ATMOSPHERIC PRECIPITABLE WATER VAPOUR IN JOS, NIGERIA

E. U. Utah and O. J. Abimbola
Department of Physics, Faculty of Natural Sciences, University of Jos, Jos, Nigeria
E-mail: current2me@yahoo.com

(Submitted: 14 November, 2005; Accepted: 8 June, 2006)

Abstract

Data from the Agro-meteorological station, Department of Geography and Planning, University of Jos (latitude: 09° 57' N, longitude: 08° 53' E and altitude: 1,159m above msl), for the periods 1992 to 2002, have been used for this investigation. The correlations between the natural logarithm of the precipitable water vapour (PWV), and the dew-point temperature $T_d$ and also relative humidity $h$, were investigated. Multiple regressions analysis was done on PWV and clearness index $K_o$, sunshine index $S$ and relative humidity $h$. Results show a new logarithmic relationship between PWV and $h$ and that the maximum precipitable water vapour in the atmosphere of Jos in the month of August has a value of 4.44±0.47cm, while the minimum of 1.54±0.47cm was found in the month of February. The regression models have been presented and discussed.

Keywords: Precipitable water vapour, dew-point temperature, relative humidity.

Introduction

Water vapour is an important link connecting the various components of the hydrological cycle. In addition to the fact that water vapour is the source of all clouds and precipitations, it has the ability to absorb not only radiant energy emitted by the earth, but also some solar energy. Therefore, along with carbon dioxide, it has a controlling influence on energy transfer through the atmosphere as a result of the heat energy from solar radiation changing the state of water from liquid to vapour at free water surfaces and bare soils in order to satisfy atmospheric water deficit. The phenomenon is referred to as evaporation. Furthermore, growing plants take up water from the soil or water body to give up more of it at leaf surfaces to the atmosphere in a process called transpiration.

An important water vapour parameter is the precipitable water vapour (PWV). It is the total amount of water in the zenith direction, between the underlying surface and the top of the atmosphere. In practice, it is the thickness of the layer of liquid water that would be formed if all the vapour in the zenith direction were condensed at the surface of a unit area; 1mm of the layer corresponding to 1kgm$^{-2}$ (Okulov et al., 2002). Precipitable water vapour plays a crucial role in atmospheric dynamics through the release of huge amounts of latent heat associated with condensation. Knowledge of the distribution of PWV is of paramount importance in weather research and forecasting (NASA, 2004). Tardy (2002), has shown that the proper way to diagnose the moisture content of the atmosphere is to use an absolute measurement of atmospheric moisture such as PWV.

 Estimates of PWV in the atmosphere have been made with sun-photometer Voltz (1974). Although the technique is viable only during clear daytime condition (Sierk et al., 1997; Plana-Fatori et al., 1998). Bevis et al. (1992) have shown that the Global Positioning Satellite (GPS) Signal method could be adapted to estimate the PWV with results comparable to those obtained from Water Vapour Radiometer (WVR) reported by Emardson et al. (1998). Reitan (1963) and later Leckner (1978) proposed ground based meteorological data incorporating water vapour and temperature to estimate the PWV. Using the exponential decrease of water vapour with height in the
atmosphere, Reitan (1963) proposed that

\[ PWV = \frac{483e_o}{T} \] (1)

and Leckner (1978)

\[ PWV = \frac{493e_o}{T} \] (2)

where \( e_o \) is the vapour pressure (in millibar) and \( T \) is surface temperature (in Kelvin). The difference between (1) and (2) arise from the choice of the most representative value for the scale height. Reitan (1963) in studying monthly means of \( PWV \) and station dew point temperature, \( T_e \) over continental United State of America, developed an excellent linear relationship between natural logarithm of the \( PWV(cm) \) and \( T_e(\degree C) \), viz,

\[ \ln(PWV(cm)) = 0.1102 + 0.0613T_e(\degree C) \] (3)

Won in 1977 developed a similar expression for all Canadian seasons (Okulov et al., 2002). In Nigeria, Maduekwe and Ogunmola (1997) have used the Reitan type of expression to evaluate \( PWV \) in Sokoto. Although, Kondratyev and Moskalenko have developed a simple correlation between \( PWV \) and surface level temperature, its application has not received a wide level of acceptance because it underestimates the amount of precipitable water (Okulov et al., 2002).

In this paper we present the evaluation of precipitable water vapour \( PWV \), its monthly variation and seasonal variations in Jos (latitude: 09° 57' N, longitude: 08° 53' E and altitude: 1,159 m above msl) using meteorological data of eleven years, 1992-2002. The aim is to express precipitable water in terms of surface humidity parameters, clearness index and sunshine hours. The values obtained in this work, it is hoped, will be comparable to those generated from satellite techniques and ground-based microwave radiometry when available at the location.

Site and Database

The agro-meteorological station of the Department of Geography and Planning, University of Jos provided the data for this work. The station is on latitude 09° 57' N, longitude 08° 53' E and at an altitude of 1159 m above mean sea level.

The station uses Sixe thermometer placed in a Stevenson screen to measure the ambient temperature, maximum and minimum temperature (°C). The Gun-Belani radiation integrator measures the solar radiation in millimeter (mm) while the sunshine duration is measured with Campbell-Stokes sunshine recorder. The dew point temperature, vapour pressure and relative humidity are all estimated from standard hygrometric tables following the readings of wet and dry thermometers (psychrometer) kept in the Stevenson screen.

Data Analysis

The mean monthly values of the data collected, ambient temperature \( T(K) \), vapour pressure \( e,(mbar) \), dew-point temperature \( T_e(\degree C) \), relative humidity \( h(\%) \), clearness index \( K \), Sunshine index \( S \), and precipitable water vapour \( PWV(cm) \) were obtained for each month of the years (1992-2002). The monthly mean of the \( PWV \) was calculated using the exponential decay model of Leckner (1978) given in equation (2). To obtain the constants of the Reitan type of equation (3) suitable for Jos the logarithm of \( PWV \) values thus obtained were plotted against the dew-point temperature \( T_e \). Also the \( PWV \) values were plotted against relative humidity values, clearness index and sunshine index. The Microsoft Excel spreadsheet computer package was used for the data analysis in fixing the line of best fit, calculating the intercepts and the standard error of estimation (SEE). Then the root-mean-square error (RMSE) and the mean bias error were estimated manually using the following expressions:

\[ \text{RMSE} = \left[ \frac{1}{n} \sum_{i=1}^{n} d_i^2 \right]^{1/2} \] (4)

and
MBE = \frac{1}{n} \sum_{i=1}^{n} d_i \quad (5)

where d_i = H_i - H_e (the difference between the i^{th} estimated and the i^{th} measured values) and n is the number of data points (in this investigation n = 129).

Results

**PWV and dew-point temperature**

The scattergram of ln(PWV) against the dew-point temperature T_d Fig. 1, shows a clear linear relationship with a very good linear correlation of 0.96 and standard error of estimation (SEE) of 0.14. The root-mean-square error (RMSE) gave a value of 0.02. The line of best fit drawn through the scattergram has the expression

\[ \ln(PWV) = 0.2979 + 0.0638 T_d \quad (6) \]

The slope value of 0.0638 °C compares well with other published values for other locations around the world as shown in Table 1. The intercept for each location varies considerably as can be seen from the table. A closer look at Fig. 1 seems to suggest two linear distributions lying side by side. An attempt was made to separate these linear distributions, which are shown in Figures 2 and 3. The linear fit of Figure 2 is the upper portion of the distribution in Fig. 1 while Fig. 3 is the lower portion. For Fig. 2, the slope = 0.0608 °C, intercept = 0.4233, correlation coefficient r = 0.995, SEE = 0.0415 while for Fig. 3, slope = 0.0641 °C, intercept = 0.0867, r = 0.995 and SEE = 0.0463.

**PWV and relative humidity, h**

The correlation between PWV and relative humidity h, is given as follows:

\[ PWV = 0.41525 + 0.05399h \]

In equation (7), r = 0.92, SEE = 0.52 and RMSE = 0.52. Figure 4 is a graph of equation 7. Another expression, which describes the correlation of PWV and humidity, is logarithmic in h and is given as

\[ PWV = 2.4631 \ln(h) + 6.2374 \]

Table 1: Slope and intercept values for different locations

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Location</th>
<th>Value of slope (°C)</th>
<th>Intercept(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reitan</td>
<td>1963</td>
<td>U.S.A</td>
<td>0.06138</td>
<td>0.1102</td>
</tr>
<tr>
<td>Won</td>
<td>1977</td>
<td>Canada</td>
<td>0.05454</td>
<td>-0.4539</td>
</tr>
<tr>
<td>Maduekwe &amp; Ogunmola</td>
<td>1997</td>
<td>Sokoto, Nigeria</td>
<td>0.06480</td>
<td>0.0546</td>
</tr>
<tr>
<td>This work</td>
<td>2004</td>
<td>Jos, Nigeria</td>
<td>0.06381</td>
<td>0.2979</td>
</tr>
</tbody>
</table>

*Nigerian Physics of Physics, 18(4), (2006)*
with the following statistical behavior: \( r = 0.92 \), \( \text{SEE} = 0.23 \) and \( \text{RMSE} = 0.50 \). Fig 5 is a graphical representation of equation (8).

**PWV, Cleanness index \( K \), and sunshine index \( S \)**

The relationship between \( PWV \) and cleanness index \( K \), is given as

\[
PWV = 5.694 + 4.521K
\]

having a correlation coefficient \( r = -0.48 \).

The scatter diagram of equation (9) is shown in Fig. 6. An expression for the relationship of \( PWV \) with sunshine index \( S \) is

\[
PWV = 6.253 + 5.925S
\]

with a correlation coefficient \( r = -0.64 \). The plot of \( PWV \) against \( S \) is given in Fig. (7). It is evident that there is little linear correlation between \( PWV \) and \( K \), or \( S \) indicated in the diagrams of Figs. 6 and 7, but on performing a simple multiple linear regression between \( PWV \), cleanness index, sunshine index and relative humidity, the multiple correlation coefficient was found to be 0.81, the standard error of estimation 0.54 and the root-mean-square error 0.63.

The multiple regression equation is

\[
PWV = 0.508436K + 0.114106S + \\
0.0544071h + 0.01704
\]
Seasonal Correlations

The two seasons experienced in Nigeria have durations in Jos as follows: rainy season, from May to October and dry/harmattan season lasting from November of one year to April of the following year. The variations of PWV described by equations (6) and (7) now have the expressions:

**Rainy season:**
\[
\ln(PWV) = 0.278716 + 0.06397T_o \\
r(\ln PWV, T_o) = 0.62
\]

\[
PWV = 1.9974 + 0.03219h \\
r(PWV, h) = 0.46
\]

**Dry/Harmattan season**
\[
\ln(PWV) = 0.2699 + 0.07052T_o \\
r(\ln PWV, T_o) = 0.94PWV = 0.003588 + 0.06586h \\
r(PWV, h) = 0.92
\]

It can be seen from equations (12) through (15) that a better correlation of PWV with \( T_o \) and \( h \) is obtained for the dry/harmattan season values than the rainy season.

Decade monthly average of PWV

Figure 8 shows the decade monthly average of \( PWV \) in Jos. The month of August records the lowest value of 4.4±0.5cm while February records the lowest value of 1.5±0.5cm. In Fig. (9) is displayed the time series of monthly-mean variation of \( PWV \) for Jos (1992 - 2002). The minima are observed to occur during the months of January and February while the maxima corresponds to the peak of the rainy season in July, August and September. The eleven-year period average of \( PWV \) in Jos is 39.6±5.8cm.
Fig. 5: Plot of Precipitable Water Vapour against \( \ln(h) \) on a linear-log scale.

Discussion

Variation of PWV with \( T_a \)
Various correlations, equations (6) to (11), of precipitable water with easy-to-measure ground-based meteorological parameters have been provided in this work for Jos. Equation (6) which is the Reitan (1963) equation applied to Jos is found to be in good agreement with the results of other investigators elsewhere. Fig. 2, being the lower distribution shown on Fig. 1, was found to represent the PWV for the years 1996 1998 and 1999. Referring to Fig. 9, it will be observed that the three years in question have values of lower PWV (or drier atmosphere) and a corresponding lower intercept of 0.1 than all the years under study. Hence it may be inferred that the intercept of equation (6) can be used to categorize the relative climatic atmospheric water burden of a place. Thus in Table 1, the intercept for Jos (0.2979cm) is seen to be higher than that of Sokoto (0.0546cm); the atmosphere of Sokoto being generally drier than that of Jos. In the same vein, Canada has the driest atmosphere of the cities listed in the table.

Variation of PWV with \( h, K, \) and \( S \)
Equations (7) and (8) giving linear relations of PWV with \( h \) and \( \ln h \) respectively should be expected because the relative humidity \( h \) is also a measure of the atmospheric moisture content. Equation (8) having a lower standard error of estimates (SEE = 0.23) gives a better fit than equation (7) with SEE of 0.52. However, from the statistical analysis carried out, their performance (both having \( r = 0.92 \)) is not as good as that of equation (6) (\( r = 0.995 \)) in estimating the PWV. Nevertheless the equations are recommended to be verified for other regions to assess their applicability.

Neither the variation of PWV with \( K \), nor with \( S \) gives a good fit as can be seen on figures 6 and 7 and the correlation equations (9) and (10). In spite of these, a multiple regression of PWV with \( K, S \) and \( h \) gives 0.81 as the correlation of multiple regression. The good regression coefficient notwithstanding, this technique is not as simple and convenient as the others.

Seasonal And Decade Variations of PWV
Using equations (12) and (14), their intercepts are of the same magnitude; hence this parameter cannot be used to describe seasonal variations at a location. In terms of correlation coefficients, a higher value of \( r \) is obtained for the dry season data. The maximum PWV value of 4.4±0.5cm in the month of August and minimum of 1.5±0.5cm in February are comparable to 3.8cm maximum and 1.0cm minimum obtained by
Utah (1993) at the same site using the Voltz (1974) multispectral sun-photometer measurements. Also the Jos maximum value of $PWV$ is similar to the value of $4.43 \pm 0.05 cm$ in the month of August obtained by Maduekwe and Ogunmola (1997) for Sokoto. In Jos, the wettest month of the year is August while the driest is February at the same location.

The eleven-year (1992–2002) monthly mean variation of the $PWV$ in Jos given in Fig. 9 shows a pattern similar to that obtained in Estonia from radiosonde data (1990–2001) by Okulov et al (2002). Except for the three years 1996, 1998 and 1999, with lower $PWV$ values, the yearly totals of $PWV$ in Jos are within a close range of 39–47 cm.

![Scattergram of precipitable water vapour against sunshine index.](image)

**Conclusion**

The correlation of precipitable water vapour ($PWV$) with dew-point temperature $T_d$ gives the best estimate of $PWV$ in Jos. The correlation of $PWV$ with meteorological parameter of relative humidity $h$ is ranked second to the dew-point temperature correlation. The introduction of sunshine index, clearness index, along with relative humidity into a multiple regression analysis of $PWV$ gives an acceptable coefficient of determination. The maximum precipitable water vapour in the atmosphere of Jos is found in the month of August while the minimum value occurs in February.

*Nigerian Physics of Physics, 18(1), (2006)*
Fig. 8: Line graph of decade monthly average precipitable water vapour in Jos, Plateau State, Nigeria.

Fig. 9: Time series of monthly-mean variation of PWV(cm) for Jos, Nigeria(1992-2002).

References


790-804.


