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Comparison of Precipitable Water Vapor from GPS and WRF model: A Case Study for Two different Egyptian Sites

A.S. Ragab[1], Ashraf E. Mousa[2], Z. Awad[3] and M.M. Abdel Wahab[3]

[1]*Basic Science Department, Faculty of Engineering, Canadian International College (CIC), Cairo, Egypt.*
[2]*Crustal Movement Lab., Geodynamics Department, National Research Institute of Astronomy and Geophysics, Cairo, Egypt.*
[3]*Astronomy, Space Science and Meteorology Department, Faculty of Science, Cairo University, Giza, Egypt.*

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ABSTRACT

Precipitable Water Vapor (PWV) is an essential factor for weather prediction and climate research due to its influence on delaying radio signals that, in turn, affects the navigation systems. This study introduces the first attempt to estimate the amount of PWV in Egypt using the available data from the ground-based Global Positioning System (GPS) data at two cities; Helwan and Alexandria. One of the key parameters extracted from the GPS data is the zenith wet delay (ZWD). We found that the ZWD range is 5.25 to 269.75 mm for Helwan and 7.125 to 319.56 mm for Alexandria. This leads to a variation in the calculated PWV values between (0.84 - 43.16 mm) for Helwan and (1.14 - 51.13 mm) for Alexandria. Throughout the year, PWV reaches its maximum at late summer and early autumn while its minimum is reached at the winter. Results were validated using the Weather Research and Forecasting (WRF) model.

The difference in the estimated PWV from the two different GPS stations in Helwan and Alexandria has a maximum value of around 18.74 mm. This difference is due to the different meteorological conditions at the two sites. On the other hand, for both stations, the PWV results show good agreement with those from the WRF model with the correlation coefficient (r) up to 0.95. The average difference of the estimated PWV between GPS and WRF are 9.16 and 8.55 mm for Helwan and Alexandria respectively. Therefore, we conclude that the methodology used to compute the PWV over Egypt using the available GPS data is accurate and can be used for different Egyptian cities.

Keywords: Global Positioning System (GPS), Weather Research and Forecasting (WRF) Model, precise point positioning (PPP) software and precipitable water vapor (PWV).

Introduction

Water vapor is the most important greenhouse gas in the atmosphere. Most of the water vapor is found in the first layer of the atmosphere (the troposphere) which might extend up to 20 km above the sea level. Most of the weather phenomena record in the troposphere, such as air temperature and pressure, the amount and type of precipitation, the strength and the direction of the wind, as well as the types of the clouds, is taken from the troposphere layer (Parthasarathy, 2006).

The GPS-radio signals that are traveling through the Earth's atmosphere suffer from delays within the tropospheric layer because the layer is non-dispersive to radio signals in the range up to 15 GHz (e.g. Mousa *et al.,* 2016). These delays occur due to refraction process of the GPS-signals that passing through the troposphere; which called zenith tropospheric delay (ZTD). Global Positioning System (GPS) radio signals are delayed in the troposphere due to refraction. This delay can be catastrophic because it might be one of the reasons for misleading navigation which in turn may cause either losing a plane, vehicle and/or a person or missing some data from military systems. These signal delays can be used to estimate the precipitable water vapor (PWV) which is the length of water in a vertical column of the atmosphere above the receiver position.

ZTD consists of two components: the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD). The ZHD component comes from dry gases and particles with an amount of 80-90% of the total ZTD. The remaining percentage of ZTD (20-10 %) is for the ZWD component originates from water vapor in the tropospheric layer (Hagemann, Bengtssoni and Gendt, 2003) and hence it can be

Corresponding Author: A.S. Ragab, Basic Science Department, Faculty of Engineering, Canadian International College (CIC), Cairo, Egypt. E-mail: asmaa_ragab2016@yahoo.com

used as a measure for the amount of PWV. GPS files gave the amount of ZTD parameter overlying each GPS station every 30 sec. Using the PPP software and equations in Section 2.1, the PWV with accuracy better than 5% in wet environments can be estimated (Bevis *et al.,* 1994). Recently, PWV was estimated in several countries using GPS data (e.g. Coster *et al.,* 1996; Chen and Liu, 2014; Zhao *et al.,* 2018). They found a good agreement with meteorological data.

In Egypt, previous meteorological studies using the GPS data from Egyptian stations were mainly concerned with the analysis of either ZWD or ZTD for water vapor (e.g. Mousa *et al.,* 2016; Farid, 2017). Neither of these studies looked into the calculations of the PWV in Egypt via the analysis of the available GPS data from the Egyptian stations.

Therefore, we are motivated to estimate, for the first time, the PWV over Egypt using GPS data and also to compare with meteorological estimates. For the purpose of the study, the GPS data were collected from Helwan and Alexandria stations to represent two different meteorological conditions. The key aim of this study is to estimate the PWV over Egypt and to find its variation during the year in two different sites; coastal and urban. This study is designed so that the estimated PWV from the GPS data will be compared to the same values evaluated using the WRF model in order to estimate the accuracy of PWV estimated using GPS. The tools of assessment are the root mean square error (RMSE), the mean absolute percentage error (MAPE) and the correlation coefficient (r).

This paper is organized as follows; in Section 2 we review our methodology and data collection. We present and discuss the results of the data analysis in Section 3, and we, finally, draw our conclusions in Section 4.

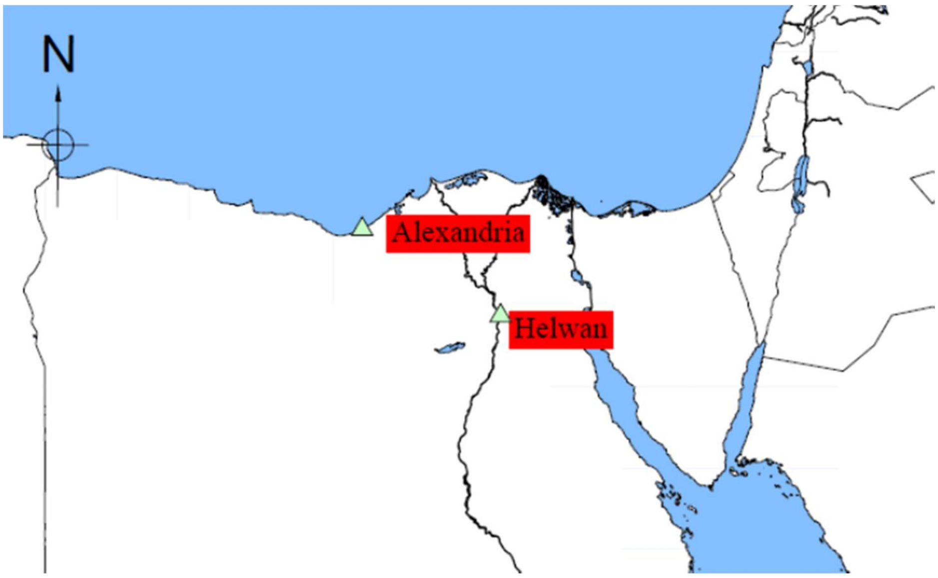

Fig. 1: Geographic location of the two Egyptian GPS-stations used for data collection.

Global Positioning System (GPS)

GPS-data of Alexandria-station are available online at ftp://www.station-gps.cea.com.eg/ALX2/DATA_30/2015/ while those from Helwan station are taken from the Space Weather Monitoring Center (SWMC) at Helwan University. For both stations, the mask elevation angle is 15^0, and the data sampling rate is 30 sec. In order to process the observed GPS-data, we use a precise point positioning software; the magic GNSS software which is available at https://magicgnss.gmv.com/. From the observed data, we extract detailed information about ZWD variation as a function of time. In this study, we are using the available data from both stations simultaneously. For this reason, we are using the 2015 data because in the following years a lot of data was missing and this year was selected as represented for both stations.

Our methodology is briefly as follows; we first compute the precipitable water vapor (PWV) using the collected GPS-data, after that, we use these results obtained from WRF in computing the required PWV; given the water density of the studied location.

The magic GNSS software gives the values of the ZWD. These values can be used to estimate the PWV, which defines the amount of water vapor contained in the vertical column above the GPS receiver, at the location of the GPS-stations. IWV is the mass of water vapor per unit area. Therefore, this parameter is, by definition, linked to the IWV as follows, (e.g. Bevis *et al.,* 1992)

$$PWV = IWV/\rho \tag{1}$$

Where, ρ is the water vapor density; adapted to be the same for both sites.

The ZWD data obtained from the GPS readings after PPP software can be linked to the PWV via the expression in Eq. (2), following Askne and Nordius (1987)

$$PWV = K \times ZWD \tag{2}$$

The temperature dependent constant, K, is given by Eq. (3) taken from Runge *et al.* (1996)

$$K = \frac{10^8}{R_w \rho_w \left(\left(\frac{K_3}{T_m} \right) + K_2 - mK_1 \right)} \tag{3}$$

In Eq. (3), m is the molar mass ratio of water vapor (M_W) and dry air (M_d) ($m = M_W/M_d$), R_w is the universal gas constant (461.5 J/Kg.K), ρ_w is the water density = 997 Kg/m^3, and T_m is the weighted mean temperature. The three physical constants, K_i (i=1-3) have these adapted values 77.6 ± 0.1 K/m bar, 72.0 ± 9.0 K/m bar, (3.75 ± 0.03) $\times 10^5$ K/m bar, respectively (e.g. Mousa, 1997).

The weighted mean temperature (T_m) is a vital factor in estimating the PWV from GPS receivers. Bevis *et al.* (1992) found that T_m is linked to the surface temperature (T_s) through linear profile can be expressed generally by the equation ($T_m = a + b\ T_s$). These authors successfully expressed T_m over the United States using Radiosonde profiles for two year period. After that, the expression becomes widely used although its accuracy differs according to the studied region (e.g. Fernandez *et al.,* 2010; Ning *et al.,* 2013; Isioye, Combrinck and Botai, 2016). The T_m is estimated by Elhaty *et al.* (2019) over Egypt from the above expression, using Radiosonde data during the years 2015 and 2016, as follows

$$T_m = \begin{cases} 0.92T_s + 14.3, & T_s \le 290\ K \\ 1.11T_s - 40.8, & 290 \le T_s \le 300K \\ -0.14T_s + 334.2, & T_s \ge 300K \end{cases} \tag{4}$$

where, the surface temperature, T_s was taken from the NOAA database which are available at https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&countryabbv=&georegionabbv=.

The obtained PWV results were then compared with the simulations of the WRF model in order to validate our methodology and to determine its accuracy.

Weather Research and Forecasting model (WRF) simulation

The WRF model was employed for the year 2015 with a horizontal resolution of 30 Km. The model output parameters are temperature, pressure, water vapor mixing ratio, and the model level height that were analyzed on hourly biases during 2015. These parameters used to calculate the WRF-IWV by taking the model level integration of the water vapor density at each level ($_{wv}(z)$) is obtained as (Simeonov *et al.,* 2016)

$$IWV = \frac{1}{_w} \int_z^{z_n} {}_{wv}(z) dz \tag{5}$$

where, $_w$ is the water density.

n is the model level number.

WRF-IWV computed every 4 seconds and saved after 1 hour, then recorded the data for every 6 hours. It is worth notice that the simulations produce IWV which is then converted into PWV using the expression in Eq. (1).

Before running the analysis, we remove the outliers from the data, so that any error greater than 2σ is removed, where σ is the standard deviation.

Results and Discussion

In this section, we are displaying and discussing the results from the data analysis, then making a comparison of PWV between the two GPS stations, and the comparison of GPS with WRF. The time variance of the PWV throughout the year 2015 and the summer months are illustrated in Figure 2 and 3 for the stations in Helwan and Alexandria. The time variations of the PWV throughout the year 2015 and seasons are illustrated in Figure 4 for Helwan station and Figure 6 for Alexandria station as compared to the WRF model.

In order to validate our methodology, we introduced the parameter "Z_{G-W}" which is the difference between the PWV values obtained from the GPS data and those simulated by WRF, and then we ran statistical calculations on these Z_{G-W} data in order to obtain some important parameters, for both stations, namely; bias, minimum, maximum, the Mean Absolute Percentage error (MAPE), the correlation coefficient (r), and the root mean square error (RMSE) are estimated. These parameters assess our measurements during the four seasons and hence the whole year. Tables 1 and 2 summarize most of these statistical calculations.

The comparison of PWV between the two GPS stations:

Helwan and Alexandria are in different meteorological sites. Helwan is an urban city with a high population and high records of air pollution, the meteorological conditions there may represent the arid climate. Alexandria is a coastal city with a higher population than Helwan city but it is less polluted. GPS data extracted zenith wet delay (ZWD) range is 5.25 to 269.75 mm for Helwan and 7.125 to 319.56 mm for Alexandria. Then by estimation, the PWV variation is between (0.84 -43.16 mm) for Helwan and (1.14 - 51.13 mm) for Alexandria. Figure 2 shows the time series of the PWV during the year 2015 for Helwan (panel a) and Alexandria (panel b).

The time variation of the whole year (panels a and b) starts with lower values of PWV at the beginning of the year (winter) to reach its minimum value, by the middle of winter, to be 0.84 and 1.14 mm for Helwan and Alexandria, respectively. After that, PWV increases gradually to reach a maximum amount of 43.16 and 51.13 mm at the end of summer and the begging of autumn for Helwan and Alexandria, respectively. The difference between the two stations is due to the meteorological differences between their locations. This difference is recorded to be around 18.74 mm during the begging of autumn. The estimated GPS-PWV for Helwan and Alexandria showed a strong positive linear relationship with a correlation coefficient $r = 0.82$ and the standard deviation 4.05 mm.

Figure 3 illustrates the variation of PWV during the summer months "July, August, and September" for Helwan (panel a) and Alexandria (panel b); due to the summer is the most humid season. In this case, the difference between the two stations in case of the summer months is around 17.29 mm. PWV variation shows a similar trend starts with lower values at the beginning of the summer after that increasing gradually at the middle then decreasing again to reach the end of the months. In this figure, we could notice that the PWV variations at Alexandria are higher than the variations at Helwan. The variation is larger at Alexandria because Alexandria is a coastal city.

Comparison of PWV with the WRF model:

Helwan Station

Figure 4 shows the time series of the PWV values in the year 2015, found from the GPS (straight blue lines) and WRF (scattered red dot) data. From the variation through the year of the parameter, panel (a), as estimated from the GPS data, we noticed that the amount of PWV at the beginning of the year, selected in this study to be the spring, has low values down to 20 mm then this amount gradually increases to reach its maximum 43.16 mm by the end of the summer and the start of the autumn. The correspondence between the PWV from GPS and WRF shows a perfect match with the trend of variations. From figure 5, that introduce the scattering plot between GPS and WRF, it is clear that there is a very strong positive linear correlation with a correlation coefficient $r = 0.95$ and a standard deviation 2.03 mm throughout the year.

Therefore, we conclude that the agreement between the two approaches for estimating PWV may lend some confidence that our proposed methodology is accurate and feasible.

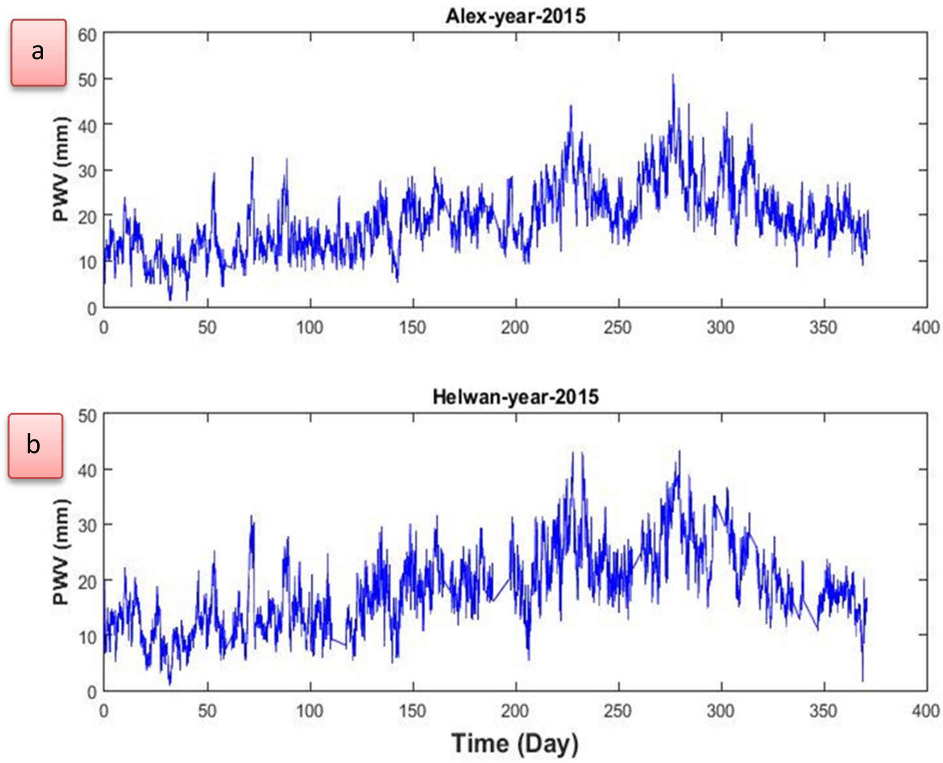

Fig. 2: Variation of the PWV as measured from GPS for Helwan and Alexandria stations during the year 2015. The panels represent (a) the whole year variations for Helwan station, and (b) the whole year variations for Alexandria station.

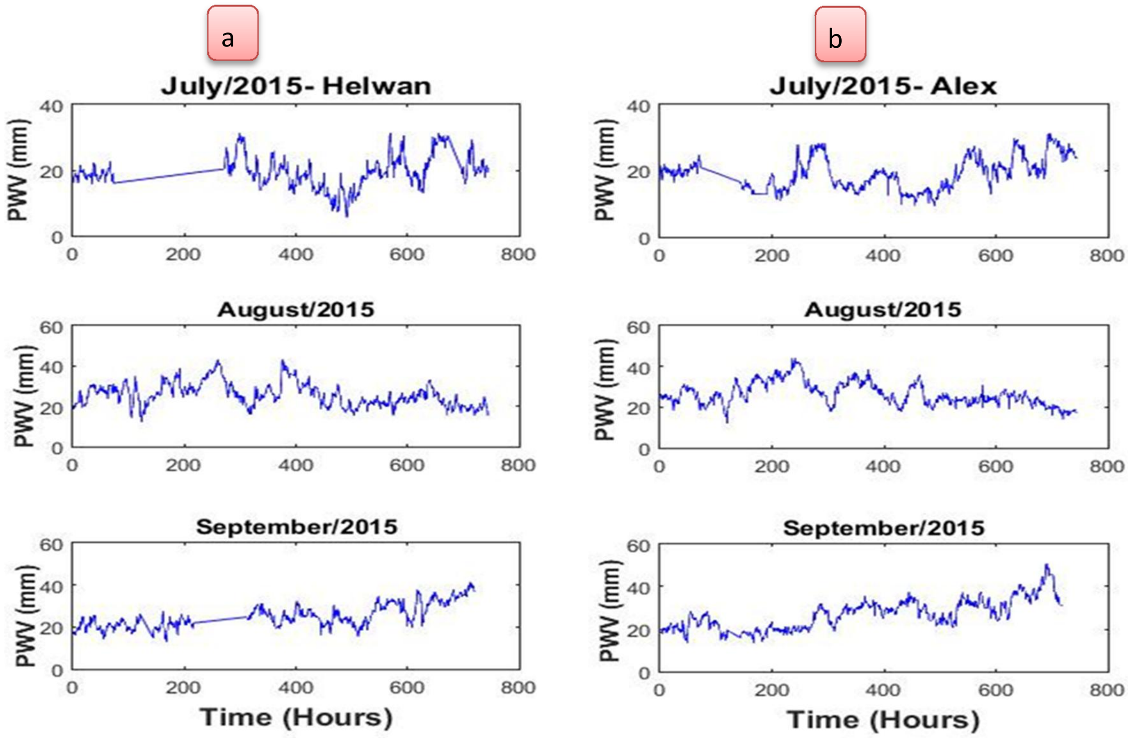

Fig 3: Variation of the PWV as measured from GPS for Helwan and Alexandria stations in case of the summer months "July, August, and September". The panels represent (a) Summer months at Helwan, (b) Summer months at Alexandria.

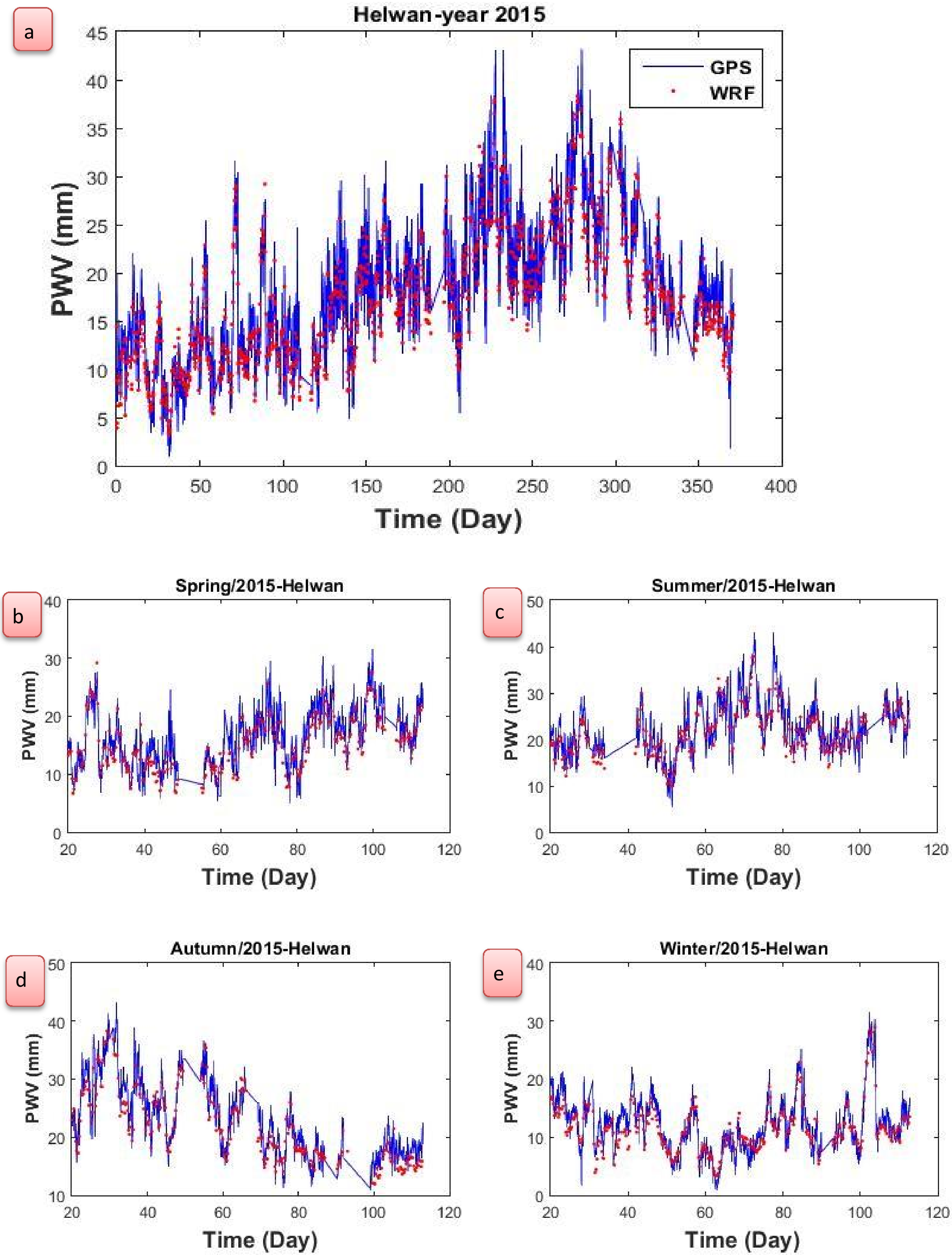

Fig. 4: The time series of PWV as measured from GPS and WRF for Helwan station during 2015. The panels represent (a) the whole year variations, (b-e) the seasonal variations for the year 2015.

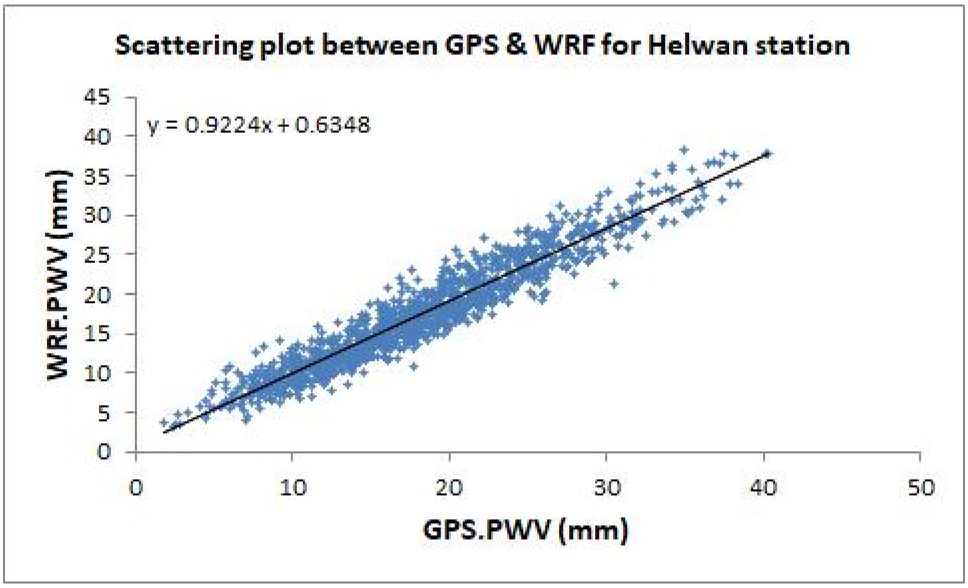

Fig. 5: Scatter plot of PWV simulated by the WRF model versus PWV measured by GPS as estimated from Helwan station during 2015.

After computing the $Z_{G\text{-}W}$ for Helwan data and run the statistical calculations, we found that bias, maximum and minimum values averaged during the year are 0.66, 9.16 and -5.45 mm, respectively. The negative sign indicates that the PWV computed from the GPS data are larger than those predicted by WRF. The root mean square error (RMSE) and the MAPE are 2.21 and 5.16 %, respectively. The statistical parameters found from the seasonal and annual variation of the PWV as well as the RMSE are summarized in Table 1 for the year and seasons of 2015.

Table 1: The statistical parameters of PWV at Helwan station computed for Seasons and all year 2015 "mm".

Analysis	Bias (mm)	Min (mm)	Max (mm)	RMSE (mm)
Spring	1.80	0.00019	6.54	2.22
Summer	0.76	-5.08	9.16	2.55
Autumn	0.96	-5.45	6.65	2.30
Winter	0.022	-4.23	4.51	1.74
Year 2015	0.66	-5.45	9.16	2.21

Alexandria Station:

Figure 6 represents the time variations of PWV from both the GPS and WRF data analysis for the whole year 2015 (panel a) and the four seasons (panels b to e) for Alexandria station. It is clear from Figure 6(a) that the trend of the variation in the PWV is similar to that obtained for Helwan in which PWV increases gradually from spring to reach higher readings in summer then it decreases until its minimum in winter. The max PWV obtained from GPS data is approximately 51.13 mm by the end of summer and the beginning of autumn. The correspondence between the PWV from GPS and WRF shows a perfect match with the trend of variations.

The correlation between the estimated PWV from GPS and WRF data is found to be linear with a strong correlation factor of 0.95 and a standard deviation of 2.29 mm (see Figure 7). This result is inline with that obtained for Helwan station which gives support to our methodology.

Table 2 lists the statistical parameters of PWV computed for both the four seasons and the whole year of 2015. This table showed that bias, maximum and minimum values averaged during the year are 0.21, 8.55 and -7.91 mm, respectively. The negative sign indicates that the PWV computed from the GPS data are larger than those predicted by WRF. The (RMSE) and the MAPE are 2.29 mm and 0.9 %, respectively

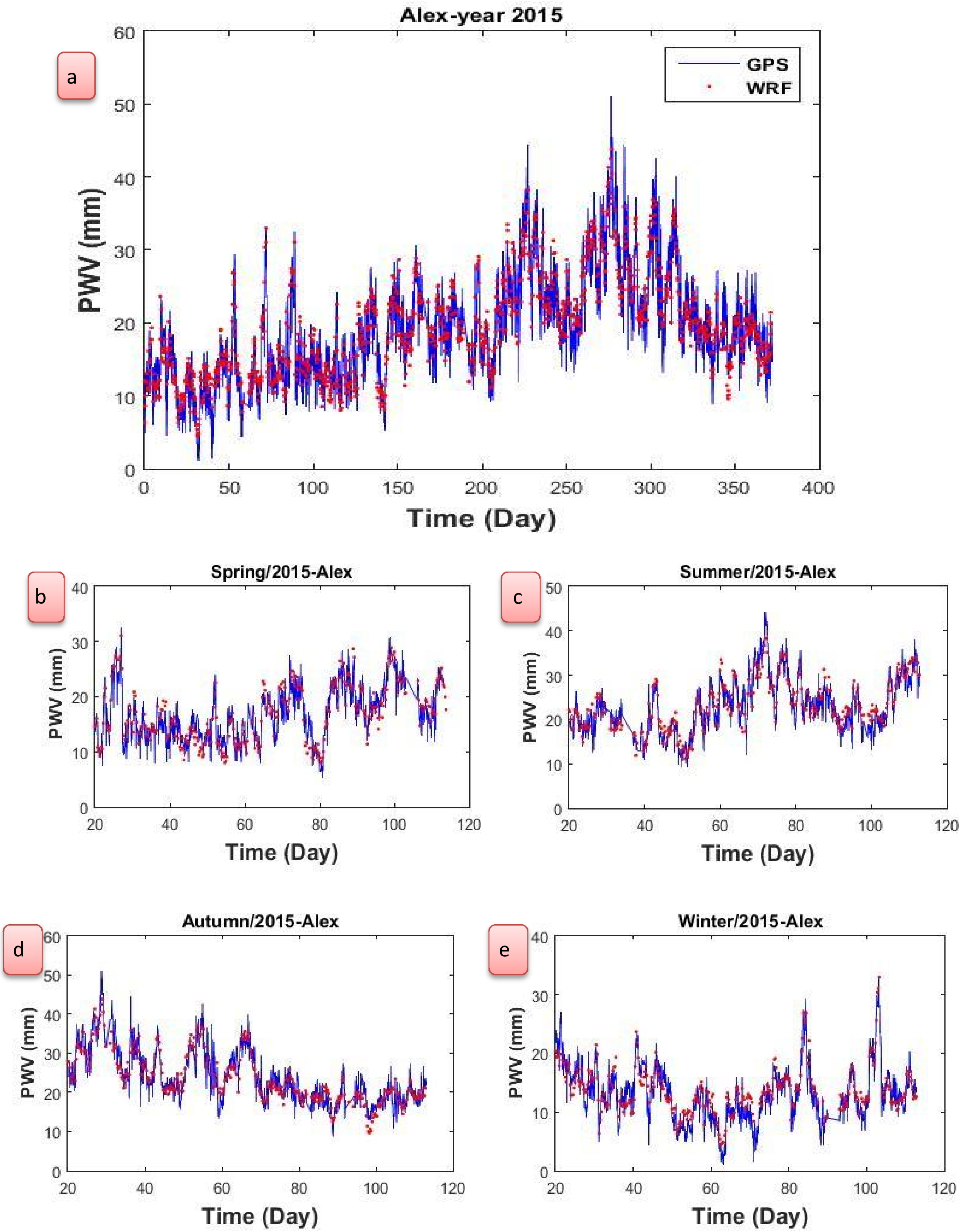

Fig. 6: The time series of PWV as measured from GPS and WRF for Alexandria station during 2015. The panels represent (a) the whole year variations, (b-e) the seasonal variations for the year 2015.

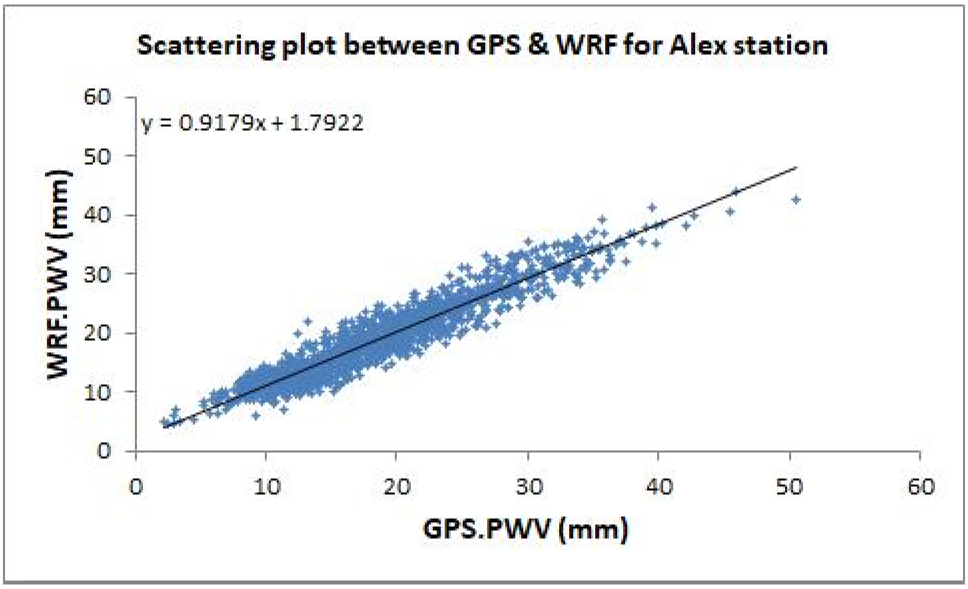

Fig. 7: Scatter plot of PWV simulated by the WRF model versus PWV measured by GPS as estimated from Alexandria station during 2015.

Table 2: The statistical parameters of PWV at Alexandria station computed for different Seasons and all year 2015 "mm".

Analysis	Bias (mm)	Min (mm)	Max (mm)	RMSE (mm)
Spring	0.055	-4.99	5.26	2.07
Summer	0.45	-5.72	8.55	2.53
Autumn	0.42	-4.74	5.18	1.93
Winter	-0.072	-7.91	6.13	2.57
Year 2015	0.21	-7.91	8.55	2.29

By looking generally to figures 4 and 6, it's clear to notes that PWV has high values during the summer season because this season is the most humid one.

Conclusion

The content of water vapor in the atmospheric layers is an important factor for several meteorological applications and measurements. Given this importance and with the growing body of GPS data in Egypt, we were motivated to introduce for the first time the calculations of the precipitable water vapor (PWV) over Egypt using data from two stations, Helwan and Alexandria, for the year of 2015. The obtained results were then validated by those predicted using the Weather Research and Forecasting (WRF) model.

GPS data analysis showed that the maximum zenith wet delay value in Egypt at the year 2015 is 269.75 and 319.56 mm during October at Helwan and Alexandria, respectively. ZWD minimum values are 5.25 and 7.125 mm during February at Helwan and Alexandria, respectively. Meanwhile, The PWV shows a maximum value of 43.16 and 51.13 mm at late summer and early autumn, while the minimum values are 0.84 and 1.14 mm during the beginning of winter.

Comparison between the two stations over the whole year shows the maximum difference in PWV of 18.74 mm during the end of summer and the start of autumn. This maximum difference is associated with the maximum point of PWV over the year. In General, The difference between the two stations values is due to the fact that Helwan and Alexandria are in different meteorological sites. Alexandria is a coastal city while Helwan is inside the country so the behavior of the climate will be different from these both sites.

Comparison between the calculated PWV from GPS and WRF revealed that GPS estimated PWV is very accurate with a correlation factor around 0.95 and accurate up to 95%. The root mean square error (RMSE) in the PWV results is estimated to be 2.21 and 2.29 at Helwan and Alexandria station, respectively, with a corresponding mean absolute percentage error (MAPE) of 5.16 % and 0.9 % for both locations. The values of MAPE (within 3.03 %) imply that the GPS estimated PWV in this study is plausible and promising. Given the wealth of GPS data from other stations in Egypt, we encourage the use of these data to obtain accurate measurements of the water vapor content above Egypt from which several meteorological implications can be investigated.

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