Original Research Article

ESTIMATION OF SURFACE WATER VAPOUR DENSITY AND ITS VARIATION WITH METEOROLOGICAL PARAMETERS IN BENIN NIGERIA

ABSTRACT

The monthly variation of Surface Water Vapour Density (SWVD) with meteorological parameters of monthly average daily mean temperature, relative humidity, surface pressure, cloud cover and sunshine hours during the period of thirty eight (38) years (1979 - 2016) for Benin (Latitude 6.32^0N, Longitude 5.10^0E, 77.8m above sea level) were investigated. The daily variation of surface water vapour density for the two distinct seasons considering two typical months in each during the period of year 2014 was examined. The comparison assessment of the developed two variable SWVD based models was carried out using statistical indices of coefficient of determination (R^2), Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), Nash – Sutcliffe Equation (NSE) and Index of Agreement (IA). The results showed fluctuation in the amount of surface water vapour density in each day of the month for the period under investigation. The monthly average daily values indicated that the surface water vapour density is higher during the rainy season than in the dry season. It was observed that the maximum average value of surface water vapour density of 21.1448 gm^{-3} occurred in the month of August during the rainy season and minimum value of 17.7134 gm^{-3} in the month of December during the dry season. The highest value of surface water vapour density was observed on 23rd May, 2014 with 27.57313 gm^{-3} and the lowest on 26th December, 2014 with 9.656676 gm^{-3}. The developed multivariate correlation regression model that relates pressure and precipitable water vapour with R^2 = 100%, MBE = -0.0204, RMSE = 0.0206, MPE = 0.1105, NSE = 99.9897% and IA = 99.9974% was found more suitable for surface water vapour density estimation with good fitting and therefore can be used for estimating surface water vapour density in Benin.

Keywords: Correlation models, dry Season, ECMWF, rainy season, SWVD

1. INTRODUCTION

Water vapor plays a very important role in climate change, hydrological processes, Earth's energy balance, and weather systems [1 – 4]. Water vapor is the most common greenhouse gas in the atmosphere, and it accounts for about 60 % of the natural greenhouse effect [1, 5]. At the surface, water vapor (or humidity) is an important meteorological and climate variable that affects human comfort [6], surface evaporation and plants' transpiration. Surface specific (*q*) and relative humidity (RH) is conventionally measured using wet and dry

bulb thermometers or RH sensors exposed in thermometer screens at a large number of weather and climate stations and on many marine platforms [7].
Water is the fundamental of the hydrological cycle, which is inter or intra movement of water, in the Earth's atmosphere, oceans, and continents. Transfer of heat and energy between the earth's surface and the atmosphere and within the planet takes place as a result of hydrological cycle. The primary and most effective greenhouse gas in the atmosphere is water vapour, as it absorbs long wave radiation and radiates it back to the surface, which contributes to warming [2, 8 – 11]. The atmosphere holds more water vapour as the temperature of the Earth's surface and atmosphere increases [2]. In the troposphere, water vapour molecules absorbed heat energy radiated from the Earth's surface [12].
As the Earth's surface temperature increases, the atmosphere tends to hold more water vapour. This atmospheric water vapour, acts as a greenhouse gas thus absorbing energy that would otherwise cause reduction of electromagnetic radiation travelling through the atmosphere, the penalty of these could be atmospheric or global warming. The proportion by volume of water vapour in the air at the ground level on the average changes from less than 0.001%in the arctic to more than 6% in the tropics [13 – 14]. This proportion decreases speedily with height [13].
Understanding the processes which manage the natural stability and variability of the climate system is one of the most intricate and challenging scientific problems faced by the climate science community today. This is due to the fact that human activities such as emission of greenhouse gases and land use change which result in external forcing are only partly predictable [15 - 16]. This is so because scientists lack the ability to actually do so since they cannot foretell population change, economic change, technological development and other relevant characteristic of future human activities [16].
The purpose of this study was to investigate the daily and monthly variation of surface water vapour density and to examine the monthly variation with meteorological parameters of mean temperature, relative humidity, surface pressure, cloud cover and sunshine hours for Benin located in South Western, Nigeria. The study also developed two variable correlation models for estimating surface water vapour density for the location under investigation.
This present study, evaluates and compares six evapotranspiration models for estimating reference evapotranspiration in Kano, Nigeria, using FAO – 56 PM method as standard. The reason for this comparison is to find out which of the six evaluated models is most appropriate to be considered as an alternative to FAO – 56 PM model for estimating ET_o in Kano based on the four adopted statistical indicators.

2. METHODOLOGY

The daily and monthly average minimum temperature, maximum temperature, relative humidity, surface pressure, cloud cover and sunshine hours meteorological data used in this study was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) at 2 m height for Benin, Nigeria. The period under study is thirty eight (38) years (1979 – 2016).
The surface water vapour density (SWVD), vapour pressure (e) and mean temperature (T) are related by the following expression [1, 14, 16] as:

$$SWVD = 216.7\left(\frac{e}{T}\right) \qquad (1)$$

they also obtained vapour pressure *e* using the expression given by

$$e = RH\left(\frac{e_s}{100}\right) \qquad (2)$$

where RH and e_s are the relative humidity and saturated vapour pressure respectively. The saturated vapour pressure is evaluated using the Claussius Clapeyron equation defined as:

$$log_{10} e_s = 9.4051 - \left(\frac{2353}{T}\right) \qquad (3)$$

The mean temperature T, is also obtained using [17]

$$T = \frac{T_{max} - T_{min}}{2} \quad (4)$$

where T_{max} and T_{min} are the maximum and minimum temperatures respectively. The SWVD is in gm^{-3} and e and e_s are in millibars (mb), T in Kelvin (K) and RH in percentage (%).

A correlation model between ambient Temperature T (Kelvin) and Partial Pressure P_s as reported by [1] is given by the semi empirical equation

$$P_s = \exp(26.23 - \frac{5416}{T}) \quad (5)$$

[18] presented the following formula, which expresses precipitable water in terms of relative humidity:

$$W = \frac{(0.493\varphi_r Ps)}{T} \quad (6)$$

where φ_r is relative humidity in fractions of one, T is ambient temperature in degrees Kelvin and p_s is the partial pressure of water vapour in saturated air.

Then dew point Temperature T_{dew} was obtained using [19]

$$T_{dew} = T - \frac{100 - RH}{5} \quad (7)$$

where T and RH are the Mean Temperature (Kelvin) and Relative Humidity in Percentage.

The virtual Temperature ($T_{virtual}$) was also obtained using [20].

$$T_{virtual} = \frac{T}{1 - \frac{e}{p}(1 - \epsilon)} \quad (8)$$

where e is the vapour pressure and $\in$ is a constant denoted by 0.622

The potential temperature $T_{potential}$ was obtained using [20]

$$T_{potential} = T_{mean}\left(\frac{p_o}{p}\right)^{\frac{R}{C_p}} \quad (9)$$

Equation (9) is called the Poisson's equation where p_o is the standard pressure generally taken as 1000hPa and $\frac{R}{C_p} = 0.286$

2.1 Validation of the Models

The validation of the estimation of the estimated values was statistically tested by computing the Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), Nash-Sutchliffe equation (NSE) and the Index of Agreement (IA), similarly, also coefficient of determination (R^2) was determined for each of the models.

The expressions for the MBE, RMSE and MPE as stated according to [21 – 28], were given as follows.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(SWVD_{i,cal} - SWVD_{i,mea}) \quad (10)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(SWVD_{i,cal} - SWVD_{i,mea}\right)^2\right] \quad (11)$$

$$MPE = \left(\frac{\frac{1}{n}\sum_{i=1}^{n} SWVD_{i,mea} - SWVD_{i,cal}}{SWVD_{i,mea}}\right).100\% \quad (12)$$

$$NSE = 1 - \frac{\sum_1^n (SWVD_{i,mea} - SWVD_{i,cal})^2}{\sum_1^n \left(SWVD_{i,mea} - \overrightarrow{SWVD_{i,meas}}\right)^2} \quad (13)$$

$$IA = 1 - \frac{\sum_{i=1}^{n}(SWVD_{i,cal} - SWVD_{i,mea})^2}{\sum_{i=1}^{n}\left(\left|SWVD_{i,cal} - SWVD_{i,mea}\right| + \left|SWVD_{i,mea} - \overrightarrow{SWVD_{i,mea}}\right|\right)^2} \quad (14)$$

From equation (10) to (14) $SWVD_{i,cal}$, $SWVD_{i,mea}$ and n are the i^{th} calculated, i^{th} measured values of daily Surface Water Vapour Density and total number of observations respectively, also $\overrightarrow{SWVD_{i,meas}}$ is the mean Surface Water Vapour Density.

Chen et al. [29] have recommended that a zero value for MBE is ideal and a low RMSE is desirable. Similarly, the smaller the value of the MBE and RMSE the better is the performance of the model, a positive MPE and MBE values provide the averages amount of overestimation in the calculated values, while the negative values gives underestimation. A low value of MPE is desirable. The percentage error between −10 % and + 10 % is considered acceptable [30 – 35]. High values of R^2, NSE and IA are desirable. The MBE and the RMSE are in gm^{-3}, while R^2, MPE, NSE and IA are in percentage (%) [36 – 39].

2.2 The Developed Two Variable Correlation Models

The proposed two variable correlation models are of the form:

$$SWVD = a + bP + cCC \quad (15)$$

$$SWVD = a + bP + cSSH \quad (16)$$

$$SWVD = a + bP + cPWV \quad (17)$$

where a, b and c are empirical constants and P, CC, SSH and PWV are Surface Pressure, Cloud Cover, Sunshine Hours and Precipitable Water Vapour respectively.

3. RESULTS AND DISCUSSION

3.1 Surface Water Vapour Density and its Variation Meteorological Parameters for Benin

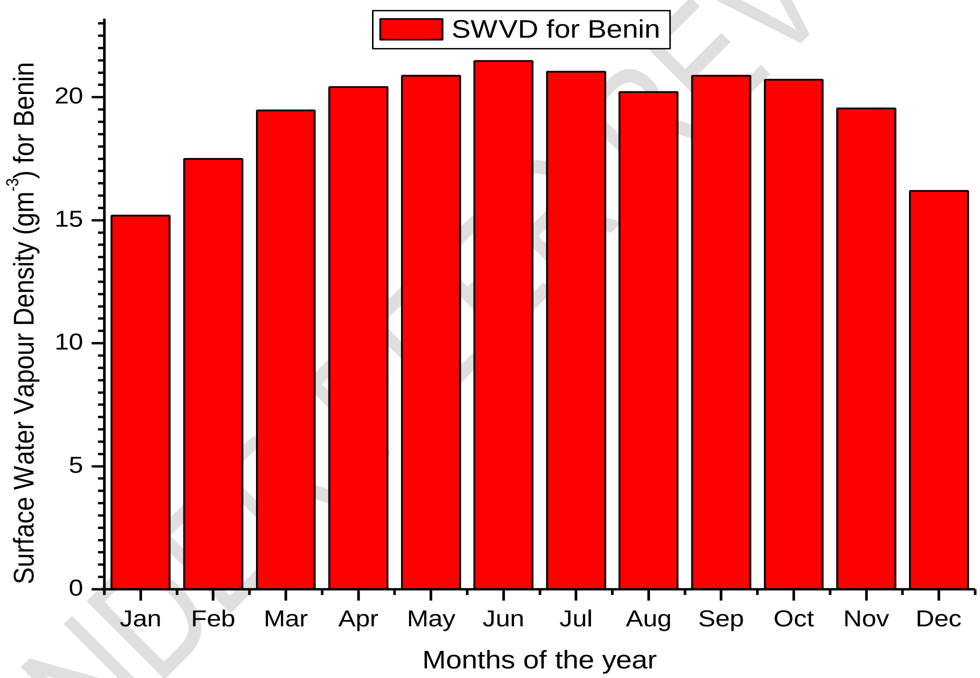

Fig. 1. Monthly variations of SWVD for Benin, Nigeria

Fig. 1 shows the monthly variation of Surface Water Vapour Density (SWVD) during the period under investigation for Benin. The result revealed that the SWVD during the rainy season is greater than in the dry season. It was observed that the maximum and minimum values of SWVD of 21.4753 gm^{-3} and 15.1798 gm^{-3} in the months of June and January respectively. It was observed that the values of SWVD decreases in the month of July and August immediately after its maximum value in the month of June and later increases in the month of September; this observation is in line with the result reported by Akpootu et al. [14] for Owerri located in the Southern zone of Nigeria.

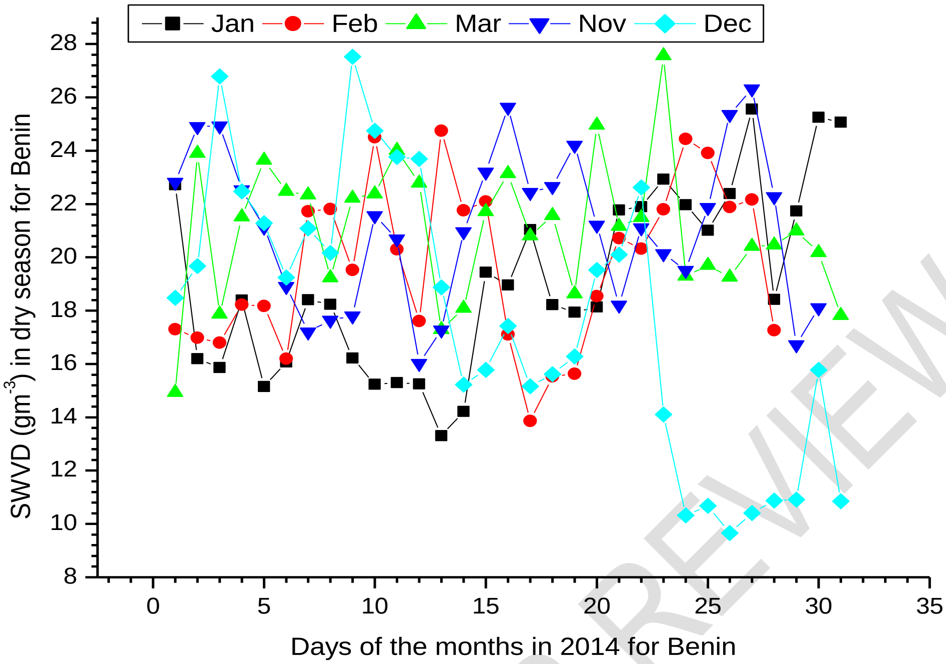

Fig. 2. Diurnal variation of SWVD in the dry season for Benin Nigeria

Fig. 2 shows the diurnal variation of SWVD during the dry season for Benin. The result showed fluctuation in the amount of SWVD with the maximum and minimum values 27.5624 gm^{-3} and 9.6567 gm^{-3} on the 23rd March, 2014 and 26th December, 2014 respectively.

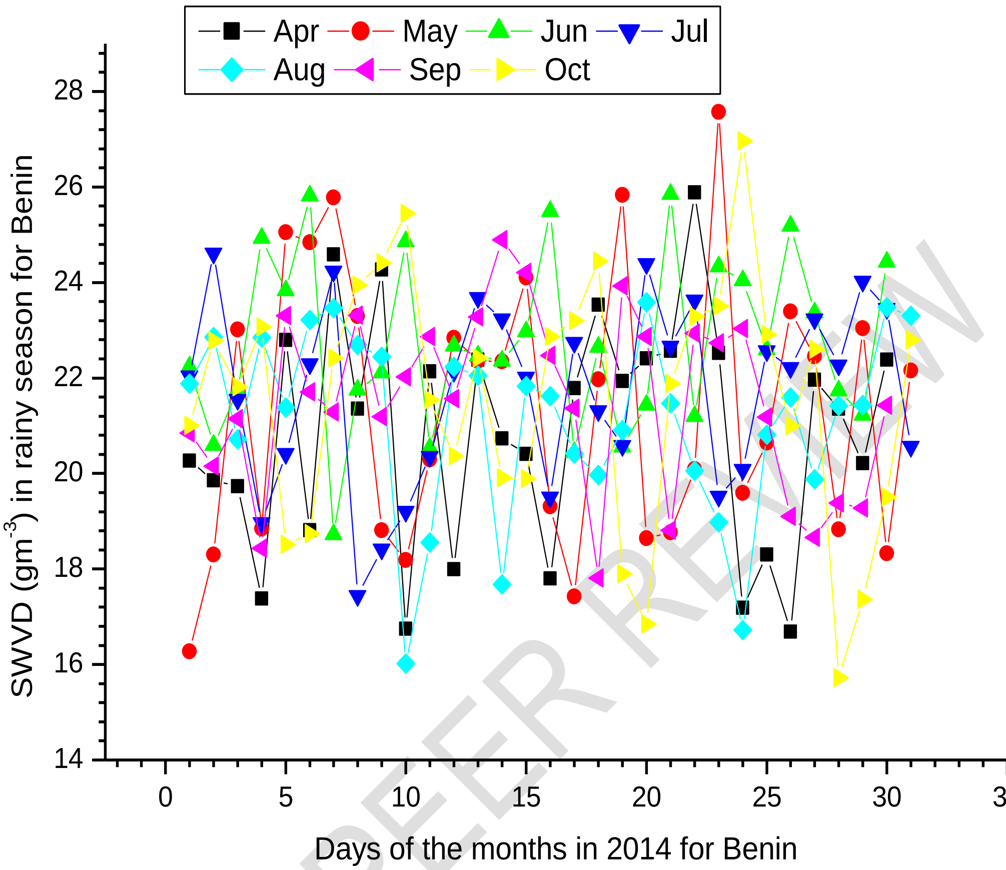

Fig. 3. Diurnal variation of SWVD in the rainy season for Benin Nigeria

Fig. 3 shows the diurnal variation of SWVD during the rainy season for Benin. The result shows that the maximum the minimum values of SWVD occurred with 27.5731 gm^{-3} and 16.0151 gm^{-3} on the 23rd May, 2014 and 10th August, 2014 respectively.

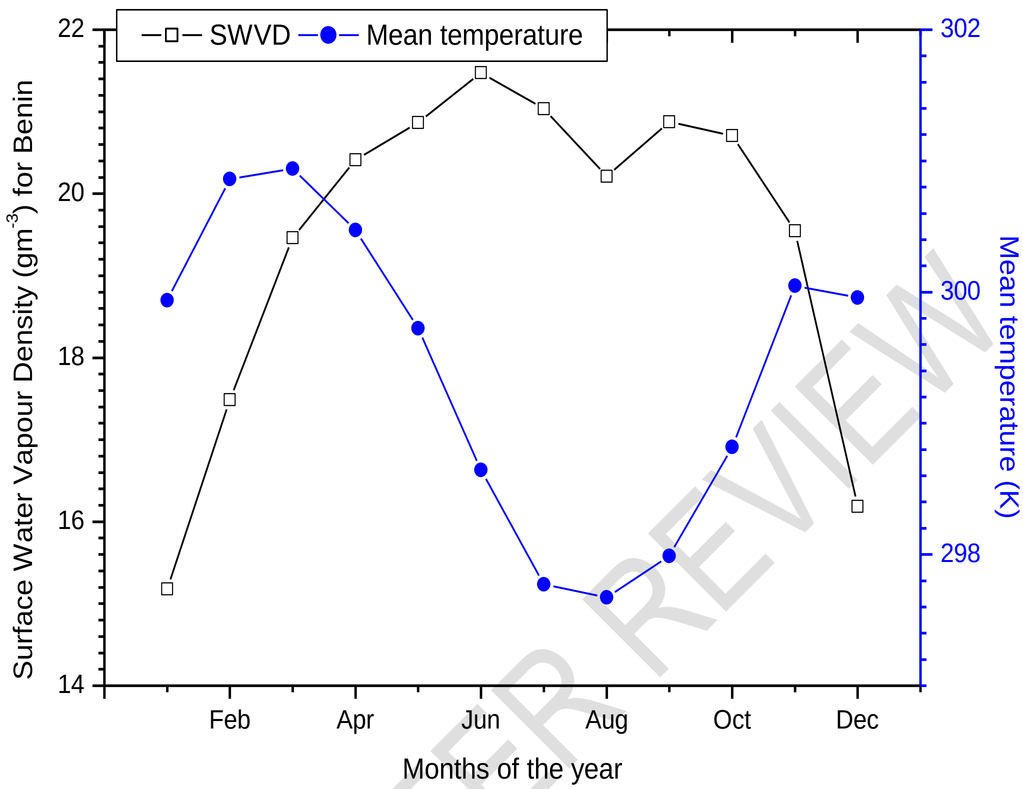

Fig. 4. Variation of SWVD with Mean Temperature for Benin

Fig. 4 shows the monthly variation of SWVD with mean temperature for Benin. The SWVD increases gradually from its minimum value of 15.1798 gm^{-3} in the month of January until it gets to its maximum value of 21.4753 gm^{-3} in the month of June and decreases in August with a dip downward which suddenly increases to September and then drop to December. The mean temperature increases with the SWVD from January and attained its maximum value of 300.9395 K in the month of March which then decreases continuously to its minimum value of 297.6724 K in the month of August and increases then to December. The drop in the SWVD as observed in the month of August may be as a result of August break, which is a period of short dryness; it is obvious that it corresponds to the period when the minimum temperature was observed in the study area. The results showed that high and low values of SWVD were observed during the rainy and dry seasons respectively; the reverse is the case for the mean temperature.

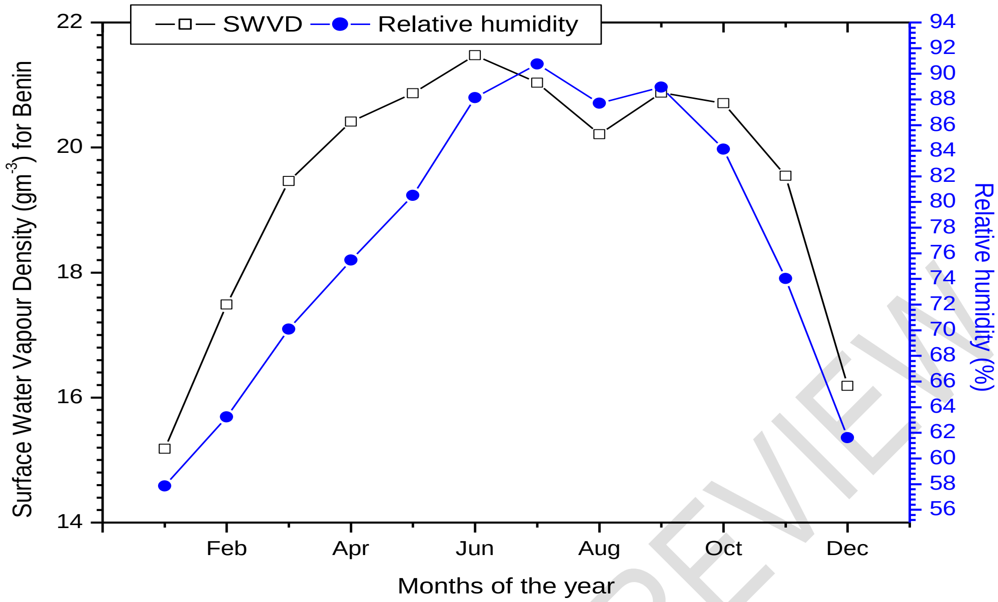

Fig. 5. Variation surface water vapour density with relative humidity for Benin

Fig. 5 shows the variation of SWVD with Relative humidity for Benin. The result shows that the relative humidity increases from its minimum value in January with 57.8482 % to its maximum value of 90.7671 % in July then drops down to August increases to September then drops down to December with 61.6150 % the variation with SWVD is in phase therefore there is a close similarities between their characteristics.

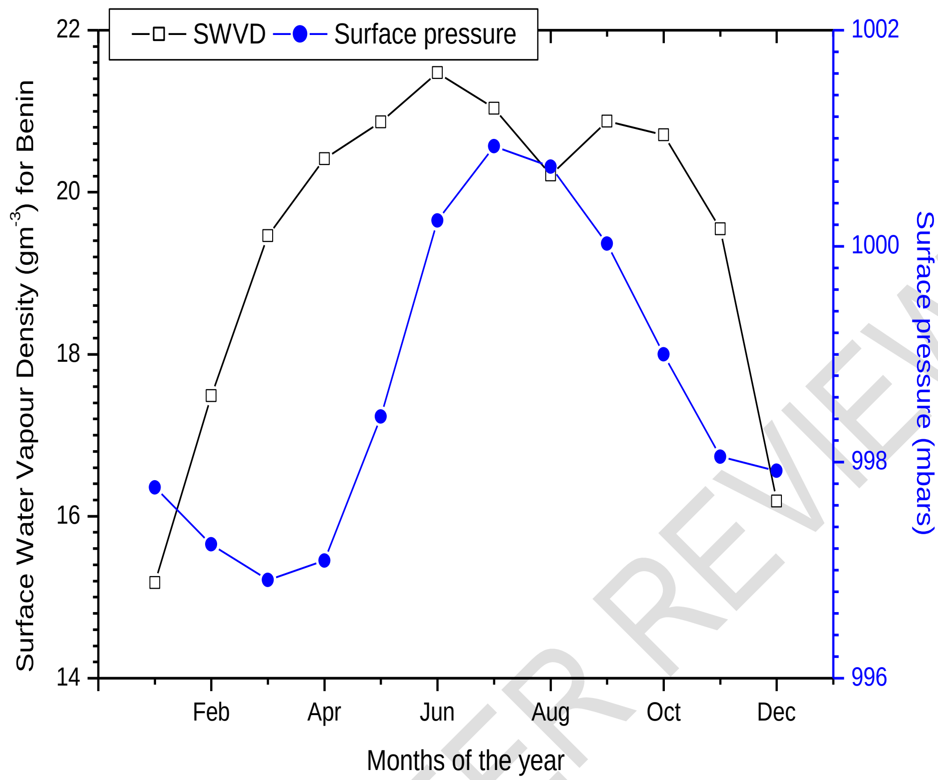

Fig. 6. Variation of SWVD with Surface Pressure for Benin

Fig. 6 is the variation of SWVD with the surface pressure; the result shows that the magnitude of surface pressure decreases from January to March then increases from April to its maximum value of 1000.9250 mbars in the month of July then continue dropping to December. The minimum value of 996.9097 mbars was observed in the month of March'

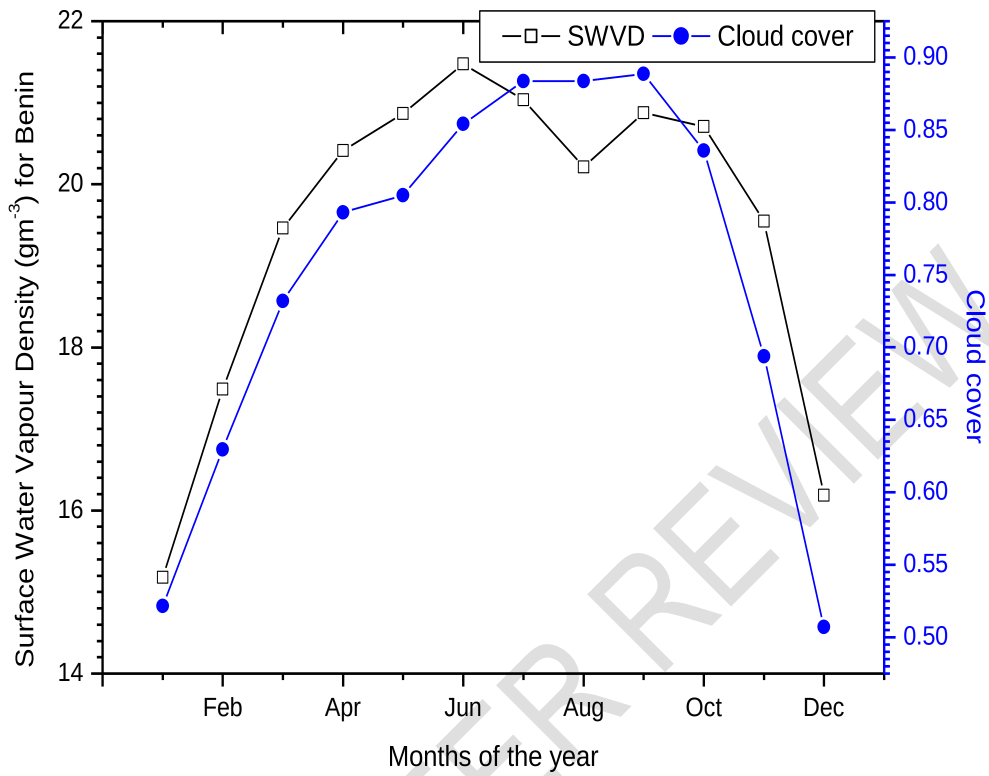

Fig. 7. Variation of SWVD with Cloud Cover for Benin

Fig. 7 shows the monthly variation of SWVD with cloud cover for Benin. The cloud cover increases with the SWVD from January to April with a little drop down in the month of May then increase to July then continue to its maximum value of 0.8886 in the month of September, then decreases from October to its minimum value of 0.5070 in the month of December.

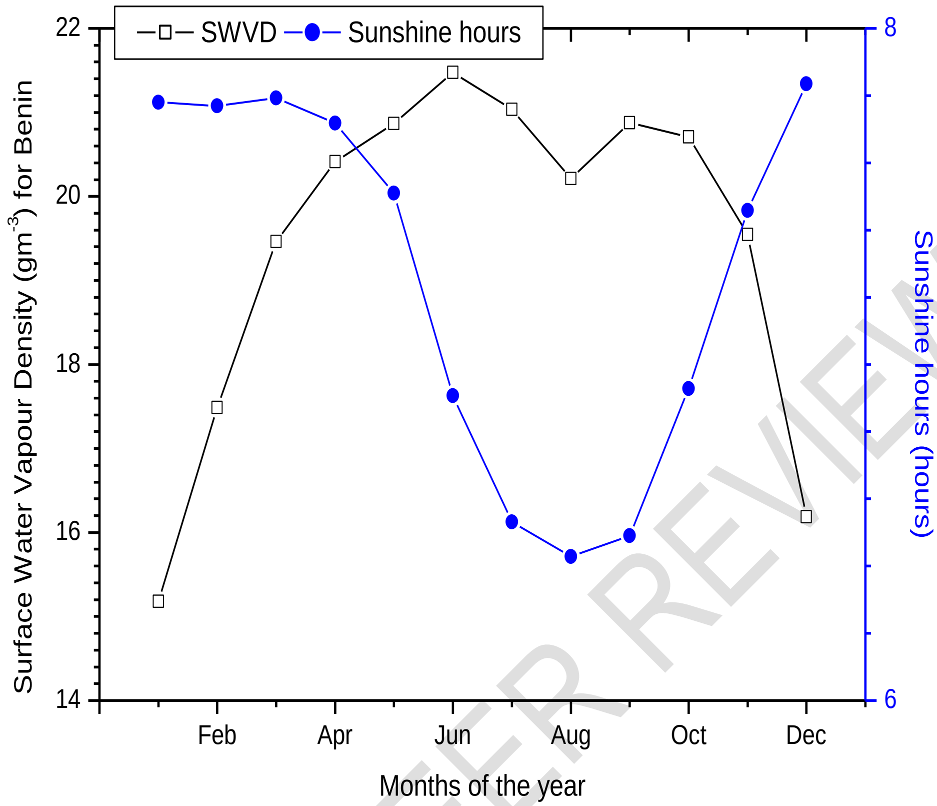

Fig. 8. Variation of SWVD with sunshine hours for Benin

Fig. 8 shows the monthly variation of SWVD with sunshine hours for Benin. The sunshine hours decreases and increases at almost an equal interval from January to May and then decreases to its minimum value in the month of August at 6.4278 hours which corresponds to the August break observed for the SWVD. The sunshine hours increases from its minimum value in August to its maximum value of 7.8356 hours in December. The result revealed that high values of sunshine hours were observed during the dry season and low values during the rainy season which is the reverse case for the SWVD.

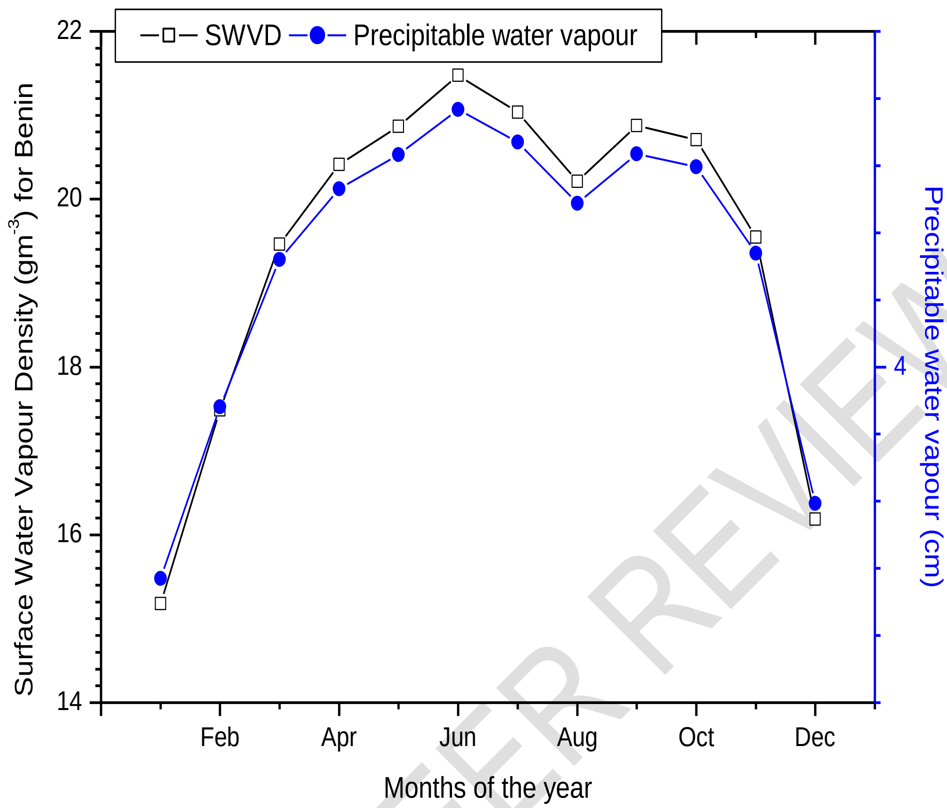

Fig. 9. Variation of SWVD with Precipitable Water Vapour for Benin

Fig. 9 shows the variation of SWVD with Precipitable Water Vapour (PWV) the result shows that the SWVD increase in the same pattern PWV they increase significantly from January until they reach their minimum value of 21.0359 gm^{-3} and 4.6697 cm in the month of July, the sudden drop in value of both the SWVD and the PWV in the month of August which is signified by the popular August break in the region.

3.2. Variation of Mean Temperature, Virtual Temperature, Potential Temperature and Dew Point Temperature for Benin

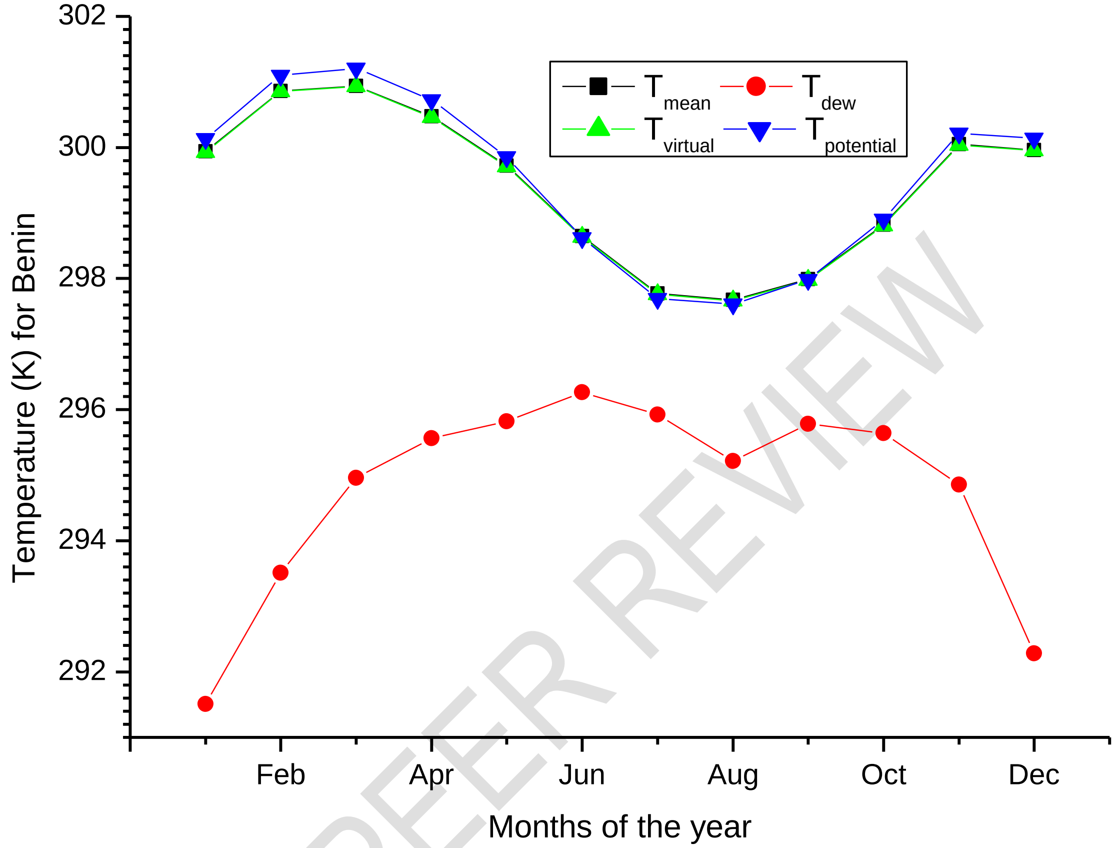

Fig. 10. Variation of SWVD with Temperature (T_m, T_p, T_v and T_d) for Benin

Fig. 10 shows the monthly variation of mean temperature, dew point temperature, virtual temperature and potential temperature (T_d, T_v, T_p and T_m) Benin. The result revealed that the mean temperature, the virtual temperature and potential temperature are almost the same and at the same rate of variation with SWVD they all increase from January to their maximum values of 300.9395 K for mean temperature, 300.9292 K for virtual temperature and 301.2060 K for potential temperature. The temperatures continue to drop down from their maximum values to August where they also reach their minimum values of 297.6724 K for mean temperature, 297.6619 K for virtual temperature and 297.6096 for potential temperature. After the minimum level the temperatures rises to November then drop to December.

3.3. Two Variable Correlation Model for Benin

The two variable correlation model developed for Benin based on equation 15 to 17 are as follows:

$$SWVD = 295 - 0.288P + 16.3CC \quad \text{18a}$$

$$SWVD = 1053 - 1.00P - 4.80SSH \quad \text{18b}$$

$$SWVD = 0.363 - 0.000364P + 4.51PWV \quad \text{18c}$$

Table 1a. Statistical validation tests for Benin

Models	R^2	MBE	RMSE	MPE	NSE	IA
18a	92.5	0.1851	0.5714	-1.0531	96.5993	99.1695
18b	47.4	-0.0064	1.4271	-0.5888	78.7859	93.8017
18c	100	0.2882	0.2882	-1.4977	99.1346	99.7986

From table 1a above equation 18c has the highest R^2, NSE and IA it also has lowest RMSE which shows that it is the best equation for estimating SWVD in the location, but equation 18b is the best in terms of MBE and MPE.

Table 1b. ranking for the Models

Models	R^2	MBE	RMSE	MPE	NSE	IA	Ranking
18a	1	2	2	2	2	2	**11**
18b	3	1	3	1	3	3	14
18c	2	3	1	3	1	1	**11**

The ranking from table 1b shows that both equation 18a and 18c are suitable for estimation of SWVD for Benin and stations with similar weather conditions, as they has equal and lowest ranking.

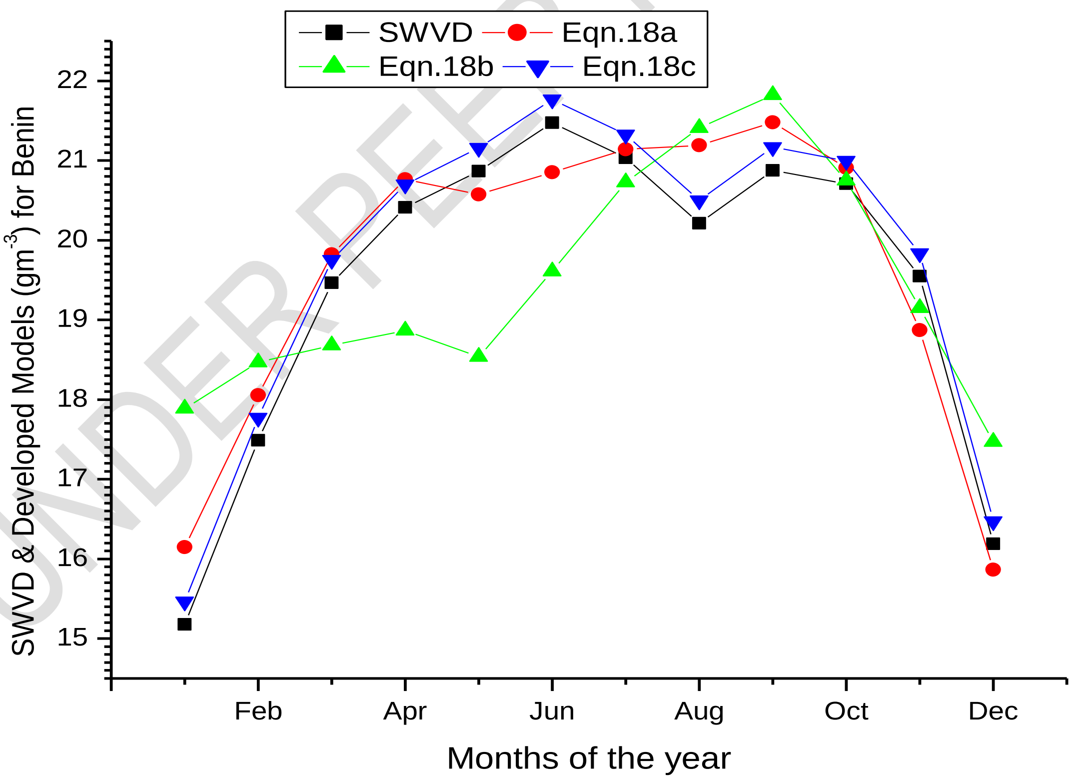

Fig. 11. Monthly variation of SWVD and developed models for Benin

Figure 11 shows the monthly variation of SWVD with and the developed equations, the result shows that equation 18b overestimates SWVD in January and February, then August September and December. It also underestimates it from March to July.

4. CONCLUSION

In this study, the question of estimating SWVD and its variation with other meteorological parameters during the period of thirty eight (38) years (1979 – 2016) and the daily variation of SWVD in each month for the year 2014 as well as the development of two variables correlation models has been addressed using monthly and daily average meteorological data obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) for Benin located in the Coastal region of Nigeria. The results of this study discovered that high values of SWVD are recorded during the rainy season and low values during the dry season for the location. The average value of SWVD was found to be 21.14479 gm^{-3}. The results of the diurnal variations of SWVD during the dry and rainy seasons show fluctuation in its values. The highest value of surface water vapour density was observed on 23rd May, 2014 with 27.57313 gm^{-3} and the lowest on 26th December, 2014 with 9.656676 gm^{-3}. Three simple two variable correlation models were developed and were statistically tested using statistical indices of coefficient of determination (R^2), Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), Nash-Sutcliff Equation (NSE) and Index of Agreement (IA) from which the model that relate Pressure (P) with Precipitable Water Vapour (PWV) was found to be the best (with the accuracy of about 100%) for estimating SWVD for the locations under investigation.

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