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Original Research Article

Estimation of Surface Water Vapour Density and its Variation with other Meteorological Parameters over Akure, Nigeria

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Abstract

In this paper, 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 Akure (Latitude 7.28^{0}N, Longitude 5.30^{0}E, 375m 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 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 densities are greater during the rainy season than in the dry season. It was observed that the maximum average value of surface water vapour density of 20.1019 gm^{-3} occurred in the month of September during the rainy season and minimum value of 15.5110 gm^{-3} in the month of January during the dry season. The highest value of surface water vapour density was observed on the 4th of June, 2014 with 26.3320 gm^{-3} and the lowest on the 31st day of December, 2014 with 6.0276 gm^{-3}. 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 developed multivariate correlation regression model that relates pressure and precipitable water vapour with R^2 = 100%, MBE = -0.0177, RMSE = 0.0179, MPE = 0.1034, NSE = 99.9956% and IA = 99.9989% 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 Akure.

Keywords: Dry season, precipitable water vapour, rainy season, surface water vapour density, correlation models.

1. INTRODUCTION

The connection between the surface and the atmosphere in the hydrological cycle is normally referred to as water vapour. Virtually all the water vapour in the atmosphere originated at the surface of the earth where water evaporates from the ocean and the continents owning to the sun's radiation and is transpired by plants and respired by animals into the atmosphere [1]. Water vapour plays a vital role in climate change, hydrological processes, Earth's energy balance, and weather systems [2]. Water vapour is the centre of the hydrological cycle, which is inter or intra movement of water, in the Earth's atmosphere, oceans, and continents. Exchange of heat and energy between the earth's surface and the atmosphere and within the planet take place as a result of this process. The primary and most effective greenhouse gas in the atmosphere is water vapour, because it absorbs long wave radiation and radiates it back to the surface, which contributing to warming [3].

Understanding the processes which control the natural stability and variability of the climate system is one of the most difficult 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 [4]. Water vapor absorbs most solar radiation and is considered the most important greenhouse gas in the atmosphere. It can also lead to global warming as it is the major cause of the greenhouse effect. It cycles continuously through the process of evaporation and condensation, transporting heat energy around the earth and between the surface and the atmosphere [4].

The hydrological cycle describes the movement of water, in all three phases, within and between the Earth's atmosphere, Oceans and Continents. In vapour phase, water moves quickly through the atmosphere and redistributes energy associated with its evaporation and recondensation. As the temperature of the Earth's surface increases, the atmosphere is able to hold more water vapour. This atmospheric water vapour, acting as a greenhouse gas, absorbs energy that would otherwise cause attenuation of electromagnetic radiation travelling through the atmosphere, which may result to atmospheric or global warming. The proportion by volume of water vapour in the air at the ground level on the average varies from less than 0.001% in the arctic to more than 6% in the tropics. This proportion decreases rapidly with height [5].

Researches on climate models have shown that an increase in atmospheric humidity by 12 – 25% will have the same global average radiative effect than doubling the Carbon (iv) oxide concentration [6]. On the contrary to the homogeneous distribution of long-lived Carbon (iv) oxide, water vapour distribution is highly variable in space and time. Apart from its direct radiative effect, water vapour acts indirectly by interacting with aerosols, clouds and precipitation [1]. This indirect effect of surface cooling offers one of the largest uncertainties in the understanding of the radiative balance of the earth's atmosphere [1].

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 Akure located in South Western, Nigeria. The study also developed two variable correlation models for estimating surface water vapour density for the location under investigation.

2. STUDY AREA

Figure 1 shows the study area which is Akure. Akure the capital of Ondo State, Nigeria and the major dominating town of Akure South Local Government. It lays between Latitude 7.28^{0}N and Longitude 5.30^{0}E in the South western Nigeria. It is bordered by Owo Local Government area in the east, Akure North and Ifedore Local Government areas in the north, Ile-Oluji/Oke-Igbo Local Government Area in the west and Idanre Local Government Area in the south. The climatic condition of Akure follows the pattern of south western Nigeria where the climate is influenced mainly by the rain-bearing south west monsoon winds from the Sahara Desert. Akure experiences a warm humid tropical climate, with two distinct seasons, the rainy and dry seasons. The rainy season lasts for about seven months, April to October. Akure and its environs experience a frequent annual rainfall of over 1500 mm with a short August break. The average temperature is about 295 K during harmattan (December to February) and 305 K in March [7]. The vegetation is tropical rainforest and drained by River Ala and its tributaries [7].

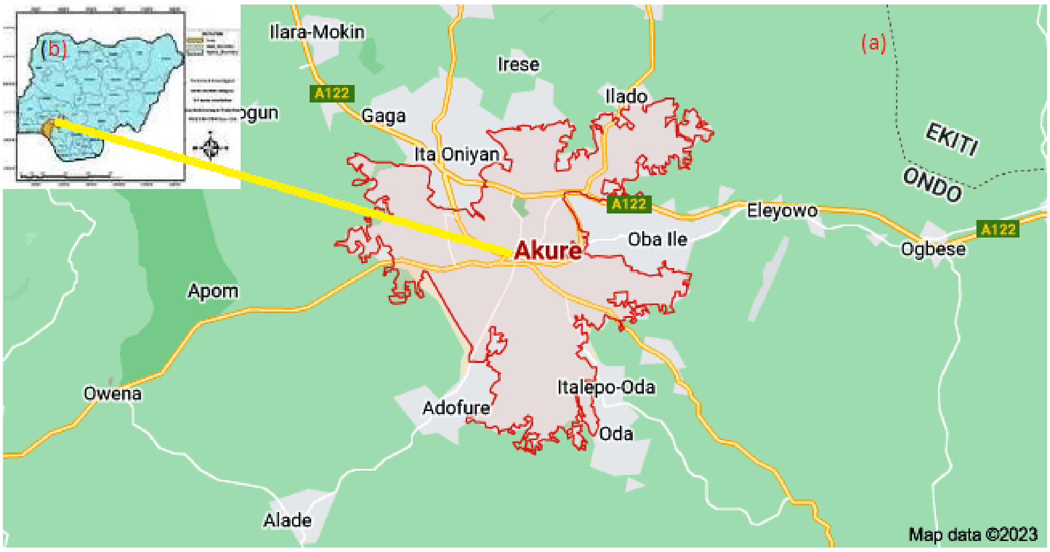

Figure 1: Map of (a) Google map showing the study area (b) Map of Nigeria showing the study area [8]

3. 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 Akure, Ikeja, south western 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 Akpootu *et al.*, [1] Akpootu *et al.*, [4], Adeyemi and Ogolo [4]:

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

The vapour pressure *e* was obtained using the expression given by

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

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:

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

The mean temperature T, is also obtained using [9].

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

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 Akpootu *et al.*, [2] is given by the semi empirical equation

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

Leckner [10] 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 [11]

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

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

The virtual Temperature ($T_{virtual}$) was also obtained using [12].

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

where e is the vapour pressure and ∈ is a constant denoted by 0.622

The potential temperature $T_{potential}$ was obtained using [12]

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

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

3.1 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 El-Sebaii and Trabea [13], 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.*, [14] 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 [15–25]. 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 (%) [26, 27].

3.3 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.

4. RESULTS AND DISCUSSION

4.1 Monthly Variation of Surface Water Vapour Density with Meteorological Parameters for Akure

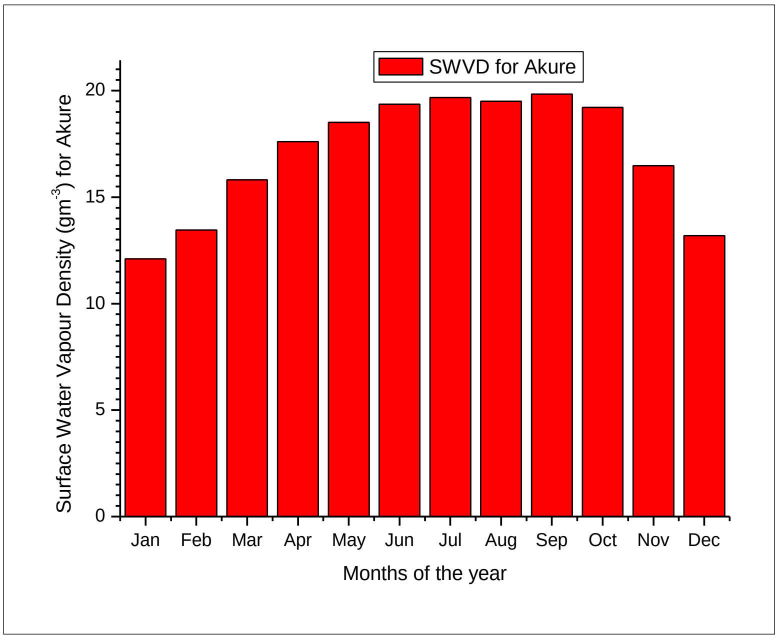

Figure 2: Monthly variation of Surface Water Vapour Density of Akure during the period under investigation

Figure 2 shows the monthly variation of SWVD during the period under investigation for Akure. The result revealed that the SWVD during the rainy season is greater than in the dry season, this is in relation with findings by Adeyemi [5]. It was observed that the maximum and minimum values of SWVD of 19.8425 gm^{-3} and 12.1013 gm^{-3}occurred during the rainy and dry seasons in the months of September and January respectively. It was observed that the values of SWVD decreases in the month of October, November and December immediately after its maximum value in the month of September.

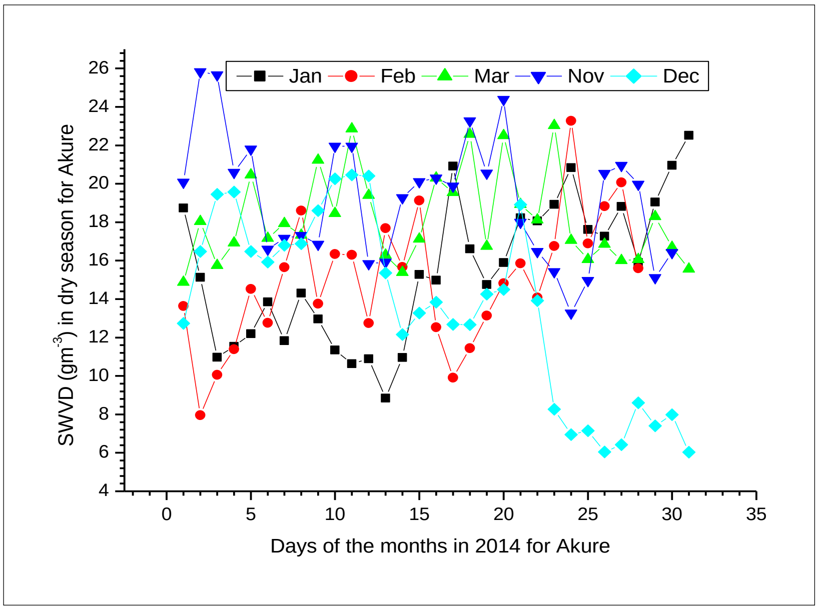

Figure 3: Daily variation of SWVD in dry season for Akure

Figure 3 shows the daily variation of SWVD during the dry season for Akure, the result is covering January, February, March November and December in the year 2014. It showed fluctuation in the amount of SWVD with the maximum and minimum values of SWVD as 25.8272 gm^{-3} on the 2^{nd} day of November, 2014 and 6.0276 gm^{-3} on the 31^{st} day of December, 2014.

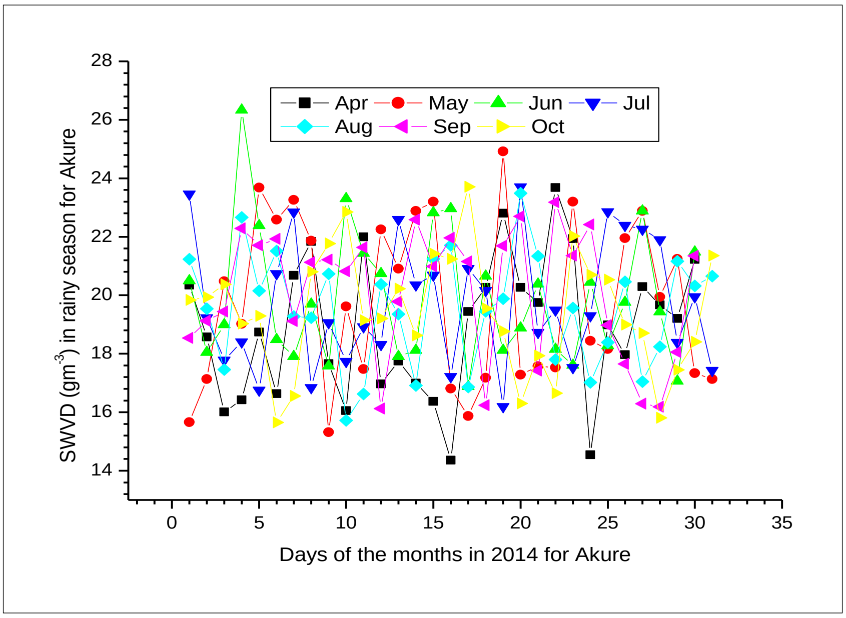

Figure 4: Daily variation of SWVD during the rainy season in Akure

Figure 4 shows the daily variation of SWVD for the months of April, May, June, July, August, September and October for Akure in the year 2014. The maximum and minimum values of SWVD obtained are 26.3320 gm^{-3}, and 14.3589 gm^{-3} on the 4^{th} of June 2014 and on the 16^{th} day of April, 2014 respectively.

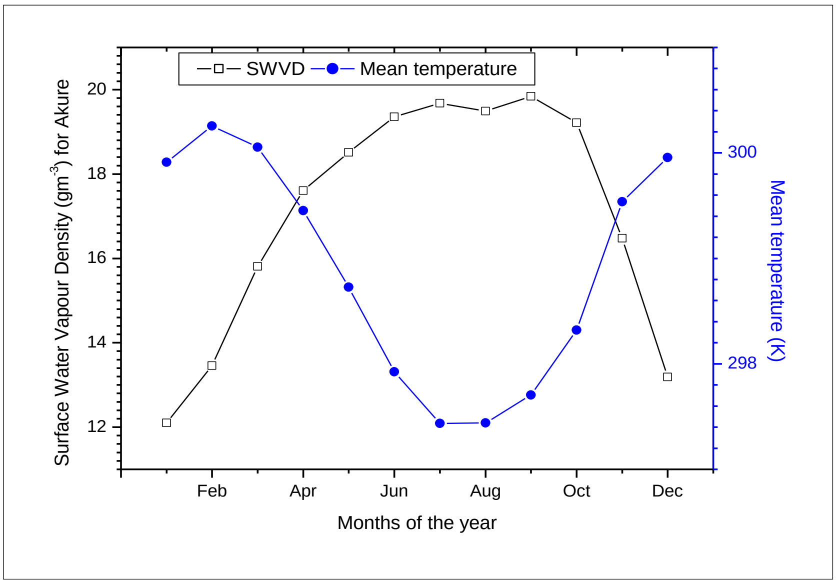

Figure 5: Monthly variation of SWVD with Mean Temperature for Akure

The monthly variation of SWVD with mean temperature is shown in figure 5 for Akure. The SWVD increases gradually from a minimum value of 12.1013 gm^{-3} in the month of January until it gets to July it then decrease slightly in August and increase to its peak value of 19.8425 gm^{-3} in the month of September and decreases suddenly to December. The mean temperature increases against the SWVD from January and attained its maximum value of 300.2566 K in the month of February which then decreases continuously to its minimum value in the month of July with 297.4342 K and increases subsequently to December. The drop in the SWVD as observed in the month of August is as a result of August break, which is a period of short dryness; it corresponds to the period when the temperature was observed to be the minimum though close to the least value of the temperature. 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.

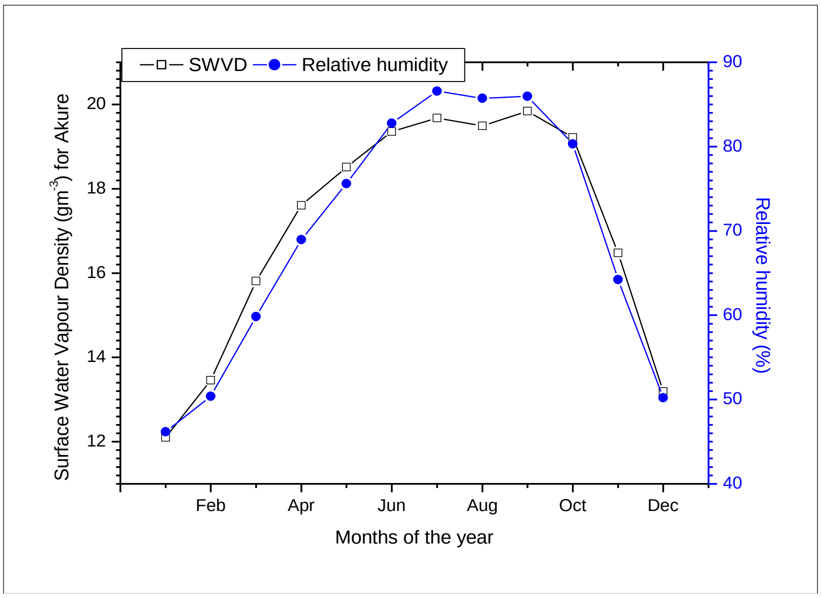

Figure 6: Monthly variation of SWVD with relative humidity for Akure

Figure 6 displays the monthly variation of SWVD with relative humidity for Akure. Relative humidity increases with SWVD from their minimum values of 46.1855 % and 12.1013 gm^{-3} in the month of January and attained their maximum value of 86.5845 % and 19.6795 gm^{-3} in July respectively. A slight dip downward was observed both for the relative humidity and SWVD in the month of August which then increases somewhat to September and then drop to December. The observed drop in the values of the relative humidity and SWVD in the month of August may be due to short period of dryness (August break) which is common in the coastal region and most parts of Nigeria. The high values of SWVD observed during the rainy season are due to high air humidity (close to 90 %) observed in this part of Nigeria, when the city of Akure is under the influence of a large quantity of moisture-laden tropical maritime air resulting from continuous movement of inter-tropical discontinuity (ITD) with the sun. The outcome revealed that high values of SWVD and relative humidity were observed during the rainy season and low values during the dry season.

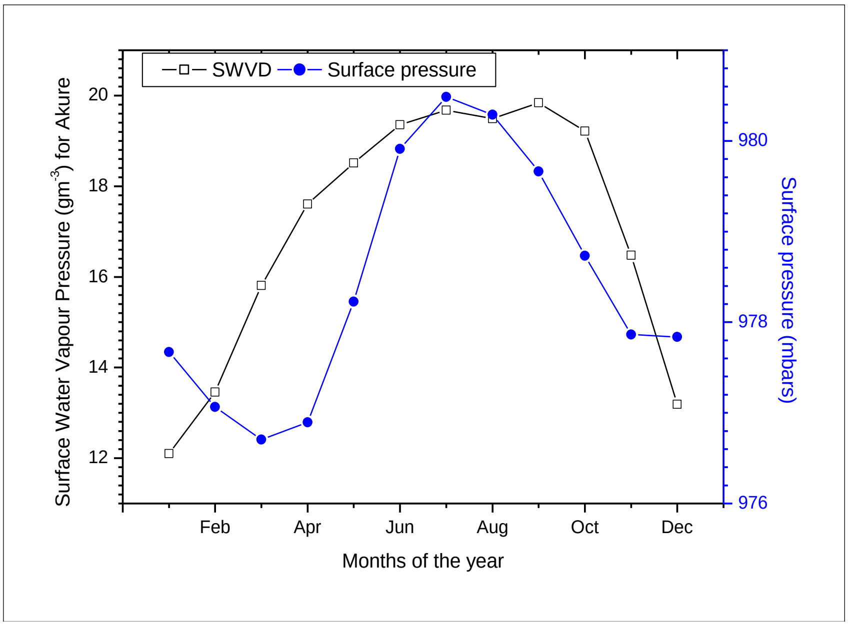

Figure 7: Variation of SWVD with Surface Pressure for Akure

Figure 7 shows the monthly variation of SWVD with surface pressure for Akure. It was observed that as the SWVD increases from its minimum value of 12.1013 gm^{-3} in January and reached its maximum value of 19.8425 gm^{-3} in September; the surface pressure decreases from January with 977.6705 mbars and reached its minimum value in March with 976.7050 mbars which then increases until it gets to its maximum value in the month of July with 980.4855 mbars and then decreases to December. The result shows that high values of SWVD and surface pressure were observed during the rainy season and low values during the dry season.

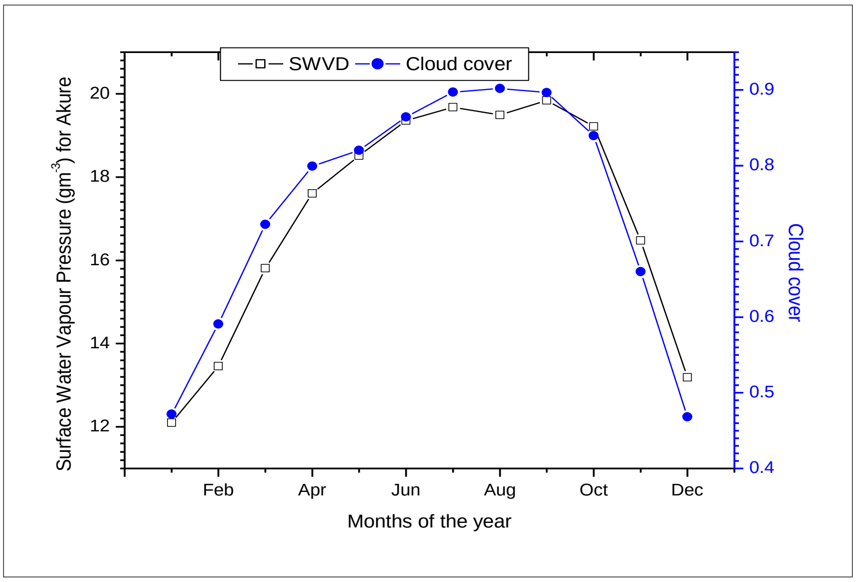

Figure 8: Variation of SWVD with Cloud Cover for Akure

Figure 8 shows the monthly variation of SWVD with cloud cover for Akure. The cloud cover increases with the SWVD from January to July while SWVD decreased to August and increase to September, the cloud cover maintain almost a constant value from July to September. The cloud cover and SWVD drop from September to December in which the minimum value of cloud cover is in December as 0.4682. The result revealed that maximum values of SWVD and cloud cover were observed during the rainy season and minimum values during the dry season.

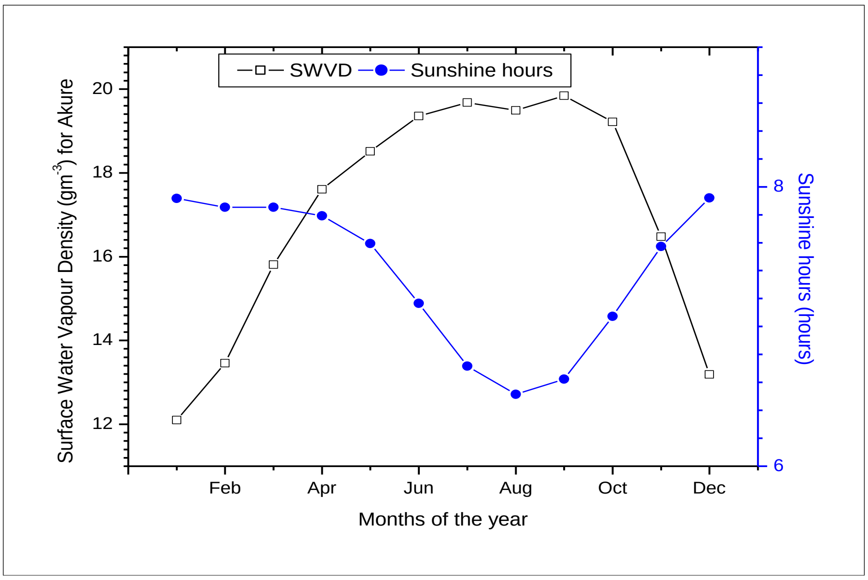

Figure 9: Variation of SWVD with Sunshine hours for Akure

Figure 9 shows the monthly variation of SWVD with sunshine hours for Akure. The sunshine hours decreases slightly from January to February with almost equal value in March and then decreases to its minimum value in the month of August with 6.5139 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

7.9203 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.

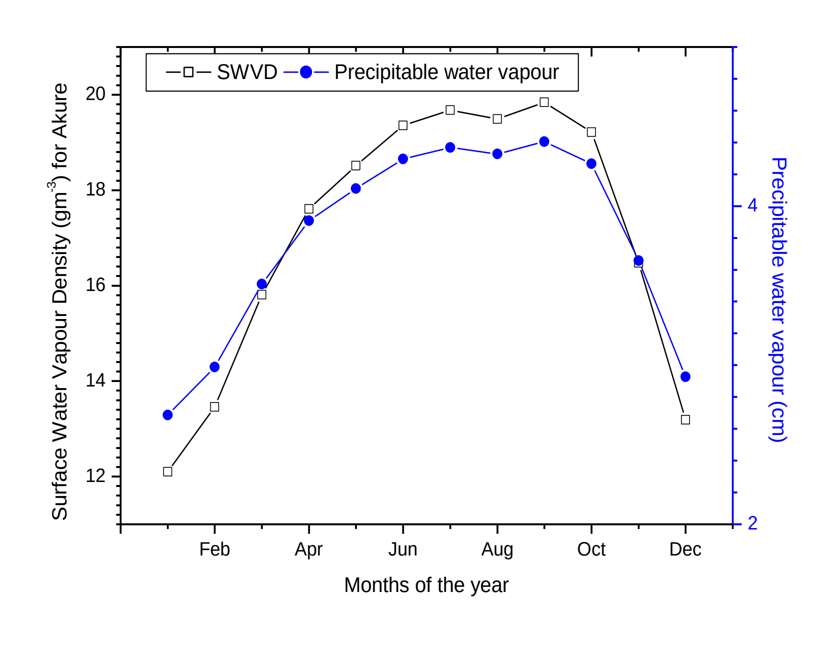

Figure 10: Variation of SWVD with precipitable water vapour for Akure

Figure 10 shows the monthly variation of SWVD with Precipitable Water Vapour (PWV) for Akure. The SWVD increases with the PWV from January to July then drops in August. The maximum and minimum values were recorded in September and January with 19.8425 gm^{-3} and 4.4047 cm, and 12.1013 gm^{-3} and 2.6862 cm respectively, then drops to December. The result shows that high values of SWVD and PWV were observed during the rainy season and low values during the dry season.

4.2 Variation of Mean Temperature, Dew Point Temperature Virtual Temperature and Potential Temperature for Akure

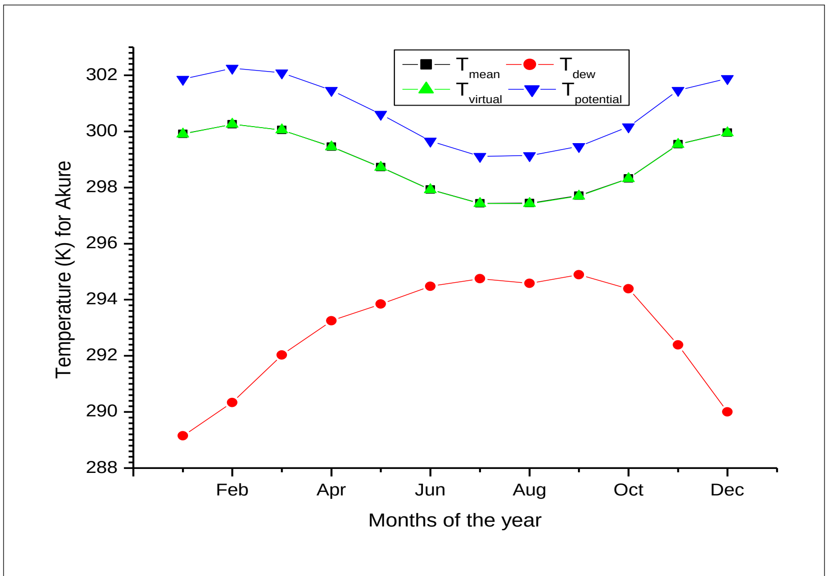

Figure 11: Monthly Variation of T_{mean}, T_{dew}, $T_{virtual}$ and $T_{pottential}$ for Akure

Figure 11 shows the monthly variation of mean temperature (T_{mean}), dew point temperature (T_{dew}), virtual temperature ($T_{virtual}$) and potential temperature ($T_{pottential}$) for the Akure. The result revealed that the maximum value of potential temperature was found to be 302.2556 K in the month of February and was observed to be greater than the mean temperature, virtual temperature and dew point temperature, while the dew point temperature has the lowest value observed in January with 289.1489 K. The mean temperature and virtual temperature follows similar pattern of variation as they are completely in phase with one another. The dew point temperature increases from its minimum value of 289.1489K in the month of January to July then decreases to August and attained its maximum value of 294.8940K in the month of September and decreases to December. The result of this study showed high values of virtual temperature, potential temperature and mean temperature during the dry season and low values during the rainy season while for the dew point temperature shows that high values were recorded during the rainy season and low values during the dry seasons; this indicates that the dew point temperature is an opposite reflection of the virtual temperature, potential temperature and mean temperature. The result indicated that the dew point temperature is always less than the mean/air temperature which implies that mean temperature cannot be lower than the dew point temperature; this helps meteorologists predict temperature lows in a weather forecast. The moderate values of the dew point temperature signifies the stability of air for the study area and less tendency of development of thunderstorms as very high dew point temperature can bring about severe weather condition.

4.3 Two Variable Correlation Model for Akure

The two variable correlation models developed for Akure based on equations 15 to 17 are as follows

$$SWVD = -246 + 0.257P + 15.7C \quad 18a$$
$$SWVD = 579 - 0.533P - 5.53SSH \quad 18b$$
$$SWVD = 0.224 - 0.000228P + 4.50PWV \quad 18c$$

Table 1a: Statistical validation test for Akure

Models	R^2	MBE	RMSE	MPE	NSE	IA
18a	96.4	0.0862	0.5176	-0.6392	96.3163	99.0550
18b	68.9	-0.4003	1.5570	1.4172	66.6726	89.6876
18c	100.0	-0.0177	0.0179	0.1034	99.9956	99.9989

Table 1a shows the various tests carried out on the models to validate their effectiveness. Model equation 18c has the highest R^2, NSE and IA, and lower values of MBE, RMSE and MPE. Therefore the equation is termed the best equation for estimating Surface Water Vapour Density for Akure and other locations with similar meteorological parameters.

Table 1b: Ranking of developed Models for Akure

Models	R^2	MBE	RMSE	MPE	NSE	IA	Ranking
18a	2	2	2	2	2	2	12
18b	3	3	3	3	3	3	18
18c	1	1	1	1	1	1	**6**

The ranking as shown in table 1b shows equation 18c is the best equation to estimate SWVD in Akure as it has the lowest ranking value.

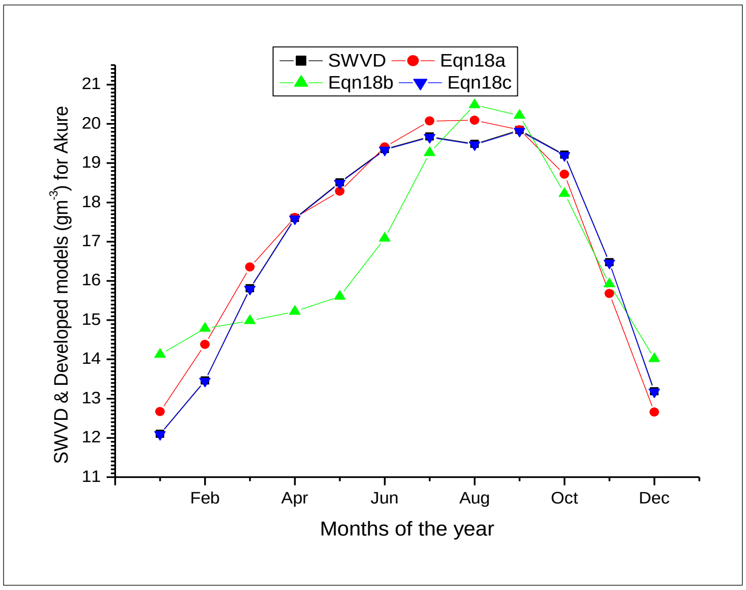

Figure 12: Monthly variation of SWVD with the developed models for Akure

Figure 12 shows the variation of the monthly SWVD with the developed models for Akure the result shows that the SWVD and the variation pattern of equation 18c are completely in phase, equation 18b overestimate the SWVD from January to February and then in August, September and December. The model equation 18b also underestimates it from March to July then in October.

5. CONCLUSION

In this present study, the issue of estimating SWVD and its variation with other meteorological parameters during the period of thirty-eight (38) years (1979 – 2016) and 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 Akure located in the Coastal region of Nigeria. The results of this study revealed 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 17.0615 gm^{-3}. The results of the diurnal variations of SWVD during the dry and rainy seasons show fluctuation in its values. The highest and lowest values of SWVD was found on the 2nd November, 2014, and 31st December, 2014 as 25.8272 gm^{-3} and 6.0676 gm^{-3} respectively. 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 relates the 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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