



## Research Article

# Estimation of Surface Water Vapour Density and its Fluctuations with Climatic Variables at Owerri, Nigeria

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## ARTICLE INFO:

## ABSTRACT

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Water vapour is the common term used to describe the hydrological cycle's connection between the surface and the atmosphere. Almost all of the water vapour in the atmosphere is derived from the earth's surface, where sunlight causes water to evaporate from the ocean and continents. Plants and animals then transpire and respire this water vapour into the sky. This study looked at the relationships between monthly variations in Surface Water Vapour Density (SWVD) and various meteorological parameters for Owerri. The data were collected over a thirty-eight-year period (1979–2016). The study looked at the daily fluctuation in SWVD for the two different seasons in 2014, taking into account two typical months in each. The findings demonstrated variations in the SWVD on a daily basis during the duration of the study. The highest recorded SWVD value throughout the investigation period was  $22.7604 \text{ gm}^{-3}$  on May 28, 2014, while the lowest recorded value was  $9.6567 \text{ gm}^{-3}$  on December 26, 2014. Three simple two variable correlation models were developed to estimate SWVD, and were statistically tested and compared using the 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) to deduce which of the three SWVD – based models is most suitable to estimate SWVD. After comparing the three simple two-variable correlation models, it was determined that the model that relates pressure and precipitable water vapour was the most appropriate for estimating SWVD. The results in this study will help hydro-meteorologist to know the amount of SWVD in the atmosphere for Owerri.

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## INTRODUCTION

Studies on hydrological processes, climate change, weather systems, and Earth's energy balance rely heavily on water vapor. "Water vapor is the most prevalent greenhouse gas in the atmosphere and is responsible for about 60% of the natural greenhouse effect phenomenon." (Held and Soden, 2000; Wang *et al.*, 2003; Trenberth *et al.*, 2005; Wagner *et al.*, 2006; Akpootu *et al.*, 2019a; Akpootu *et al.*, 2023a).

Water vapour, which makes up a very small percentage of the atmosphere, is crucial to its dynamics. It also has a great deal of responsibility for the biosphere's existence (Oladiran *et al.*, 2017). Water vapor is the common term used to describe the link in the hydrological cycle between the atmosphere and the surface. Almost all of the water vapor in the atmosphere is released into the atmosphere by plants and animals through transpiration, and it originates at the earth's surface where water vapor from the sun's radiation evaporates from the ocean and continents Akpootu *et al.*, (2023a).

When water returns to the earth's surface as rain or snow, the cycle is considered complete. Through the three-dimensional circulation of the atmosphere, the atmosphere and water vapour can be moved both horizontally and vertically. They can also condense to produce liquid water or ice crystals in clouds. Trends in temperature and the cycle are closely related (Akpootu *et al.*, 2023a).

As the Earth's surface temperature rises, the atmosphere tends to hold more water vapor, which acts as a greenhouse gas by absorbing energy that would otherwise cause attenuation of electromagnetic radiation travelling through the atmosphere; the consequences of these could be atmospheric or global warming as reported by Akpootu *et al.* (2019a); Akpootu *et al.* (2023c). The energy balance of Earth, hydrological processes, meteorological systems, and climate change are all significantly impacted by water vapour. As a result, it may be said that water vapor accounts for roughly two thirds of the

atmosphere's natural greenhouse effect (Akpootu *et al.*, 2023c).

Until radiosonde data were available, scientists were unable to analyze the distribution of water vapour in space and time, even though it is essential for several applications. According to Gerding *et al.*, (2004); Kuwahara *et al.*, (2008), radiosondes, ground-based microwave radiometers, LIDAR systems, GPS satellites, and LASER systems are the typical approaches for monitoring PWV as reported Maghrabi and Danjani (2013). Every technique has its limitations, though. LIDAR measurements are expensive. Utilizing space-based devices is hampered by low spatial resolution, and radiosondes only provide restricted coverage (i.e., they can only watch a select few sites). Using sun photometers or similar devices to measure the atmospheric transmittance is an additional method (Holben *et al.* 2001; Elies *et al.* 2010; and Torres *et al.*, 2010). Methods and algorithms to investigate how to calculate the PWV from temperature readings using infrared (IR) radiometers (Clay *et al.*, 1998; Brooks *et al.*, 2007; Maghrabi *et al.* 2009; Maghrabi and Clay, 2010).

The world's population is currently close to 7 billion, and projections indicate that by midcentury, it will approach 10 billion. As a result, the only way to meet future energy demands is to introduce an increasing percentage of alternative energy sources (Foster *et al.*, 2009). As a result, alternatives for estimating Surface Water Vapour Density (SWVD), such as modeling, are necessary to support hydrometeorologists in better utilizing SWVD. In the work of Akpootu *et al.* (2019b), they developed several models for estimating SWVD for Owerri, their results showed that the model that relates mean temperature and relative humidity was found more suitable for SWVD estimation.

This study looked at the SWVD's daily and monthly variations as well as the monthly

variations with surface pressure, mean temperature, relative humidity, cloud cover, and sunshine hours for Owerri, Nigeria. In order to estimate the SWVD of the location under investigation, the study also created two variable correlation models.

### METHODOLOGY

The daily and monthly average minimum temperature, maximum temperature, relative humidity, surface pressure, cloud cover, and sunshine hours for Owerri, Imo state, located in South Eastern Nigeria, at a height of two metres

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

The expression used to determine vapour pressure is given by Adeyemi and Ogolo (2014), Akpootu *et al.*, (2019a), Akpootu *et al.* (2019b), Akpootu

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

where RH and  $e_s$  are the relative humidity and saturated vapour pressure respectively. Akpootu, *et al.*, (2022a), Akpootu, *et al.*, (2022b), Akpootu,

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

The mean temperature, T was obtained using Akpootu, *et al.* (2019e)

$$T = \frac{T_{max} + T_{min}}{2}$$

where the highest and minimum temperatures are denoted by  $T_{max}$  and  $T_{min}$ , respectively. T is expressed in Kelvin (K), RH in percentage (%), e

Akpootu *et al.*, (2019f) reported that the ambient temperature T and Partial Pressure  $P_s$  are related by a correlation model which is expressed by the semi empirical equation;

$$P_s = \exp \left( 26.23 - \frac{5416}{T} \right)$$

Leckner (1978) presented the following formula, which expresses precipitable water in terms of relative humidity:

$$W = \frac{(0.493 \phi_r P_s)}{T}$$

where  $\phi_r$  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.

Lawrence (2005) was used to determine the dew point temperature  $T_{dew}$ .

$$T_{dew} = T - \frac{100 - RH}{5}$$

where T and RH are the mean temperature (Kelvin) and relative humidity (%).

According to Wallace and Hobbs, (2006), the virtual temperature ( $T_{virtual}$ ) is given by

$$T_{virtual} = \frac{T}{1 - \frac{e}{P}(e - \epsilon)}$$

where  $e$  is the vapour pressure and  $\epsilon$  is a constant given as 0.622

were provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and were used in this study over a sixteen-year period (2000–2015).

Equation (1) describes the relationship between the surface water vapour density (SWVD), vapour pressure ( $e$ ), and mean temperature (T). According to Akpootu *et al.*, (2019a), Akpootu and Gana, (2014), Adeyemi and Ogolo (2014), Gerding *et al.*, (2002), Ajayi (1989), Akpootu and Iliyasu (2015a), Akpootu and Iliyasu (2015b) as:

$$(1)$$

and Abdullahi (2022), Akpootu and Sanusi, (2015), Akpootu, *et al.* (2019f), as:

$$(2)$$

*et al.*, (2019c) stated that the saturated vapour pressure was evaluated using the Clausius Clapeyron equation defined as:

$$(3)$$

and  $e_s$  in millibars (mb), and the SWVD in ( $\text{gm}^3$ ).

$$(4)$$

$$(5)$$

$$(6)$$

$$(7)$$

$$(8)$$

The potential temperature  $T_{potential}$  was estimated using Wallace and Hobbs (2006).

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

expression (9) is the Poisson’s equation.  $p_o$  represents the standard pressure usually taken as 1000hPa and  $\frac{R}{c_p} = 0.286$

The regression models used in this study to estimate SWVD are of the following types:

$$SWVD = a + bP + cCC \tag{10}$$

$$SWVD = d + eP + fSSH \tag{11}$$

$$SWVD = g + hP + iPWV \tag{12}$$

where the empirical SWVD constants are a, b, c, d, e, f, g, h and i.

The estimated values were statistically assessed for validity by computing the Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), Nash-Sutcliffe equation (2005).

$$MBE = -\frac{\sum_{i=1}^n (SWVD_{i,cal} - SWVD_{i,mea})}{n} \tag{13}$$

$$RMSE = \left[ -\frac{\sum_{i=1}^n (SWVD_{i,cal} - SWVD_{i,mea})^2}{n} \right]^{\frac{1}{2}} \tag{14}$$

$$MPE = -\frac{\sum_{i=1}^n \left( \frac{SWVD_{i,mea} - SWVD_{i,cal}}{SWVD_{i,mea}} \right) * 100}{n} \tag{15}$$

Together with the total number of observations, the  $i^{th}$  computed and observed values of the daily surface water vapour density and the mean surface water vapour density, are obtained from equations (13) through (15).

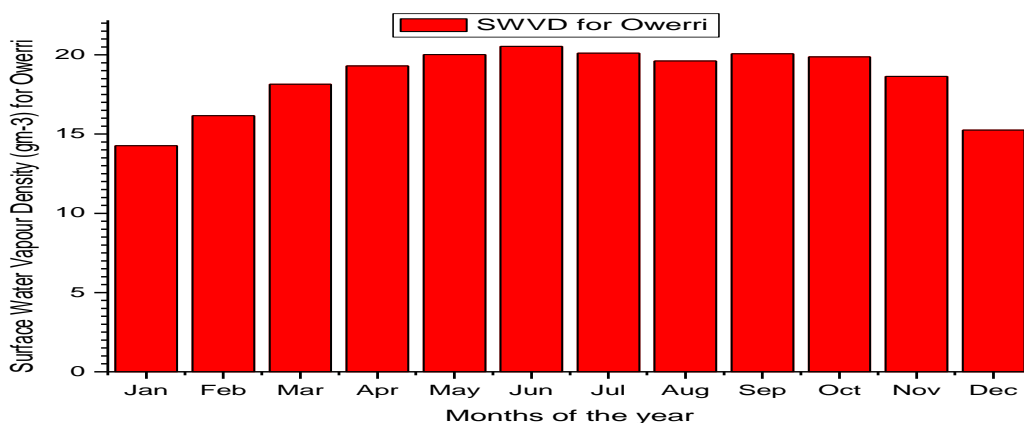
According to Chen et al. (2004), a low RMSE is preferred and a zero value for MBE is optimal. The model performs better when the MBE and RMSE values are less. Positive MBE and MPE

(NSE), and Index of Agreement (IA) in a comparable manner. The coefficient of determination ( $R^2$ ) was determined for each model. The following are the MBE, RMSE, and MPE expressions as reported by El-Sebaei and Trabea

values indicate an average level of overestimation in the computed values, whereas negative values indicate underestimating. It is preferable for MPE to be low. The permissible range for the percentage inaccuracy is  $-10\%$  to  $+10\%$ . Merges et al., (2006). It is preferred to have high  $R^2$ , NSE, and IA values.  $R^2$ , MPE, NSE, IA, and MBE are expressed in percentage (%), whereas RMSE and MBE are expressed in  $gm^{-3}$ .

## RESULTS AND DISCUSSION

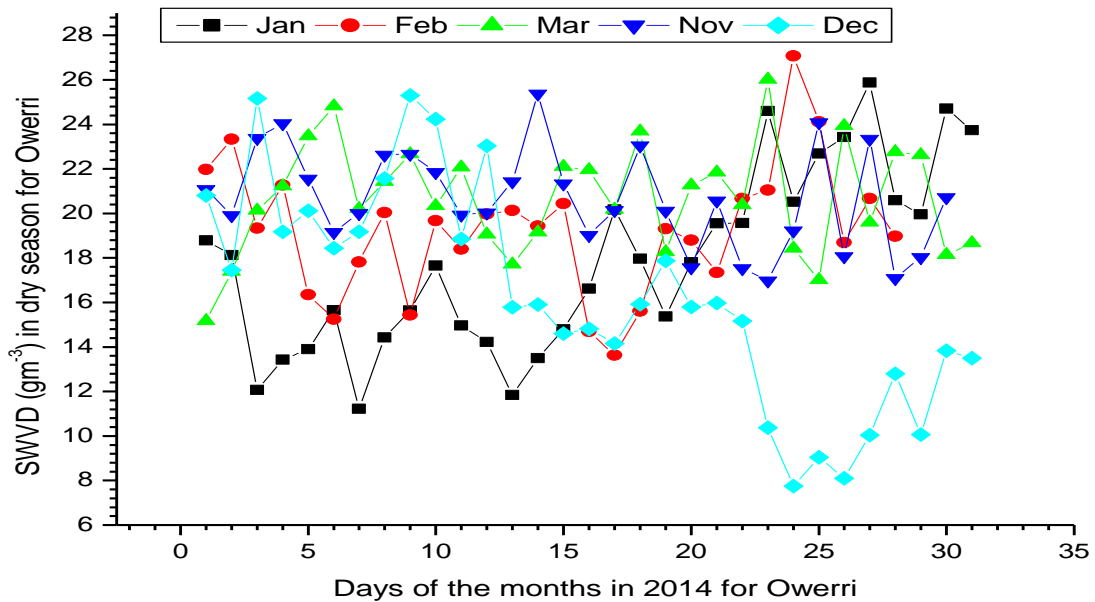
### SWVD and its Variation with Meteorological Parameters for Owerri



**Figure 1:** Monthly Variation of SWVD for Owerri Nigeria.

Figure 1 shows the monthly change in Owerri's Surface Water Vapour Density (SWVD) over the course of the study. The result shows that during the wet season, the SWVD is higher than it is during the dry season. This is closely related to the findings of Akpootu *et al.* (2019a) for Owerri. It was observed that in the wet and dry seasons, respectively, during the months of June and January, the maximum average value of SWVD

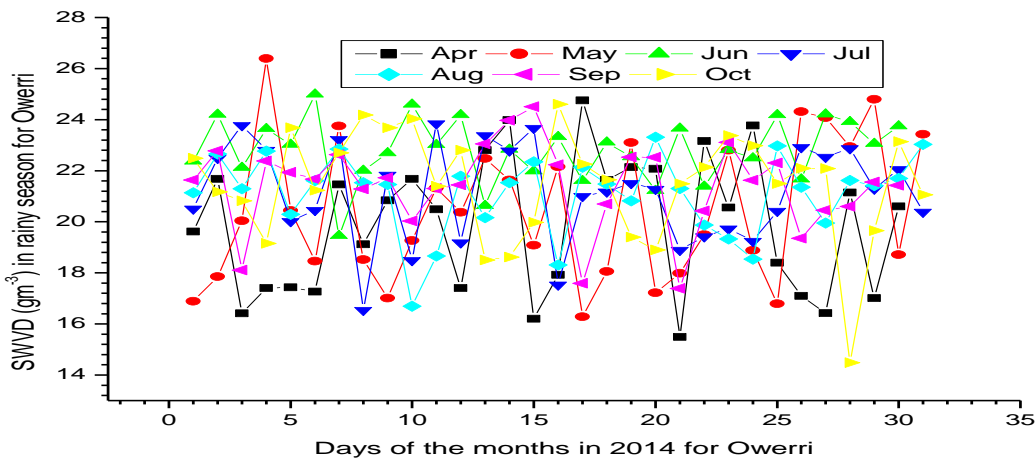
was recorded at  $20.5387 \text{ gm}^{-3}$ , while the minimum value was recorded at  $14.2589 \text{ gm}^{-3}$ . The levels of SWVD were seen to fall in July and August just after reaching their maximum value in June, and then increase in September; this finding is consistent with the results that were published by Adeyemi and Ogolo (2014) for Ikeja and Ibadan located in the Southern zone of Nigeria.



**Figure 2:** Diurnal Variation of SWVD during the dry Season for Owerri Nigeria

Figure 2 depicts the daily fluctuation of SWVD in Owerri during the dry season. According to the results, the value of SWVD reached its highest on

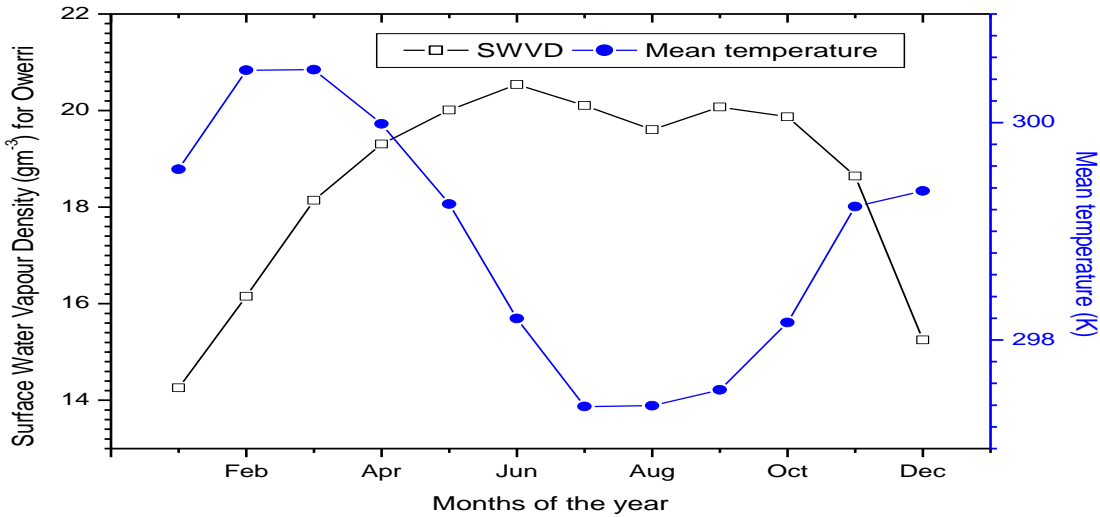
February 24, 2014, at  $24.4450 \text{ gm}^{-3}$ , and its minimum on December 26, 2014, at  $9.6567 \text{ gm}^{-3}$ .



**Figure 3:** Diurnal Variation of SWVD during the rainy Season for Owerri Nigeria

Figure 3 shows the diurnal variation of SWVD during the rainy season for Owerri, Nigeria, the result shows that the maximum value of  $22.7604 \text{ gm}^{-3}$  on the 28<sup>th</sup> day

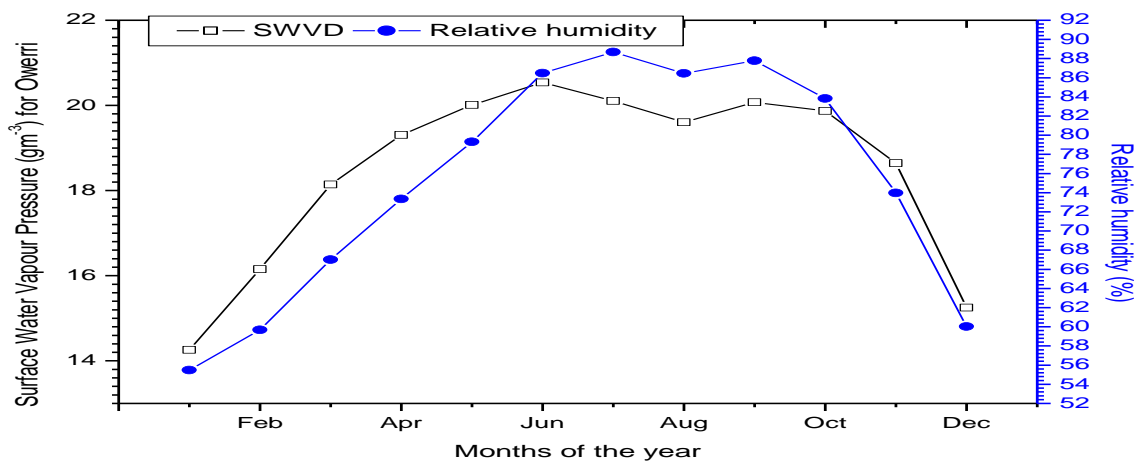
of May, 2014 and minimum value of  $15.4918 \text{ gm}^{-3}$  was observed on the 21<sup>st</sup> day of April 2014.



**Figure 4:** Variation of SWVD with Mean Temperature for Owerri

The monthly variation of SWVD with Owerri's mean temperature is displayed in Figure 4. From a minimum value of  $14.2589 \text{ gm}^{-3}$  in January to a peak value of  $20.5387 \text{ gm}^{-3}$  in June, the SWVD increases gradually. Subsequently, it decreases to August and then has a drop that sharply rises to September and then falls to December. Beginning in January, the mean temperature increases with

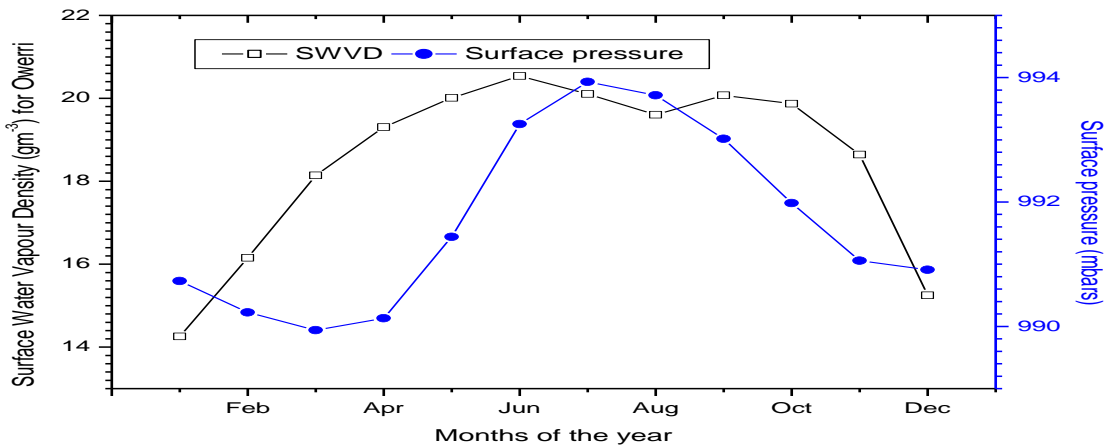
the SWVD and reaches its highest value of  $300.4882 \text{ K}$  in March. After that, it continually falls to its lowest value of  $297.3882 \text{ K}$  in July and rises again in December. The observed decrease in the SWVD for the month of August could potentially be attributed to the August break, this represents a brief dry spell.



**Figure 5:** Variation of SWVD with Relative Humidity for Owerri

The Surface Water Vapour Density (SWVD) change with Relative Humidity (RH) for Owerri, Nigeria, as shown in Figure 5. The outcome demonstrates that whereas relative humidity reaches its peak value in July at 88.685 percent, SWVD increases with relative humidity, with minimum values in January at 55.4871 percent and 14.2589 gm<sup>-3</sup>, and maximum values in June at 20.5387 gm<sup>-3</sup>

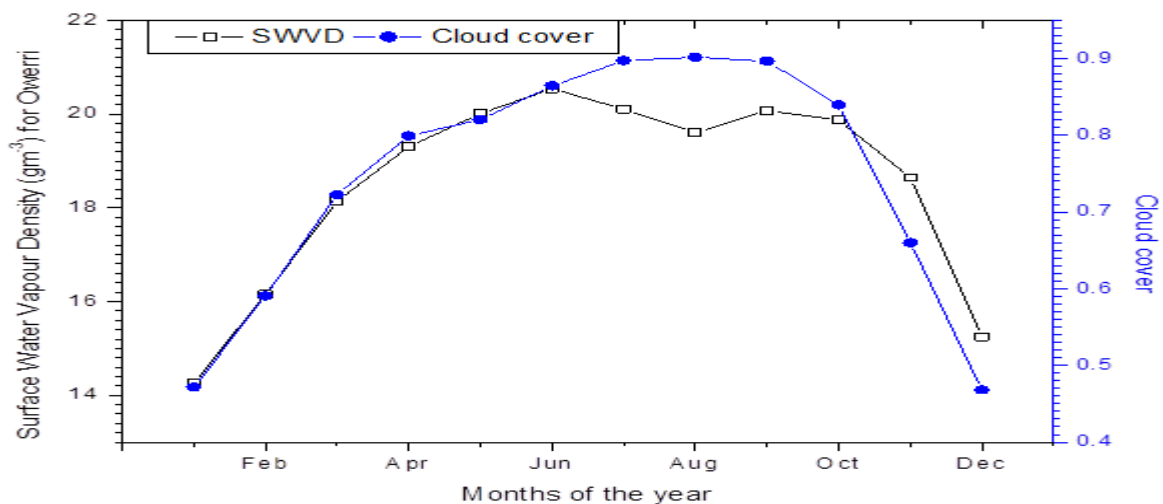
<sup>3</sup>. In August, there was a modest decrease in both the RH and SWVD. This was followed by a slight increase in September and a subsequent decline in December. The observed drop in the values of SWVD and relative humidity in August may be related to the August break, a brief period of aridity that is characteristic in the coastal region and most of Nigeria.



**Figure 6:** Variation of SWVD with Surface Pressure for Owerri

For the location. Figure 6 displays the monthly variation of SWVD with surface pressure. The surface pressure decreased from January to reach its least value in March at 989.9049 mbars. It then increased until it reached its peak value in July with 993.9318 mbars and then decreased to December. This was seen as the SWVD increased

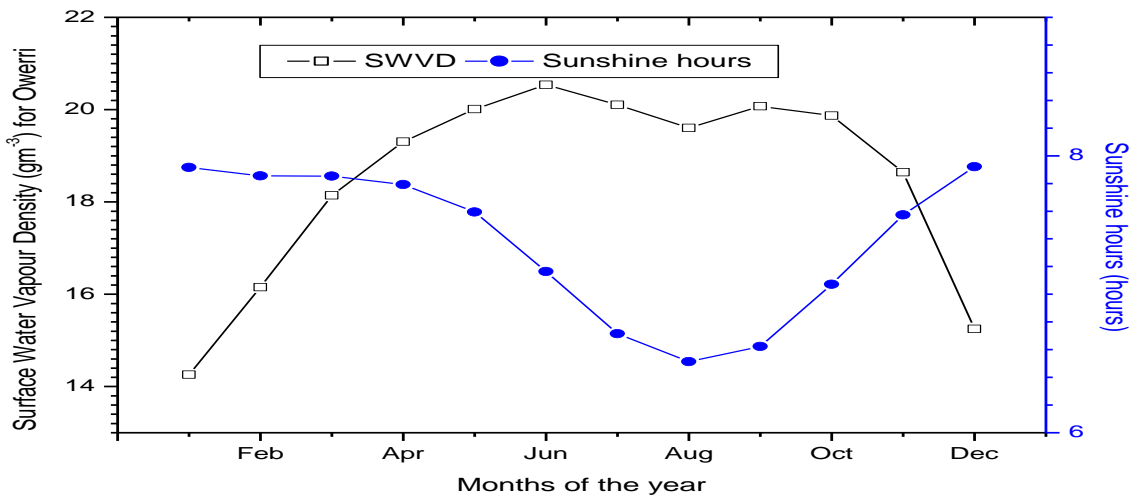
from its least value in January at 14.2589 gm<sup>-3</sup> to its maximum value in June with 20.5387 gm<sup>-3</sup>. The findings showed that during the wet season, high values of surface pressure and SWVD were detected, while low values were observed in the dry season.



**Figure 7:** Variation of SWVD with Cloud Cover for Owerri

The seasonal changes of SWVD with cloud cover for Owerri is displayed in Figure 7. The SWVD reaches its maximum value of  $20.5387 \text{ gm}^{-3}$  in June, at which point the cloud cover increases to 0.9019 in August before falling to its lowest

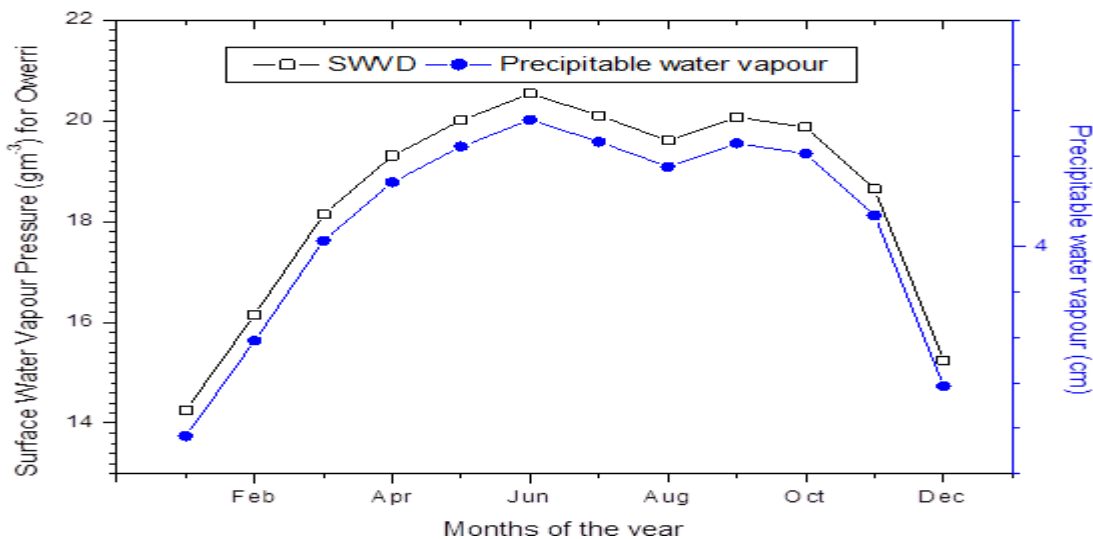
value of 0.4682 in December. The two variables increase nearly simultaneously from January to June. From June to August, the SWVD declines, then rises until September, and finally falls until December.



**Figure 8:** Variation of SWVD with Sunshine hours for Owerri

The seasonal variation of SWVD with sunshine hours for Owerri is displayed in Figure 8. From January through May, sunshine hours rise and fall nearly equally. From August to August, they reach their lowest value of 6.5140 hours, which is in line with the SWVD's August break. The

number of sunlight hours rises from its lowest point in August to its highest point of 7.9203 hours in December. The findings showed that, in line with the SWVD, during the dry season, high sunshine hour values were reported, and during the wet season, low values.



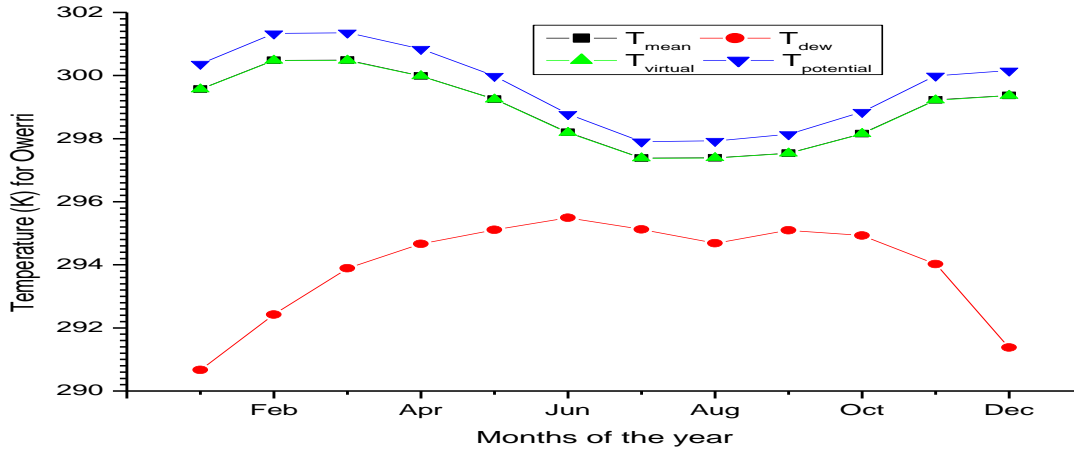
**Figure 9:** Variation of SWVD with Precipitable water vapour for Owerri



The change of SWVD, or precipitable water vapor (PWV), is displayed in Figure 9. The results indicate that the PWV and SWVD increased in the same pattern from January to

July, when they reached their highest values of 20.1033 gm<sup>-3</sup> and 4.4627 cm, respectively. The region's well-known August break is a sign of the abrupt decline in both the PWV and SWVD values in August.

**Change in Mean Temperature, Dew Point Temperature, Virtual Temperature and Potential Temperature for Owerri**



**Figure 10:** Variation of SWVD with Temperatures (T<sub>m</sub>, T<sub>v</sub>, T<sub>p</sub> and T<sub>d</sub>) for Owerri

The monthly variations of Owerri's mean, dew point, virtual, and potential temperatures (T<sub>m</sub>, T<sub>d</sub>, T<sub>v</sub>, and T<sub>p</sub>) are displayed in Figure 10. The findings showed that the mean temperature and the virtual temperature are fully in phase. In August, the two temperatures reached their lowest values of 297.3934 K and 297.3832 K, respectively, and their highest values of 3004882 K and 3004786 K, in March. The maximum temperature in Owerri at this time of year is also the potential temperature, which reaches its maximum in March at 301.3583 K and its lowest at 297.9063 K. The temperature of dew point is

entirely dependent on the other temperature; conversely, the minimum value of T<sub>d</sub> is reached in January at 290.6682 K and rises dramatically to May has 295.4913 K, which decreases to August, rises to September, and then decreases to December. This result is in line with the work reported by Akpootu *et al.* (2023b) and Iliyasu *et al.* (2023)

**Two Variable Correlation Models for Owerri**

Based on equations 10 to 12, the two variable correlation models created for Owerri are as follows

$$SWVD = 162 - 0.155P + 13.6CC \tag{16a}$$

$$SWVD = 433 - 0.390P - 3.70SSH \tag{16b}$$

$$SWVD = 0.326 - 0.000329P + 4.50PWV \tag{16c}$$

**Table 1:** Statistical Validation test for Owerri

Models	R <sup>2</sup>	MBE	RMSE	MPE
16a	92.6	-0.0842	0.5582	0.3583
16b	49	0.4271	1.5106	-3.0585
16c	100	-0.0204	0.0206	0.1105

The validation table for the developed models is shown in table 1 above. According to the results, equation 16c has the lowest MBE, RMSE, and MPE and the highest R<sup>2</sup>. The equation is therefore thought to be the best.

**Table 2:** Ranking of the Developed Models

Models	R <sup>2</sup>	MBE	RMSE	MPE	Ranking
16a	2	2	2	2	8
16b	3	3	3	3	12
16c	1	1	1	1	<b>4</b>

The model equation 16c has a lower ranking in table 2, indicating that it is the best equation for estimating SWVD in Owerri and any other place with comparable weather.

### CONCLUSION

For the purpose of this study, monthly average and daily average meteorological data obtained at 2 metres above sea level for Owerri (Latitude

5.48°N, Longitude 7.00°E, and 91 metres above sea level) in Imo state, South Eastern Nigeria, were utilized. These data were used to evaluate SWVD and its variations with other meteorological parameters over a thirty-eight-year period (1979–2016) as well as the daily variation of SWVD in each month for the year 2014. The study's findings showed that the rainy season is when high levels of SWVD are recorded, while the dry season is when low values are. The average value of 18.4955 gm<sup>-3</sup>, as well as the maximum and minimum values of 20.5387 gm<sup>-3</sup>, and 14.2589 gm<sup>-3</sup> were discovered in June and January, respectively, during the

rainy and dry seasons. On May 28, 2014, the greatest value of SWVD was recorded at 22.7604 gm<sup>-3</sup>, while on December 26, 2014, the lowest value was recorded at 9.6567 gm<sup>-3</sup>. Using statistical indices such as the coefficient of correlation, mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE), Nash-Sutcliffe Equation (NSE), and index of agreement (IA), three simple two-variable correlation models were developed during the investigation period. Of these, it was discovered that the model that links precipitable water vapour and pressure was better appropriate for determining surface water vapour density (SWVD) at the study site if temperature, relative humidity and pressure are measured in the study area.

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