CAPÍTULO 7

THE PRECIPITABLE WATER VAPOR COLUMN OF THE ATMOSPHERE ON THE REGION ABOVE MEXICO CITY

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ABSTRACT: In this work we present the results of the analysis of data taken with radio sondes to estimate the atmospheric water vapor content over the region of Mexico City. The water vapor in the atmosphere, integrated in altitude is referred to as Precipitable Water Vapor (PWV), it is an important factor to determine the opacity of the atmosphere for astronomical observations at mm and IR wavelengths. The aim is to identify feasible periods for astronomical observations at locations of the center of Mexico. Also, we want to compare the PWV at mid altitudes with that for high altitudes. With this purpose, the PWV is estimated by calculating the PWV from various lower limits up to the highest altitude where the sonde takes data (about 20 km). We take 2.0 km as the lowest value for the lower limit of integration. The next lower limit is 2.5 km, and so on. The largest lower limit is 6.0 km. Histograms of PWV obtained for different values of lower limit of integration have been made. The histograms for high altitude lower limits (5.5-6.0 km) have prominent maxima at low values of PWV. The maximum, shifts to larger values of PWV as the lower limit of integration decreases, besides that, as going to lower limits of integration, the PWV spreads more to low values. The spread is larger for Winter time than the Summer one. As a consequence, the PWV, integrated from the altitude of Mexico City (2-2.5 km), has values as low as those observed when integrating from lower limits of 5-6 km altitude. It means, the water vapor content at the region of Mexico City are feasible for Astronomical observations during Winter time.

KEYWORDS: precipitable wáter vapor, infrared wavelength, meteorological sondes

INTRODUCTION

The importance of the atmospheric water vapor in the climate, and in general in the Earth life, makes it the subject of study in a variety of Sciences, including Astronomy (Otárola et al., 2009), Meteorology, Geophysics (Vogelmann et al., 2008), and also for Weather Forecasting. For all of them, the study of the atmospheric water is important, particularly in the last years due to the global climate change, which is leading to a general warming. Also, it is leading to more extreme short time-scale phenomena, for example, strong precipitations and even floods at some locations and, to the lack of water and even droughts at other sites. The atmospheric water vapor could also play an important role in the Green-House effect.

The amount of Water Vapor at the atmosphere depends on many factors, for example, winds at different directions and different altitudes, convective motions at different altitudes, time-variable local conditions, the orography, masses of water and rivers. All this makes the water vapor at the atmosphere to be highly variable with geographic coordinates and with time.

The water vapor mostly lies in a layer called Troposphere, with its density decreasing with the altitude. The amount of water vapor integrated from the surface of the Earth, in a given site, to the highest altitude of this layer (~ 20 km) is referred to as Precipitable Water Vapor (PWV). The estimation of the water vapor content at a given altitude interval is also useful and we will refer to it as Water Vapor Content (WVC).

The PWV can be estimated by several ways, which include the use of GPS, observations from space at near and mid infrared bands, spectral observations, from the land surface, at water lines at radiowavelengths, Meteorological radio sondes and others. Balloons are released, at given stations, carrying Meteorological sondes that take data of the atmospheric parameters at several altitudes, while the balloon is rising. For each altitude, a series of data is taken and send by telemetry to a ground station. The data may be integrated either from the surface or from other altitude. The computation of the WVC and PWV could be done with various purposes: 1. To compare the WVC at a given altitude with the PWV, with the aim to estimate the input due to a given altitude. 2. To compare the WVC, at a same altitude, over two different sites, to compare the humidity over these two sites. 3. To compare the WVC at a given altitude, with the WVC at another altitude. 4. To compare the PWV integrated from a given altitude to the highest one, estimated at two different times, to compare the atmospheric conditions at the two times.

Looking for Low PWV Sites in Central Mexico for Astronomical Observations

The water vapor content gives an important input for the opacity of the atmosphere and then it plays a central role for Astronomical observations from the land surface. Also, it is important for observations of the Earth from the space. Due to the emission and absorption of several water vapor emission lines, the astronomical observations at the millimeter wavelength range (Otárola et al., 2009 and Delgado et al., 1999) and at the infrared bands are particularly affected by the water vapor content. The PWV is highly variable with geographic coordinates and at different time scales.

To decrease the influence of the atmospheric opacity in the observations, many astronomy facilities are located at high altitudes. However, the requirements to install and maintain instruments at high altitudes are more difficult to accomplish than at low altitudes, where even the times for installation could be shorter and less expensive, and also the services to maintain the facilities are more affordable. As above pointed out, the PWV is the total water vapor content over a given site. Its monitoring at particular sites could allow one the use of the facilities, during periods of low PWV, improving the quality of the observations (Hills and Richer, 2000) and even giving the possibility to plan the observations based on the PWV forecasting (Pérez-Jórdan et al., 2015).

The central region of Mexico is in a medium altitude plateau, surrounded by mountain ridges at the East and West sides. The West ridge is roughly parallel to the coast at the Pacific Ocean and the East one to the Gulf of Mexico. In central Mexico there are several cities at elevations of the order of 2.0-2.5 km and mountains of the order of 3-4 km, as well as volcanoes of 4.5 - 5.6 km.

A phenomenon of an air flow at altitudes of about 10 km, from the Pacific Ocean that arrives to the West coast and travels to the East direction is called subtropical jet stream. The latitude of this stream varies from those of the North of Mexico and South of USA to latitudes at the central region of Mexico, carrying clouds and humidity from the West to the East. Then, it is expected that the humidity at the central region of Mexico, at altitudes of the jet stream, would depend on the humidity at the West coast. However, its relation with the WVC at lower altitudes, in the center of Mexico, has not been studied. It is seen that, the water vapor content in this region is affected by several factors and consequently it undergoes complex variations of various time-scales.

To diminish the influence of the PWV in the observations, many astronomy facilities are located at high altitudes. In the central region of Mexico some astronomical facilities are in operation at high and mid altitudes. The quality of the observations with some of these instruments depends on the atmospheric opacity, which in turn is a function of some parameters, in particular as above mentioned, the water vapor content. For the prospective of new facilities at these sites, or the performance of those already in operation, is of particular interest to have a better knowledge of the variations of the WVC at different time-scales, including long-term variations. Some data, as radio sonding data can be used with the purpose of studying the WVC around this region.

The PWV between low altitude sites could differ respect the one at a higher altitude making the low altitude site more suitable for using telescopes for a given period or season of the year with similar opacity respect the high altitude one. In this work, we analyze radio sonde data with the aim to look for good periods for astronomical observations at mm and

IR wavelengths at mid-altitudes.

Data Acquisition and Data Analysis

We use data of meteorological radiosondes of the station at Mexico City. Meteorological sondes are released in Mexico City two times a day, at noon and at midnight. In this work data taken from 1973 to 2015, at noon, are analyzed, through the different seasons of the year. Mexico City spreads over a large territory. Its nominal altitude is 2.33 km (the altitudes we refer to, here and further, are given respect the sea level), and consequently the data are taken from altitudes above this one. Nevertheless, it is possible to extrapolate the values obtained to estimate the PWV, as if it would be integrated from 2.0 km.

The estimation of the WVC values, for the data of a given sonde, has been made for intervals from h_{ii} to $h_{ii} + \Delta\Delta h$, with $\Delta\Delta h = 0.5\ km$, as made by Mendoza-Torres et al. (2021). The first interval used goes from 2.0 km to 2.5 km and so on, it means, further intervals are taken for the next subsequent *0.5 km* at higher altitudes. For a series of WVC values of a given sonde, the computation of PWV have been made by summing WVC values, from a given lower limit altitude h_{loll_ii} to hup, with h_{up}= 9.5 km. Various values of PWV have been computed by taking the lower limit of integration (h_{loll_ii}): 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 and 6.0 km. In all the cases, the upper limit used was hup = 9.5 km.

In the case of the center region of Mexico a lower altitude limit of particular interest (h_{loll_ii}) is 4.5 km, because it is near the altitude of the summit of the Sierra Negra volcano (4.55 km) in the state of Puebla, a site that harbors various Astronomical facilities.

As above mentioned, the Meteorological sondes at balloons make in-situ measurements. The temperature (*T*), pressure (*P*) and relative humidity (*RH*), typically from altitudes of some dozens of meters, above the surface at the site of release, up to the altitudes attained by the balloons are transmitted to the ground station and recorded.

The column of liquid water equivalent to the column of water vapor is computed. It is the Precipitable Water Vapor (PWV), which is given in mm (Giovanelli et al. 2001), is computed as follows: The temperature of the dew point for each altitude T_d(h) can be estimated according to Lawrence (2005). With these values, the water vapor pressure ($P_s(h)$), also as a function of altitude, may be computed (Alduchov and Eskridge, 1996). Then, using the local temperature at the altitude h, the pressure (P_s), and the ideal-gas law, we can estimate the number density of water vapor molecules at each altitude nll(h). The volume density of water vapor molecules at a given altitude (h) is the product of the number density n_{ll}(h) and the mass of the water molecule, which is 18 amu or 2.99×10^{-23} g. The mass M of a column of water vapor between two different altitudes can be estimated by using the average of (h) between the two given altitudes. The difference between these altitudes may be considered the length of the column for the average volume density. The volume of this column is given by the product of the given length and the base of the column (which we consider 1 cm^{-2}). Then, the mass of water vapor in a column between two altitudes is obtained just by multiplying the volume of the column and the average volume density between the two given altitudes. The total mass of a column is obtained by integrating (or summing) over all the altitudes. Finally, using the mass of the water vapor column, and the density for liquid water (1 g/cm^3), the column of liquid water equivalent to the column of water vapor is computed. Both, the WVC and PWVare given in mm (Giovanelli et al. 2001).

The WVC is estimated as in Mendoza-Torres et al. (2021). The PWV is estimated from various lower limits up to 9.5 km, which is near the highest altitude where most of the sondes take data (about 10 km). We take 2.0 km as the lowest value for the lower limit of integration. The next lower limit is 2.5 km, and so on. The largest lower limit is 6.0 km.

RESULTS AND DISCUSSION

In Figure 1 the values of PWV integrated from the different lower altitudes (which go from 2.0 to 6.0 km) are shown. The different colors of the data points are for the PWV integrated from different lower altitudes (as indicated in the figure). It may be seen that the PWV integrated from 6 km (data in red) takes the lowest values. The PWV obtained from lower altitudes of integration takes larger values. As expected, the largest PWV values are obtained for the 2 km lower limit of integration. In Figure 2 the PWV data integrated from a series of lower altitude limits (red dots for 6 km, green crosses for 5.5 km, blue circles for 2.5 km and violet crosses for 2 km) are shown, in the left panel the PWV data for August of each year of an interval from 1999 to 2011 and in the right panel for January of each year. These two months are representative of Winter and Summer conditions, respectively and have been chosen to show their behaviour, but in Figures 1 and 5 data for all months are shown.

The PWV of a given station have been averaged over each month of each year. In the left panel of Figure 2, the average for January for the lower limit of 2.0 km is plotted with violet crosses and with blue circles for 2.5 km, green crosses for 5.5 km and red dots for 6.0 km. In the right panel the averaged values of the PWV for data of the August of each year are shown.

Histograms of PWV obtained for different values of lower limit of integration have been made. In Figure 3 the histograms for data from 1973 to 2015 for August (left panel) of the whole interval and for January (right panel). The front-side histogram corresponds to PWV data for the lower limit of 2.0 km. The next histogram in the back is for 2-5 km, and the last at the back-side is for 5.5 km. In Figure 4 the histograms for some given lower limits are shown.

From Figure 2, it may be seen that in August, of the years of the interval plotted, the PWV values for 5.5 km (green crosses) and 6.0 km (red circles) lower limits, considerably differ to the PWV for 2.0 and 2.5 km. In August, there is only one value below 10 mm of PWV for a 2.0 km lower limit of integration. Contrary to this, in January there are many values smaller than 10 mm for a integration from a lower limit of 2.0 km (violet crosses in the right panel of Figure 2). Also, for a 2.5 km lower limit of integration (blue circles) there are many values below 10 mm in January.

From Figure 3, it is clear that the histograms for August have a prominent maximum at ~ 2 mm (PWV), indicating that values around it take place considerably more frequent than at other PWV. The maximum of the histogram shifts to larger values of PWV as the lower limit of integration decreases. Also, as going to lower limits of integration, the data spreads more over larger ranges of PWV. This behavior is seen also in other Summer months. For January, the histograms for high altitudes (5.5-6.0 km) have prominent maxima but for low altitudes, the histograms are considerably more spread, to low values of PWV, than for Summer data. As a consequence of this behavior, the PWV, integrated from the altitude of Mexico City (2-2.5 km), has values as low as those observed when integrating from lower limits of 5-6 km altitude. It means, the water vapor content at the region of Mexico City is feasible for Astronomical observations during Winter time.

The data plotted on both, the left panel of Figure 2 and the left panels of Figure 3 and 4, it may be seen that a part of the integrated PWV from 2.0 km has values lower than 5 mm, which are feasible for Astronomical observations at MIR. Also, in Figure 5 the histogram for the PWV data computed for the 2.0 km lower limit is very spread. This indicates that the behavior of the PWV data, for 2.0 km limit, is more influenced for the PWV data of Winter than for Summer

CONCLUSIONS

It is found that for summer time the histograms of the PWV have a clear maximum that shifts to lower values as the lower limit altitude increases. For winter time, the histogram for PWV at low altitudes does not have a prominent maximum and the histograms are considerably more spread than in summer. The behavior of the histograms indicates that, for some periods, the PWV at 2 km could be as good as at 6 km for Astronomical observations. Nevertheless, for an altitude of 6 km, the PWV is predominantly low.

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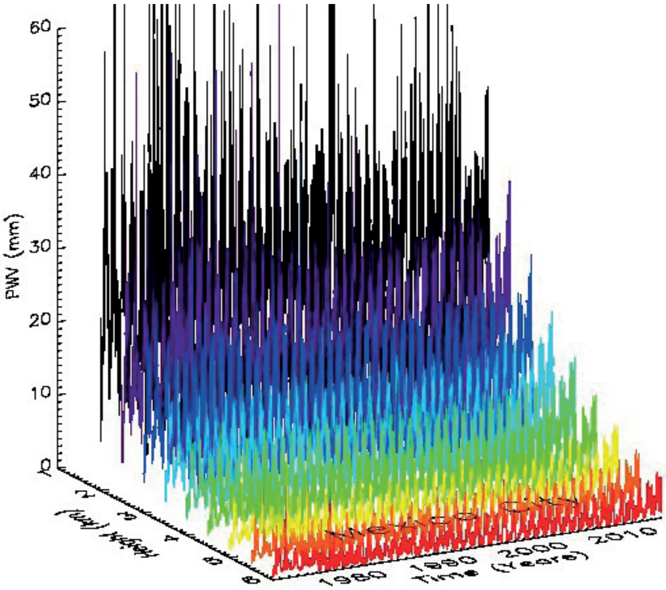

Figure 1. PWV data for the whole period (from 1973 to 2015), integrated from different lower altitudes (black-2 km, violet-2.5 km, dark-blue-3 km, light-blue-3.5 km, dark- green-4 km, light-green-4.5 km, yellow-5 km, orange-5.5 km and red-6 km. In the X- axis the time is given, in the Y-axis the lower limit altitude is given and in the Z-axis the PWV

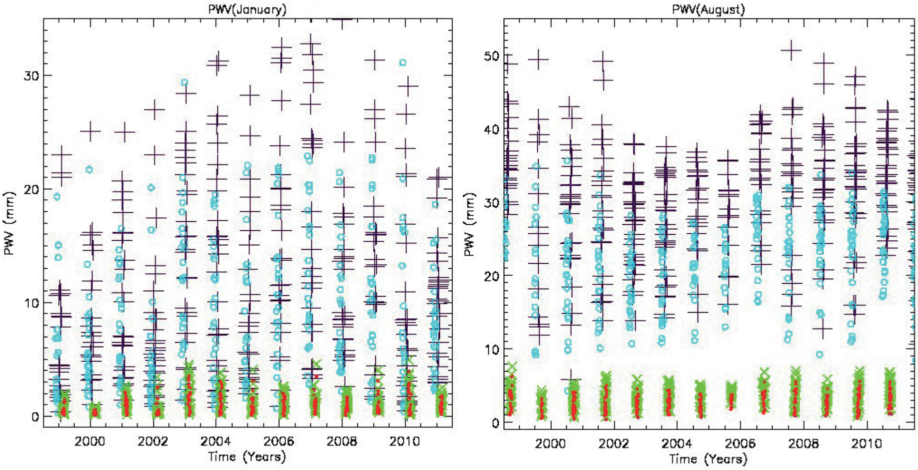

Figure 2. *Left*. The PWV data for January of each year of an interval from 1999 to 2011. The red dots correspond to the PWV integrated from 6 km, the green crosses to the PWV integrated from the lower altitude of 5.5 km, blue circles from 2.5 km and violet crosses from 2 km. *Right.* The PWV for data of August of each year.

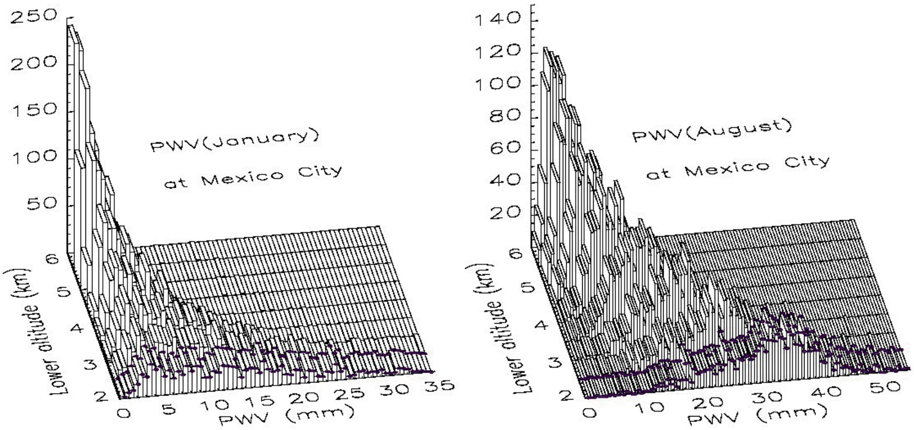

Figure 3. Three dimensional histograms of PWV for monthly data, in the X-axis the PWV (in mm) is given, in Y-**axis (which goes from the front to the back-side)** the lower altitude (in km) from which the PWV is integrated and in the Z-axis the frequency of occurrence (the values of the Z-axis correspond to adimensional numbers). The histograms are made with data for the entire time interval, from 1973 to 2015 integrated, from back-side to the front-side 5.5, 5.0, 4.5,4.0,3.5,3.0, 2.5 and 2.0 km. *Left,* for January of the whole interval and *Right,* for August, also for data of the whole interval.

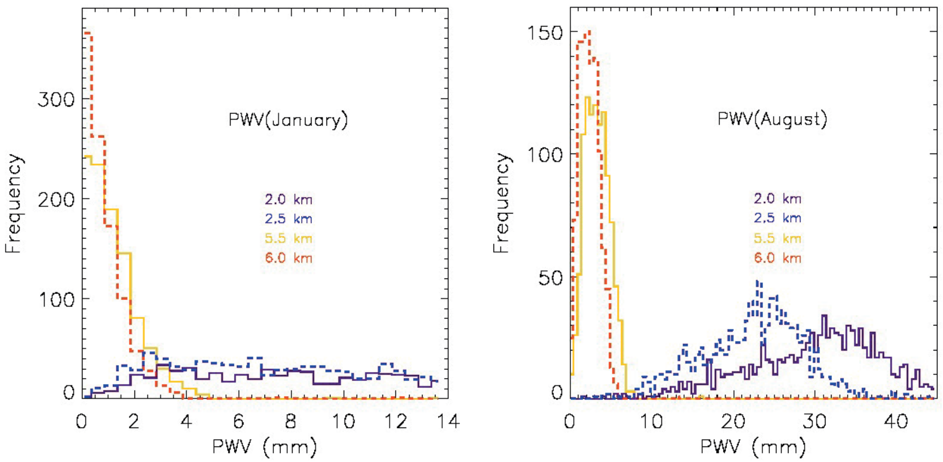

Figure 4. Histograms for the PWV values obtained for different lower altitudes of integration (given in a list in the center of the plot) for the time interval from 1973 to 2015. The plots are like front views of cuts at some selected Lower altitudes (given in Y-axis) of Figure 3, the one at the back-side and an additional one for a 6 km lower limit of integration. *Left.* For PWV data of January of the entire interval. It may be seen that the maximum of the histogram shifts to lower values of PWV with the altitude and that the frequency of occurrence around this maximum grows (also with altitude). *Right.* For PWV values of January of the entire interval.

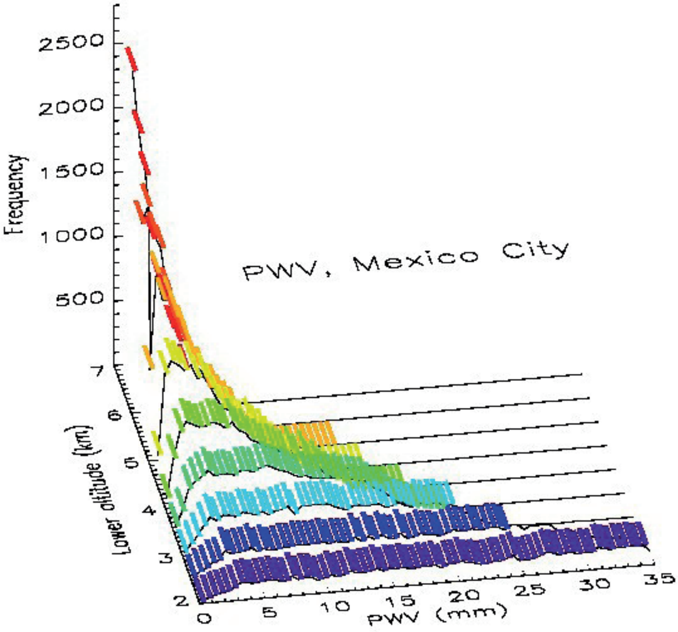

Figure 5. The same as Figure 1, from back-side to the front-side are for 6.0, 5.5, 5.0, 4.5, 4.0, 3.5, 3.0, 2.5 and 2.0 km lower limits of integration. The histograms are made with data of all months for the entire time interval, from 1973 to 2015.