Surface mixing ratio and total precipitable water in Barcelona

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Abstract: Relationship between total precipitable water and mixing ratio in Barcelona is studied using a ten year period of data set, based on radiosondes and ground base stations. A good correlation coefficient of 0.94 for daily data pairs is obtained. A higher correlation coefficient of 0.99 is obtained when monthly data means are used, due to the fact that variability is smoothed. The function obtained is appropriate for monthly averaged total precipitable water prediction, however it would have more error as a system of daily prediction since particular conditions are not considered.

I. INTRODUCTION

The study of water vapor in the atmosphere is of crucial importance to many fields of meteorology. Water vapor plays a central role in terms of attenuation of radiation coming from the sun, differentiating between two cases: longwave and shortwave radiation. This radiation is very sensitive to the amount of water vapor in the atmosphere. The frequency intervals where this attenuation is lower are called atmospheric windows, and the attenuation of the electromagnetic waves in these windows is a function of the total water vapor throughout the optical path. The attenuation also depends strongly on the angle of inclination at which is measured, since at low degrees of inclination the amount of mass traversed increases considerably [1]. For these reasons, water vapor plays an important role in satellite telecommunications from space, as well as in the calculation of the radiative balance and forecasting radiation loss in the atmosphere. Besides applications related to radiation, the water vapor measurement is used also for precipitation forecasting, and probable minimum temperature [2].

The total precipitable water (TPW) is defined as the thickness that all the water vapor above a particular point would occupy if condensed into a layer on the land surface, and it is expressed in cm or mm.

The TPW can be derived from satellite observations as well as from radiometric measurements. In addition, it can be also determined from radiosonde measurements. This requires a vertical profile of temperature, pressure and relative humidity for its indirect calculation. Radiosondes have their limitations, since normally a couple are performed daily. These radiosonde stations have a cost, and they are not as abundant as conventional weather stations, so their geographical distribution is also limited. For this reason, for some time now, attempts have been made to approximate the total precipitable mass from surface measurements, since these are easier to record and have a much wider distribution over the earth's surface. The accuracy of the TPW calculation from surface humidity depends on several factors, such as the degree of air mixing in the vertical profile. For this reason, if lower layers of the atmosphere are not connected with upper layers, this prediction may not be correct [2]. Other studies about the determination of TPW from surface humidity have been conducted over time, in a multitude of different geographic locations and with different time intervals of radiosonde data records as well. [1-7]

The present work aims to apply the same techniques as in previous studies, to determine the degree of correlation between TPW and surface humidity in Barcelona, as well as to find empirical functions that relate them, with radiosonde and surface humidity data recorded between 2011 and 2021.

II. DATA AND METHODOLOGY

The scope of this work covers meteorological data from a ten-year period, from 2011 to 2021, gathered in the Faculty of Physics in Barcelona. The main data for this study come from two different sources: meteorological ground-based instruments, and daily radiosondes.

The ground-based station provided several magnitudes, such as temperature (T), pressure (P) and relative humidity (RH), measured on the roof of the faculty and recorded as 10-min averages . The radiosondes are launched twice a day, at 11 and 23 UTC . This instrument consists of several sensors and electronic devices, protected with expanded polystyrene, and assembled with a helium-filled balloon that is automatically launched from the roof of the Faculty of Physics. The specific sonde model is the M10 of the Meteomodem brand. The sonde performs a vertical profile of the lower atmosphere up to about 30 km including temperature and relative humidity. In addition, the Global Positioning System (GPS) included inside the sonde is used to derive the horizontal wind from differences in position, as well as, to determine the atmospheric pressure from the vertical position. The pressure at any altitude is estimated with the barometric equation using altitude inferred by the GPS and the temperature lapse rate mesaured by the radiosonde. The sensors of the sonde are a thermistor and a capacitor with $0.01°C$ and 0.1% resolution, respectively, and the pressure derivation has an accuracy of less than 1hPa up to 100hPa.

The methodology to obtain the total precipitable water consisted of its derivation from the vertical profiles of temperature, pressure and relative humidity. The expression of TPW is shown in Eq. (1)

$$TPW_{radiosonde} = -\int_{-\infty}^{0} \frac{w(P)}{g} dP \approx -\frac{1}{g} \sum_{i=1}^{TOA} w_i \Delta P_i \tag{1}$$

where g corresponds to the gravitational acceleration, w to the mixing ratio, and ΔP to a pressure layer. The mixing ratio is derived using the following expression

$$w = 0.662 \frac{e_0}{P - e_0} \tag{2}$$

The vapour pressure e_0 is not measured by the radiosonde but, it is calculated with relative humidity RH as percentage, and the saturation vapour pressure over a plane liquid water surface $e_s(T)$

$$e_0 = \frac{e_s(T) RH}{100} \tag{3}$$

The saturation vapour pressure is a function of temperature and shows a sharp increase with increasing temperature. In the literature there are several expressions to derive it but in this study we used the Bolton's equation

$$e_s(T) = 6.112 \exp \frac{17.67T}{T + 243.5} \tag{4}$$

where T is in $^\circ C$ and e_s in hPa.

The above magnitudes were computed for each altitude provided by the radiosonde. Measurements of two consecutive pressures from the data set were considered as one layer. Hence, the mixing ratio from equation (1) was averaged at each layer, and then summed layer by layer to obtain the total precipitable water. This method was applied to each morning and night data file, and the result was two corresponding TPW values per day.

Fig. 1 shows, as an example, the vertical profile of temperature and relative humidity for one day. In this case, the temperature clearly decreases with altitude and the relative humidity ranges from 60% to 80% at lower levels and then decreases. The vertical profile of mixing ratio was calculated according the the described methodology and shows that the main contribution to the TPW is located at lower levels. In this case, at around 500 hPa (about 5500 m) the mixing ratio is close to zero. This behaviour is observed in most of the cases.

Equations 2, 3, 4 were also used to derive the surface mixing ratio. Since our goal was to compare the TPW and the surface humidity, it was necessary to average the surface 10-min mean data to be representative of the duration of the radiosonde ascent, from launch to the highest altitude when the balloon bursts. One hour was considered the time takes for to complete the ascent, therefore measurements between 11:10-12:00 UTC and 23:10-00:00 UTC were selected. It is worth noting that the 11:10 measurement corresponds to the average of the previous ten minutes. The previous intervals were averaged and associated to a day, whether they corresponded to morning or night measurements, and the mixing ratio was computed with that averaged T, HR and P.

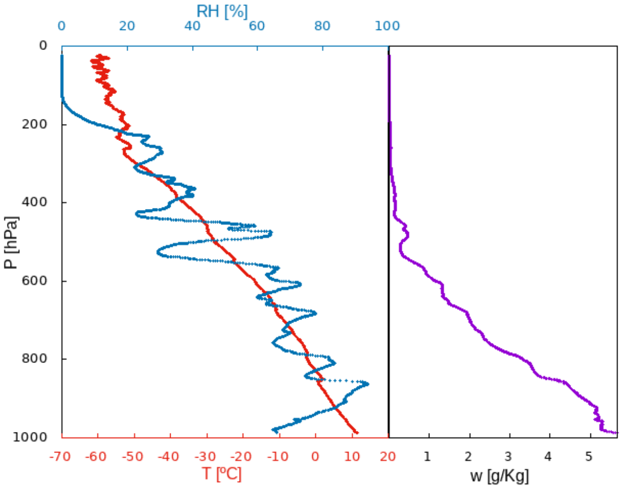

FIG. 1: Vertical profile of T, RH and mixing ratio of a random specific day. Values from T ans RH are represented directly from radiosondes data files, and mixing ratio is derived from them.

There are several options when choosing the variable to describe surface humidity. For example, [1] used vapour pressure, [3] used the mixing ratio, while [2] used both of the above variables and the dew point. [2] concluded that there are minor differences in the results using any of these humidity variables, since after all they are measures of the same thing. In the present work, the mixing ratio has been chosen for convenience.

All this operations and calculations were done through the Fortran programming language, with programs written from scratch. The advantages of using this language were that the calculation times were fast. The program that took the longest time was the one that calculated the morning and evening TPW for each day. To do this calculation, the program had to open each radiosonde file, determine the mixing ratio for each row and perform a summation to determine the TPW. This process took a few minutes on average. All figures were plotted with gnuplot.

At this point, we finally obtained a data set composed of morning and night TPW values, as well as morning and night surface mixing ratio values, associated to a specific day, month and year. A difficulty arose when merged both data. Considering that measurement devices are not perfect and that a ten-year period is a wide interval in which temporal technical problems can occur, both data sets had some days or short periods with no data. Nevertheless, these days with missing data represent a minor proportion compared to the total days, representing only a 0.05% of total data.

III. RESULTS

The results obtained for TPW in Barcelona vary from values very close to zero to values around 50 mm. On the other hand, the range of values obtained for the mixing ratio varies between 0 and 25 g/Kg. As can be seen in Fig. 2, there is a general increasing trend between TPW and w: the higher the surface humidity, the higher the total mass of precipitable water.

The relationship between TPW and mixing ratio is shown in different ways: showing daily pairs of values, daily pairs of values separated by seasons and monthly averaged values.

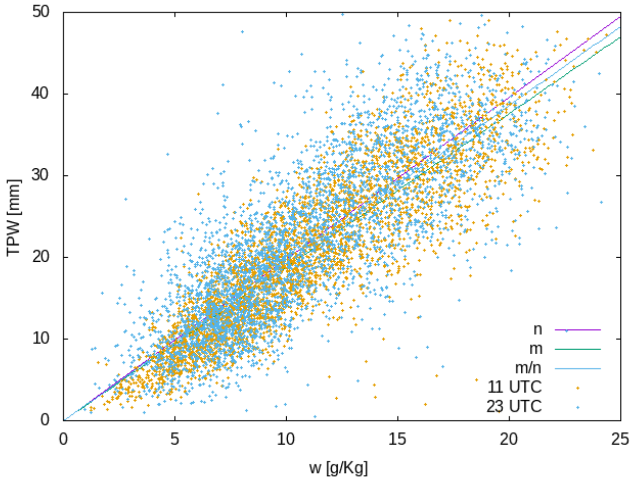

FIG. 2: Total precipitable water vs surface mixing ratio from daily radiosonde measurements at 11 and 23 UTC. Lines represents the linear fit for morning (m), night (n) and all (m/n) data

As we can see in Fig. 2, morning and night daily data are similarly distributed. Linear regressions are calculated considering night, morning and both data sets.

	C (mm/g·Kg^{-1})	R^2
Morning	1.88	0.96
Night	1.98	0.93
Morning/Night	1.93	0.94

TABLE I: Coefficients for linear regressions for all data and considering day/night. "C" stands for regression coefficient, and R^2 corresponds to correlation coefficient.

Correlation coefficients are very high (Table I), being morning data the case with more correlation, and night data the less. This could be caused by a more mixed air column during the higher day temperatures due to solar radiation. The regression considering both data sets, show an averaged correlation, as we could expect. Comparing to similar studies in this field, these results are above the reported by [4], who found a correlation coefficient of 0.91 for 190 summer days in Phoenix. These results are also above these reported by [2], who did a study for three different stations in New Zealand for a year duration, and found annual correlations between 0.81 and 0.88. These good results in correlation terms may be due to our wide time interval of data set. Relation between surface mixing ratio and TPW may vary greatly on a given day, but these local differences are blurred when considering a statistical sample of ten years.

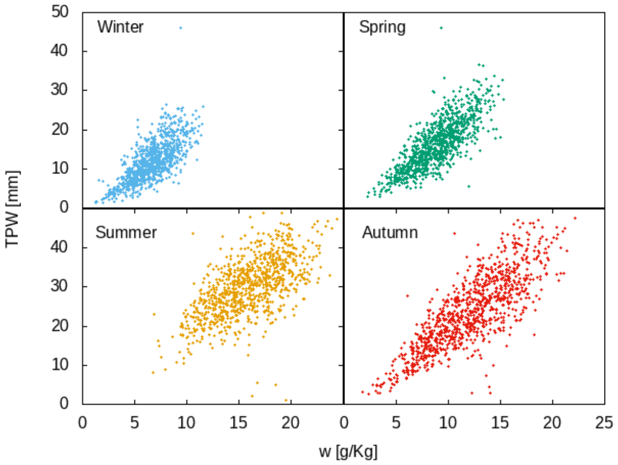

FIG. 3: Daily TPW and surface mixing ratio pairs separated by seasons

A seasonal analysis of data shows that the range of each magnitude has a strong seasonality (Fig. 3). The following months have been considered for each season: Summer (June, July, August), Autumn (September, October, November), Winter (December, January, February) and Spring (March, April, May). In the case of winter months, with lower temperatures in general, the TPW ranges between 0 and 28 mm, while the surface mixing ratio varies between 0 and 12 g/Kg. This would be the season with the lowest values. For the spring months, the same range of low values as in winter is observed for the two magnitudes, but in this case the upper range widens reaching values up to 38 mm for TPW, and 16 g/Kg for surface humidity. On the other hand, both the lower and upper data increase in magnitude in summer. TPW ranges from 10 mm to 50 mm, while w ranges from 8 g/Kg to 25 g/Kg. We can affirm that the summers in Barcelona are months of high humidity at the surface and a higher amount of water vapour in the atmosphere than the rest of the stations. This is reasonable taking into account that vapor pressure is a function of temperature, and a higher temperature leads to a higher humidity. Finally, the autumn months have the greatest variability. Ranges extend from 0 mm to 50 mm for TPW, and from 2 g/Kg to 23 g/Kg for the mixing ratio. Autumn would be the season with the greatest changes in surface moisture and atmospheric water vapour.

If we compare seasonal values with those obtained from annual data, we see that the correlation coefficients are somewhat reduced (Table II). This may be due to the fact that the sample size is reduced by about a quarter. Comparing the results between seasons, it is observed that there is a higher correlation in summer, autumn, and spring, while winter is the season with the lowest correlation.

	C(mm/g·Kg^{-1})	R^2
Winter	1.82	0.90
Spring	1.90	0.94
Summer	1.91	0.95
Autumn	2.01	0.94

TABLE II: Linear regressions coefficients for the data pairs separated by seasons

If the values are presented as pairs of monthly averages (Fig. 4), the dispersion is reduced and a stronger correlation is observed, which is confirmed by a correlation coefficient of 0.99 for morning, evening and both values (Table III). These results are comparable to those obtained by [5], who also used monthly averaged data over a three-year interval from fifteen different stations in the United States, obtaining a correlation coefficient of 0.98. They are also comparable to those obtained by [6], with coefficients between 0.92 and 0.98 from 34 Canadian stations, or to those reported by [7], who used data from seven South African weather stations over a seven-year period, with coefficients of 0.97 and 0.98.

	C(mm/g·Kg^{-1})	R^2
Morning	1.88	0.99
Night	2.01	0.99
Morning/Night	1.95	0.99

TABLE III: Linear regression coefficients for the monthly averaged data.

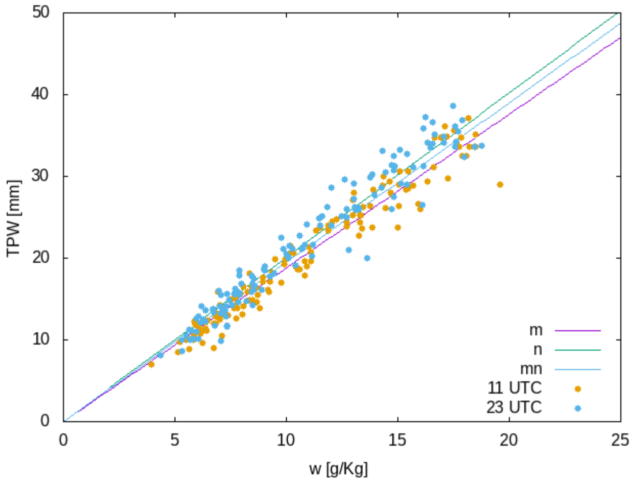

FIG. 4: Monthly averaged TPW vs w data pairs. Lines represents the linear fit for morning (m), night (n) and all (m/n) data.

The high correlation coefficients are related to the long time series as well as that monthly means smooth differences related to particular conditions.

As discussed in the introduction, in order to have a good ratio between TPW and w, the column air has to be well mixed, ensuring a good connection between the lower and upper layers of the atmosphere. One of the situations that can affect this connection is the occurrence of cloudiness. Therefore, in order to extend the conclusions that can be drawn from this work, data from radiosondes and meteorological stations have been combined with data from a ceilometer. This instrument uses electromagnetic waves, such as a laser, to determine cloud base height. The data from this device consisted of a value indicating the height when it detected clouds, and a dummy value when the sky was clear. These data were combined with the TPW and w data pairs. Then cloudy days were discriminated and followed the same procedure as above to represent only the clear sky days. The results can be seen in Fig. 5. It is important to clarify that the data available, as measured by the ceilometer, only ranges from July 2015 to December 2020.

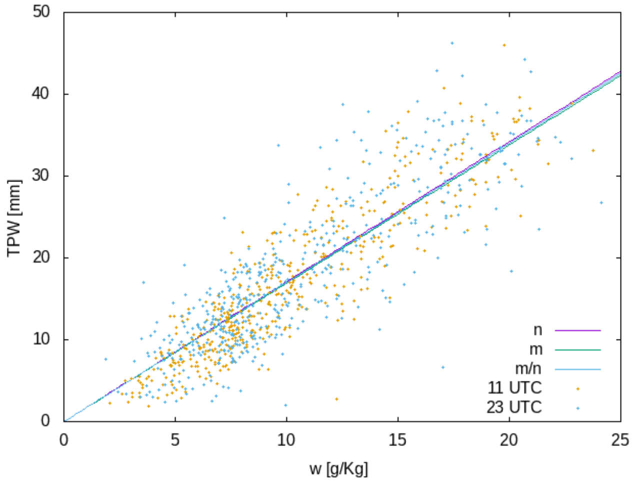

FIG. 5: TPW and w daily data pairs, where only the days under clear sky conditions are considered. Lines represents the linear fit for morning (m), night (n) and all (m/n) data

The range of data for both the TPW and the mixing ratio under clear sky conditions are quite similar to those obtained in the day-to-day data. At first sight we could only state that there is a lower density of points near the regression lines, and this is a consequence of the decrease in the amount of available data. The small observed differences results in the same correlation coefficients (Table IV) that have been obtained for the case of the daily val-

	C(mm/g·Kg^{-1})	R^2
Morning	1.69	0.96
Night	1.71	0.94
Morning/Night	1.70	0.95

TABLE IV: Linear regression coefficients for daily data pairs under clear sky conditions.

ues, and similar proportionality coefficients. However, it has to be taken into account that we are dealing data with a large dispersion. That dispersion probably comes from the fact that some radiosondes are displaced by a few kilometers from the launch point. Hence, there may be pairs where the surface humidity is compared with a TPW integrated from a displaced vertical profile. Eliminating the cloudy days, dispersion is not affected, and the error is very similar to the one obtained considering all the points.

IV. CONCLUSIONS

The main objective of the present work was to determine a function that relates TPW with mixing ratio, and discuss its validity. We can conclude that between these two magnitudes exist a strong relation. For the daily data pairs the correlation coefficients are quite good, in fact they are higher than those found in other studies. The correlation is higher for morning pairs of data, attributing this fact to the higher temperature and better mixing of the lower layers. The data presented by seasons lowered a bit the correlation, especially in the case of winter months, but this reinforced the temperature effect in the correlation. Moreover, summer and autumn days were the seasons with higher correlation, being summer the case with more humidity in general, and autumn the months with a major variability and correlation coefficient. Comparing to other referenced studies, in the cases were monthly mean data were used, better correlation was found. In the present study, the best results were also found for monthly mean data, with a correlation coefficient of 0.99 for morning, night and all data. This high correlation may be due to the fact that when averages are done, the variability of every month is smoothed, and this causes a better fit to the regression line. Also this high correlation even compared with other studies, may be due to the good and large data used, that made this study foundations stronger. However, it can not be demonstrated a stronger correlation for the days with clear sky from daily data pairs. We attributed this to the fact that variability is wide for daily data, and it continues being large even when only clear-sky are considered. For this reason, improvements can be done in this study. Data can be discriminated with more restrictive criteria, for example taking into account data from the soundings that not exceed a five kilometer radius displacement from the launch point. This would ensure that surface and vertical data are referencing the same point. Another improvement would be considering only the first vertical kilometers of sounding, i.e. the closest one to the surface. In this way it would be only considered the mixing layer. This layer height depends on temperature and is more influenced by the surface. These latter enhancements can be suggestions for further studies. It is hoped that this work have contributed new and useful data in the study of water vapor over Barcelona, as well as its relationship with specific surface humidity.

Acknowledgments

I wish to thank the Servei Meteorològic de Catalunya and the Grup de Meteorologia de la UB, for the sounding and surface data, respectively. This work would not have been possible without the consistent and wide data provided by them, which this work is based.

Also I want to thank to my advisor Yolanda, for her attention, commitment and involvement during the whole process of this work.

I would also like to thank my family, for the support I have received, both financially and emotionally, in pursuing this university degree. I would not have done it without them.

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