and in Algeria (Meddi & Meddi 2009; Taibi et al. 2013).

The evaluation of radiosonde profiles in this region is very important to understand the local variability of water vapour**.** Algeria is country with large area, featuring more than few thousand kilometres EW and NS. This means that the northern part has a Mediterranean climate, while mostly the rest of the country has a desert climate. However, between these two major types of climates, there exist transitional climates. This includes the semi-arid climate with drought, which is only limited during the summer season and corresponds to a Mediterranean climate season (Zeroual et al. 2019). In this context, the evaluation of water vapour with precision from different satellites data is very important as long as there is a lack of radiosonde stations. Indeed, only data from Three (3) stations out of four (4) stations in Algeria are available for this study.

In addition, recent experiments have proved the ability of GPS to measure the water vapour with the same accuracy as other methods, notably- radiosondes and radiometers (Abdellaoui, Zaourar & Kahlouche 2019; Namaoui, Kahlouche & Belbachir 2017; Namaoui et al. 2017; Torres et al. 2010; Van Malderen et al. 2014). However, products derived from remotely sensed data require a rigorous validation protocol to contrast with in situ data**.** Moderate Resolution Imaging Spectroradiometer (MODIS) is not really a sounding instrument, but it does have 16 infrared bands, with (bands 20–36 covering the spectral range from 3 μm to 14 μm,) that allow the retrieval of temperature and moisture profiles as well as the total column integrated magnitudes (Sobrino et al. 2015).

Under the referred framework, the objective of this study is to present:

1. a comparison of MODIS PW data with radiosondes in Algeria with the corresponding report on difficulties for obtaining good agreement for data in a dry region with low PW;
2. the importance of developing a dense measuring network in Algeria and further proceeding analysis of data in local African processing infrastructure.

2 Data and Methods

Algeria is located in Northern Africa, more precisely in the range of latitude from 19° to 37° N and of longitude from 9° W to 12° E. The area of the country is the largest in Africa, which amounts to 2,381,741km². The relief of Algeria consists of three main sets: the Tell, the highlands and the Saharan Atlas in the north part of the country, and the Sahara in the south, which represents 84% of the territory (African Economic Outlook 2008).

2.1 Radiosondes Data

Due to the availability of radiosondes data during all the year 2012 and in order to study different atmospheric and climate conditions, this work focuses on three stations: Algiers (DZAL, WMO code 60390) located in the north with Mediterranean climate, Bechar (BECH, WMO code 60571) located in the south inserted in a subtropical desert, and Tamanrasset (TTAM, WMO code 60380 located in the geographical centre of the Sahara desert, situated in the extreme south of Algeria (Figure 1).

It should be noted that pressure, temperature, relative humidity, wind direction, and wind speed are the parameters that can be obtained from radiosondes observations. Most stations provide twice observations in one day. One of them, is collected at 00:00 UTC and the other one at 12:00 UTC, while some stations can also provide four times observations per day. The 2012 observations processed have been downloaded from the website of the University of Wyoming at: http://weather.uwyo.edu/upperair/sounding.html.

During post-processing, the high-resolution data were interpolated to 5 hPa levels and the water vapour mass (kg.m^{-2}) was derived for each layer and accumulated through the column. Total precipitable water is the amount of water that can be obtained from the surface to the "top" of the atmosphere if all the water and water vapour were condensed to a liquid phase.

Even if the radiosonde data do not exactly correspond to a vertical profile (due to the displacement of the balloon with the wind), such information is still totally relevant for our IWV analysis, as it does not bring much issue in our climatological study. The balloon is not moving farther than 100 km from the position of the launch, which is acceptable.

The calculation of PW from the radiosonde profiles is given by:

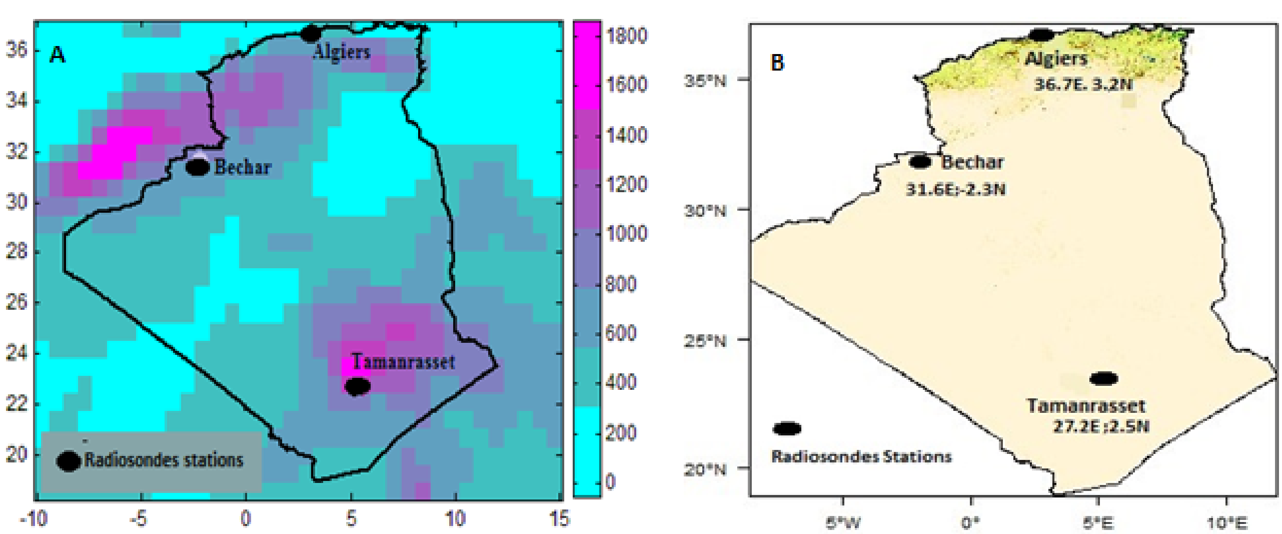

Figure 1 Radiosondes stations over Algeria: A. with surface height guidelines (in meters); B. coordinates of each station.

$$IWV = \int_{h_1}^{h_{21}} \rho_w \, dh = \sum_{i=1}^{n} \rho_{d,i} r_i \Delta h_i \qquad \textbf{(1)}$$

where ρ_w the water vapour density, n is the total number of layers between h_1 and h_2, an $\rho_{d,i}$, r_i, Δh, are respectively the dry air density, the mixing ratio, and the altitude step for layer. (Realini et al. 2014)

Dropping the index i for the sake of simplicity, the dry air density ρ_d is expressed as

$$\rho_d = \frac{M_d}{R}\frac{P}{T} \qquad \textbf{(2)}$$

with the molar mass of dry air M_d = 0.0289644 kg mol^{-1} and the universal gas constant for air R= 8.31432 J mol−1 K^{-1}. T is the observed air temperature in Kelvin. P is the air pressure.

The mixing ratio r is defined as the dimensionless ratio of the mass of water vapour to the mass of dry air. Based on the ideal gas law, the following relations can be derived:

$$r = 0.622\frac{e}{P} \qquad \textbf{(3)}$$

where e is the partial pressure of water vapour and P is the air pressure.

The partial pressure of water vapour e is computed from radiosonde observations as follows:

$$e = \frac{U}{100} e_s \qquad \textbf{(4)}$$

where U is the observed relative humidity and e_s is the saturation vapour pressure.

Figure 2 shows the diagram of pressure and temperature in Algiers station for one day of January 2021 for illustrative purpose. We can clearly see the variation of temperature in different levels of pressure. The bold red line is a plot of the vertical temperature, and the bold green line is a plot of the vertical dewpoint temperature.

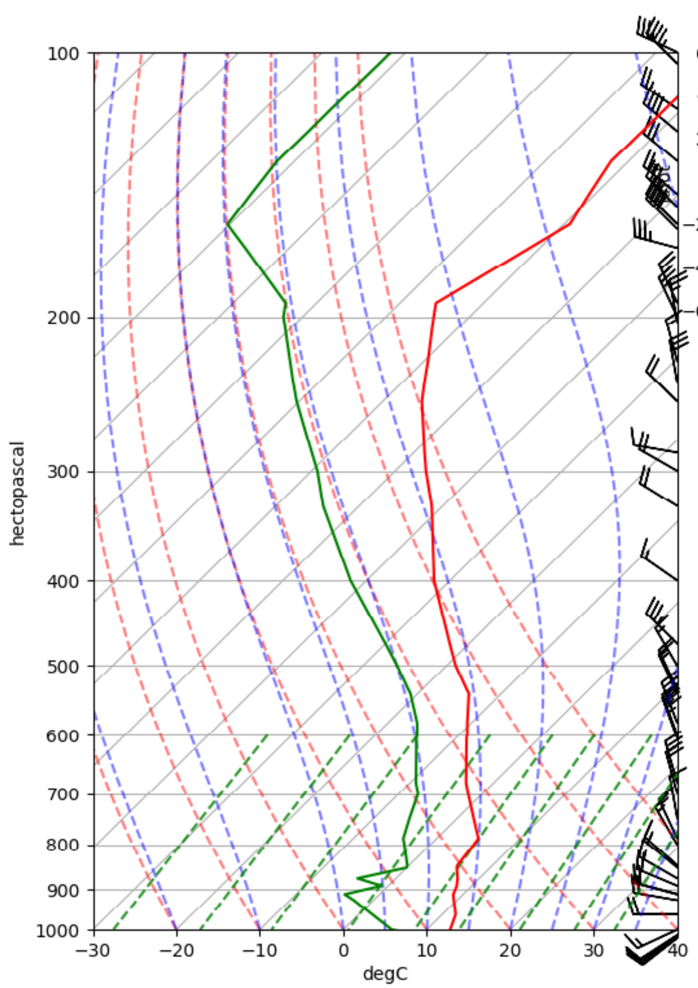

Figure 2 Skew T- log P diagram of Algiers station (January 01, 2021).

The vertical axis is the air pressure in millibars (mb), and the horizontal lines on the graph are lines of constant pressure. The numbers printed on top of these pressure lines indicate the height above sea level in meters (m) at each of the pressure levels.

2.2 MODIS Data

MODIS (Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the Equator in the morning, while Aqua passes south to north over the Equator in the afternoon. The instruments capture data in 36 spectral bands ranging in wavelength from 0.4 µm to 14.4 µm and at varying spatial resolutions (2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km).

The equivalent total vertical amount of water vapour can be derived from a comparison between the reflected solar radiation in the absorption channel, and the reflected solar radiation in nearby no absorption channels. Descriptions of techniques for water vapour remote sensing using near-IR channels were previously reported (Borel, Clodius & Johnson 1996; Thai & Schonermark 1998).

We have used Level-3 MODIS gridded atmosphere daily global joint product. It contains daily 1 x 1-degree grid average values of atmospheric parameters related to atmospheric aerosol particle properties, total ozone burden, atmospheric water vapour, cloud optical and physical properties, and atmospheric stability indices. The precipitable water from MODIS, namely the product MOD08_D3 clear column level 3 daily global from the Terra platform. This data is freely available at ftp://ladsweb.nascom.nasa.gov/allData/6/MOD08_D3.This daily product has been calculated as the mean of Level 3 weighted daily means. The metadata contains many details on the content and pixel nomination method.

Because MODIS PWV is sensitive to the presence of clouds in the field of view, only MODIS-PWV values collected under clear sky conditions were used in this study. The cloud mask product used had to indicate at least 95% confidence clear. The elevation correction is applied for each MODIS pixel within a pixel grid 5 × 5 before averaging. Then spatial averaging is performed if there are at least 10 pixels available (under 99% clear-sky conditions and with best quality flag).

2.3 Statistical Analysis Adopted

For this study, we have used a linear regression between precipitable water vapour from radiosondes and MODIS data.

The following formulas were applied in our statistical analysis (Shuaimin et al. 2020):

$$MBE = \frac{\sum_{i=1}^{N}\left(PW_{Mi} - PW_{Ri}\right)}{N} \qquad \textbf{(5)}$$

$$\text{RMSE}= \sqrt{\frac{\sum_{i=1}^{N}\left(PW_{Mi} - PW_{Ri}\right)^2}{N}} \qquad \textbf{(6)}$$

$$R = \frac{\sum_{i=1}^{N}\left(PW_{Mi} - \overline{PW_M}\right)\left(PW_{Ri} - \overline{PW_R}\right)}{\sqrt{\sum_{i=1}^{N}\left(PW_{Mi} - \overline{PW_M}\right)^2 \sum_{i=1}^{N}\left(PW_{Ri} - \overline{PW_R}\right)^2}} \qquad \textbf{(7)}$$

where N is the number of PW pairs, PW_{Ri} is PW value of radiosondes, PW_{Mi} is PW value of MODIS satellites, $\overline{PW_R}$ is the mean PWV value of radiosondes, and $\overline{PW_M}$ is the mean PWV value of MODIS satellites.

3 Results and Discussion

In this paper, we focus mostly on analysing PW retrieved by radiosondes and MODIS satellites.

The evaluation was based on statistical parameters MBE (mean bias error) and RMSE (root-mean-square error) to analyse and evaluate the retrieved PWV precision based on different types of measurements. A Matlab script has been developed to calculate the precipitable water vapour from radiosonde profiles.

The time series of PW on the three stations (Algiers, Bechar and Tamanrasset) and the values of the radiosonde and MOD08_D3 product are plotted in Figure 3 (A, B, and C). We chose the time closest to the passage of the MODIS satellite, which is 10:30UTC, and then we compared these-values with the measurements of radiosonde profile in the same moment.

We can see clearly that the PW values per station allow the following interpretation:

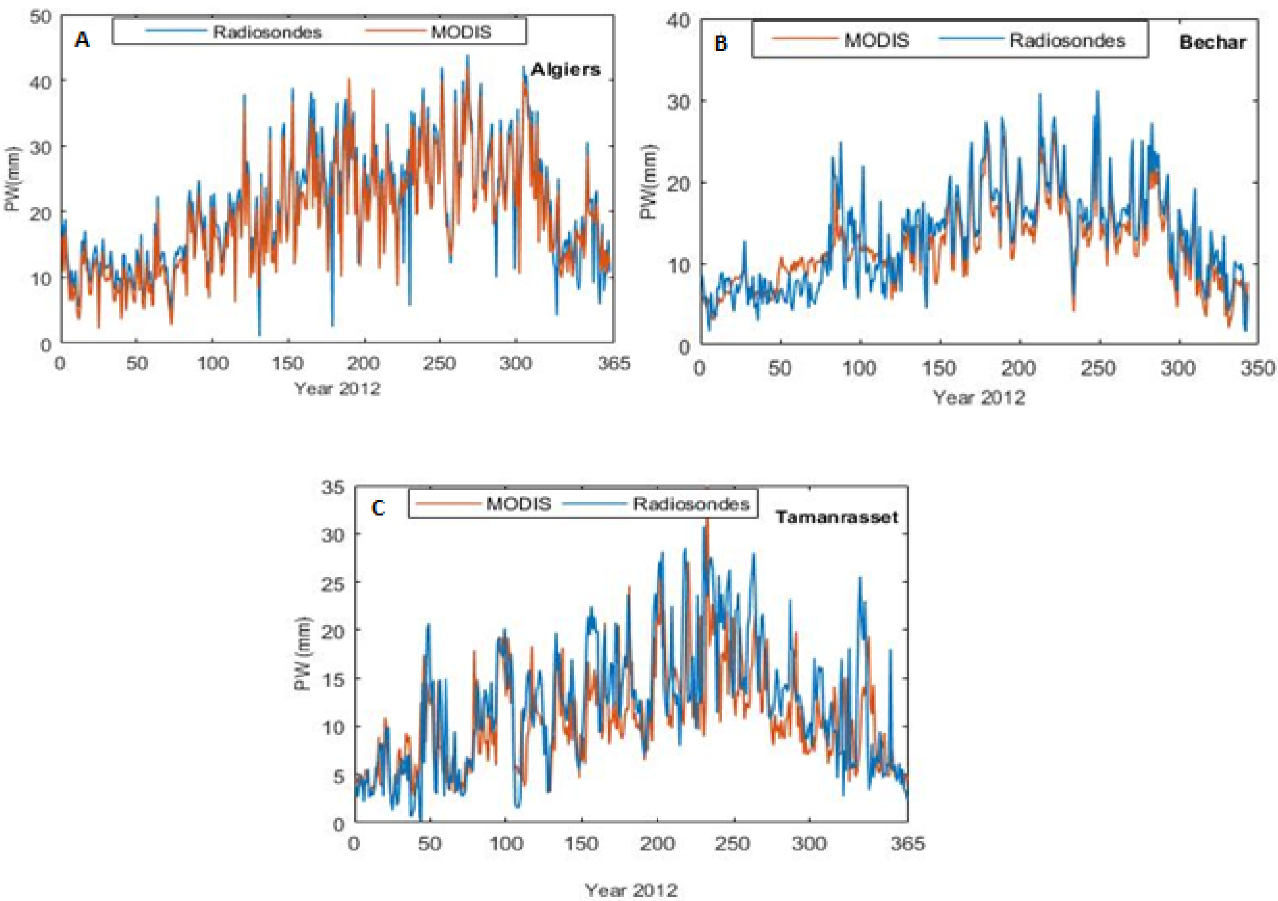

Figure 3 Estimation of water vapour from radiosondes and MODIS: A. Algiers station; B. Bechar station and C. Tamanrasset station.

Algiers station exhibit larger PW values than southern stations (Bechar and Tamanrasset). This is due mainly to their geographical location and the presence of a significant amount of water evaporation coming from the Mediterranean Sea. Note that rain precipitation is frequently measured during the autumn and winter seasons.

If we look at Bechar station, this it is a station located in the south (hot climate, desert) known for having ground temperature of around 45 °C with an average IWV value of 13.5 mm. On the other hand, Tamanrasset recorded low values comparing to other stations. This station is located at an altitude of 1400 meters above sea level. It has a very healthy climate, dry and sunny all year round. In winter, it can get cold at night, while the days are mild; in summer, the heat is scorching, but the maximums are normally around 35 degrees, with peaks of 40 ° C. The rains in Tamanrasset, which are rare and sporadic, slightly exceed 50 mm per year.

Low values of water vapour are observed in the Saharan regions and their neighbourhoods. This is due to the small amount of water presents in these regions and the very high temperatures, which is not in favour to maintain or to supply water vapour in the local atmosphere.

The performance of the MODIS PWV data was assessed using radiosonde PWV based on some commonly used statistical indicators such as correlation coefficient, bias, and RMSE. Generally, the correlation coefficient (R) is mostly used to assess the degree of consistency instead of absolute agreement, and a positive (negative) bias indicates an overestimation (underestimation) of PWV. The scatter plots of PW for radiosondes against MODIS are shown in Figure 4 (A, B, and C) with respect to the three stations, Algiers, Bechar and Tamanrasset, respectively. The statistical measurements are included in the scatter plots (Figure 4) and the differences are mentioned in Table 1.

For Algiers and Bechar, the correlation is 0.95 and 0.92 respectively with a bias, which does not exceed 1.5 mm between PW RS and PW Modis.

The lower correlation between RS and MODIS was registered in Tamanrasset station with small bias of 1.4 mm.

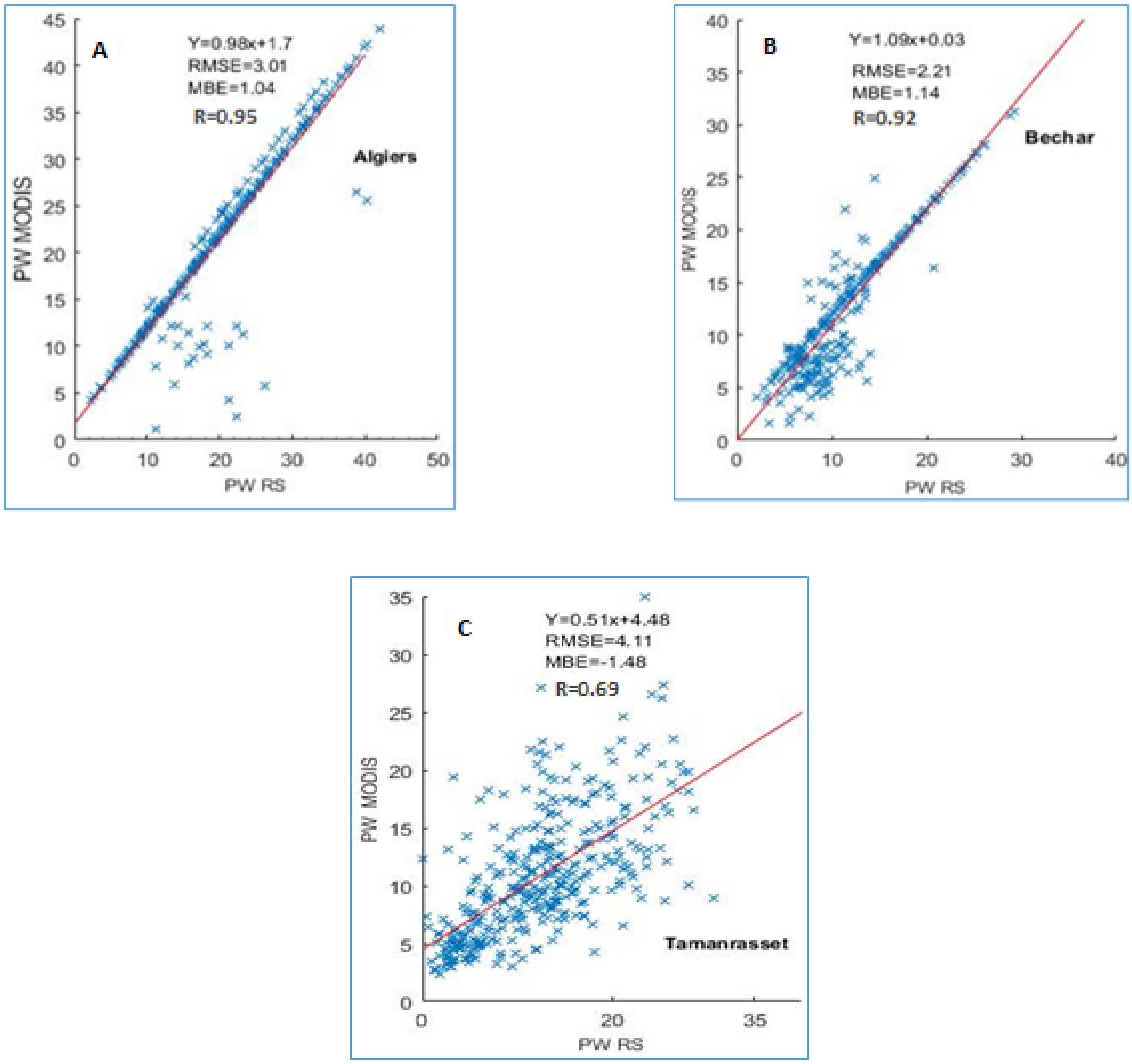

Figure 4 Scatter plots of PW radiosondes and PW MODIS A. Algiers station; B. Bechar station and C. Tamanrasset station including MBE, RMSE and R.

This can be explained by sand dune movements, which is an important parameter because the sandstorm reduces visibility (Alfaro & Gomes 2001; Brook & Legrand 2000; Chaboureau, Tulet & Mari 2007).

The airborne dust particles interact with radiation directly due to their optical characteristics such as scattering and absorption, and indirectly due to their physicochemical properties. Such particles can act as cloud condensation nuclei and therefore modify the characteristics of clouds and rates of water vapour quantity.

Table 1 Statistical metrics for the comparison between RS-PWV and MODIS- PWV.

Stations	RMSE(mm)	MBE(mm)	R
Algiers	2.63	1.5	0.95
Bechar	2.21	1.14	0.92
Tamanrasset	4.11	1.48	0.69

4 Conclusion

This study provides some first results of comparing different precipitable water data sources for three stations in Algeria (Algiers, Bechar and Tamanrasset). The variation of precipitable water vapour depends on the location and climate indicators (i.e., humidity, altitude, temperature, among others).

The comparison between PW MODIS and PW GPS shows small differences (generally higher than 0.9 Pearson correlation coefficient). The bias varies from station to station. Our results show a good correlation over all stations except for Tamanrasset station (correlation of 0.69). The correlations are low in the southeaster area where the amount of PWV is usually low.

In summary, this study of intercomparison of PWV from different instruments over Algeria, which is a country with a large area, intends to introduce observational datasets to improve our understanding of the water vapour mechanism.

These preliminary results are encouraging, in particular for meteorological applications in the sites evaluated and for extended potential use in other regions in Algeria.

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