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ESTIMATION OF PRECIPITABLE WATER VAPOUR AT SUB-SAHEL REGION OF CENTRAL NIGERIA USING SURFACE METEOROLOGICAL DATA

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ABSTRACT

Using a ten-year monthly averaged data from the Nigerian Meteorological Agency, for three stations in Nigeria, an empirical model of the form $\ln W = a + bT_d$ (where W is the precipitable water vapour, T_d is the dew-point temperature, a and b are constants) was found to be the best model estimation of precipitable water vapour at the sub-Sahel central region of Nigeria. The model was found to agree with other similar models found elsewhere and the goodness of fit statistic for this model was found to be $R^2 = 0.998$, SSE = 0.049 and RMSE = 0.015. Kolmogorov-Smirnov (K-S) test was used to validate the model. Other models using surface relative humidity (RH) and surface ambient temperature (T) were also found with satisfactory statistical performance. The minimum precipitable water vapour for the region was observed to be 24.88±7.82mm in the month of January while two maxima were found in the months of May and October as 46.79±7.82mm and 47.48±7.82mm, respectively. The link between el niňo/la niňa events and the variation of precipitable water vapour in the study area was attempted.

Keywords: Precipitable water vapour, Dew-point temperature, Relative humidity, sub-Sahel, Nigeria.

INTRODUCTION

Water vapour is a very variable and minute component of the Earth's lower atmosphere (the troposphere) and in the warm and wet tropics it may account for up to 4% by volume of the atmosphere whereas in the air of deserts and Polar Regions it may constitute but a tiny fraction of 1% (Lutgens&Tarbuck, 1989). But despite its variability and meagre quantity, it is nevertheless a very significant contributor to the weather and climate of the Earth's atmosphere. The vapour phase of water plays an important role in the hydrological cycle and it affects the climate and weather systems through its effect on the atmospheric temperature and energy transport (Garrison, 1992;Follette*et. al.*, 2008). Atmospheric water vapour attenuates and scatters electromagnetic radiations passing through the atmosphere and this fact is well known to astronomers and radio propagation engineers.

A very important measure of the atmospheric water vapour is the precipitable water vapour (W). Precipitable water vapour (W) is a measure of the total amount of water vapour content in a vertical column of air with unit area of horizontal cross-section and extending from the surface to the top of the atmosphere. This is the equivalent depth of water which would results if all the water vapour in the atmosphere were condensed into a layer of liquid water(Raj *et. al*., 2008), hence the unit of W is that of length (centimetre, millimetre, inches) and it should be noted that 1*mm* of precipitable water vapour is equivalent to 1kgm^{-2} of precipitable water vapour(Okulov *et. al.*, 2002).

The more traditional way of measuring precipitable water vapour is by employing radiosonde (Willoughby *et. al.*, 2008), by which a vertical profile of the precipitable water could be made, but radiosonde observations are not regularly made due to the expensiveness of the method. Other more expensive and technically more advanced methods of retrieval such as sun-photometer, water vapour radiometer (WVR), satellite retrieving method, Global Positioning System (GPS) receiver methods have been employed and their results found to be in good agreement with the radiosonde method (e.g., England *et. al.,* 1992; Coster*et. al.,* 1996; Linfield *et. al.,* 1997; Boccolari*et. al.,* 2002; Bai and Feng*et. al.,* 2003; Jade *et. al.,* 2005; Park *et. al.,* 2012). Several researchers have been finding empirical models that employed easily measurable surface meteorological parameters to estimate precipitable water vapour. Reitan (1963) and later Leckner (1978) proposed ground-based meteorological data incorporating water vapour and temperature to estimate the W, using the exponential decrease of water vapour with height in the atmosphere, Reitan (1963) proposed

$$W = \frac{483e_o}{T} \qquad (1)$$

and Leckner (1978)

$$W = \frac{493e_o}{T} \qquad (2)$$

where e_o is the vapour pressure (in *millibar*), and T is the surface ambient temperature (in *Kelvin*). The difference between (1) and (2) arises from the choice of the most representative value for the scale height.

Reitan (1963), studying monthly means of W and station dew-point temperature T_d over the continental U.S.A, developed a linear relation between natural logarithm of the W (*cm*) and T_d (^oC) i.e.,

$$lnW = 0.1102 + 0.0613T_d \qquad (3)$$

Won, quoted by Okulov et al. (2002), developed a similar expression for all Canadian seasons in 1977. In Nigeria, Maduekwe and Ogunmola (1997), as well as Utah and Abimbola (2006) found a form of Eqn. 3 for Sokoto and Jos respectively.

It is our aim in this work to find some suitable empirical equations with easy to measure surface meteorological parameters and to recommend the best model for the estimation of precipitable water vapour at the central region of Nigeria.

MATERIAL AND METHODS

Site and Database

The data used in this work were collected from the Nigerian Meteorological Agency (NIMET), Oshodi Nigeria. The data obtained spanned a period of ten (10) years, from 2002 to 2011, for the stations which include Ilorin (8.5 ^oN latitude: 4.55 ^oE longitude, and 290*metre* above sea level), Makurdi (7.74^oN latitude: 8.51^oE longitude and 104*metre* above sea level), and Yola (9.2^oN latitude: 12.48^oE latitude and 163*metre* above the sea level). Makurdi and Yola are along the bank of River Benue, while Ilorin is very close to the basin of River Niger (Figure 1); the stations are in the central region of Nigeria.

The *El-niňo*/*La-niňa*information and data were obtained from www.ggweather.com/enso/oni.htm.

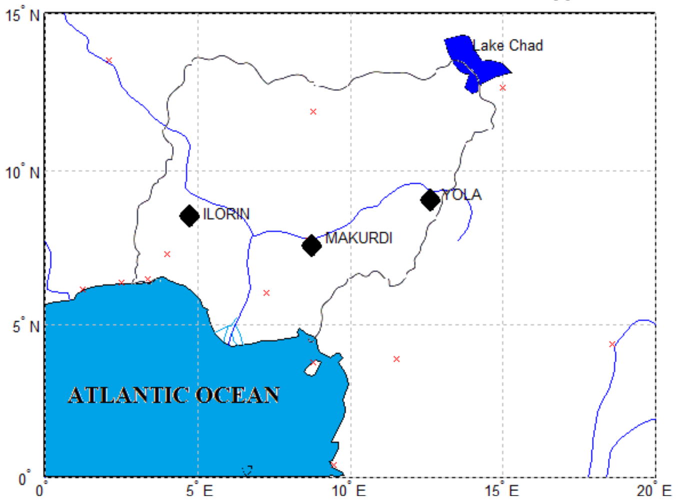

Figure 1: Geographical location of the stations (Ilorin, Makurdi and Yola) used in this work.

The central region of Nigeria is in the tropical guinea savannah climate which exhibits a well-marked rainy and dry seasons with a single peak known as the *summer maximum* due to its distance from the equator. In this region, the temperatures are above 18^oC throughout the year, for instance, Abuja, a city in this region has a temperature range of 18.45 to 36.9^oC and an annual rainfall of ~1500mm with a single rainfall maxima in September.

Beginning from around November to around late March, a continental tropical (cT) airmass laden with dust from the Sahara desert blows over this region thus, bringing with it a single dry season usually experienced in the Nigerian central region.

With the Inter-tropical Convergence Zone (ITCZ) swinging northward over West Africa from the Southern hemisphere in April, heavy showers coming from pre-monsoonal convective clouds, mainly in the form of *squal line* formed mainly as a result of the interactions of the maritime tropical (mT) and the continental tropical(cT)airmasses, begins in the central region while the monsoons from the South Atlantic Ocean arrives in the central region of Nigeria in July bringing with its high humidity, heavy cloud cover and heavy rainfall which can be daily occurrence lasting till September when the monsoons gradually begin retreating southward to the Southern part of Nigeria.

Data Analysis

The mean monthly values of ambient temperature T(K), vapour pressure $e_o(mbar)$, relative humidity RH($\%$) and dew-point temperature T_d(^oC) were collected and prepared using Microsoft Excel® Spreadsheet computer program, while the precipitable water vapour was calculated for each month (120 data points) of the year using the Leckner (1978) model, i.e., Eqn. 2. The data analysis was done using MATLAB®, with its "*cftool*" function used to fit models to the plotted values and also obtaining the goodness-of-fit statistic of sum-squared-error (SSE), root-mean-squared-error (RMSE) and the coefficient of determination (R^2). The "*kstest2(x1 x2)*" function of the MATLAB® was also used to validate the derived models against existing data using Kolmogorov-Smirnov (K-S) test.

RESULTS

Modelling Precipitable Water Vapour (W) with Dew-point Temperature (T_d)

Annual average of precipitable water vapour, relative humidity, dew point temperature and ambient temperature for the central region of Nigeria, together with the ten year average (for the year 2002 to 2011) of the values is shown on Table 1.

Table 1: Annual Average of Precipitable Water Vapour (W), Relative Humidity (RH), Dew Point Temperature (T_d) and the Ambient Temperature (T) for the Region of Study Spanning the Year 2002 to 2011.

Period	Precipitable Water Vapour W (mm)	Relative Humidity RH (%)	Dew point Temperature T_d(^{0}C)	Ambient Temperature T(K)
2002	38.5	64.6	18.9	301.0
2003	39.1	66.4	19.3	301.2
2004	38.7	67.2	19.2	301.0
2005	39.6	67.0	21.0	301.4
2006	39.5	67.7	19.7	301.0
2007	39.4	65.5	19.5	300.9
2008	38.1	66.9	19.1	300.6
2009	41.0	69.6	20.5	300.9
2010	41.5	68.9	20.1	301.3
2011	39.0	66.5	19.3	301.0
Decade Average	39.4	67.0	19.6	301.0

The plot of the natural logarithm precipitable water vapour (lnW) against the dew-point temperature T_d, for Ilorin and Yola, representing the central region of Nigeria is shown in Fig. 2. With a linear distribution shown on the plot, a linear fit was made and the linear model in Eqn. 4 was obtained

$$lnW = 0.05433T_d + 2.584 \qquad (4).$$

The goodness-of fit statistic for Eqn. 4 was found to be given as: SSE = 0.04848, RMSE = 0.01465 and R^2 = 0.998.A K-S test of Eqn. 4 with the available precipitable water vapour data in Makurdi, through MATLAB® function, returns h = 0 and p = 0.1653. The time series comparison of Eqn. 4 and the Makurdi data is shown in Fig. 3.

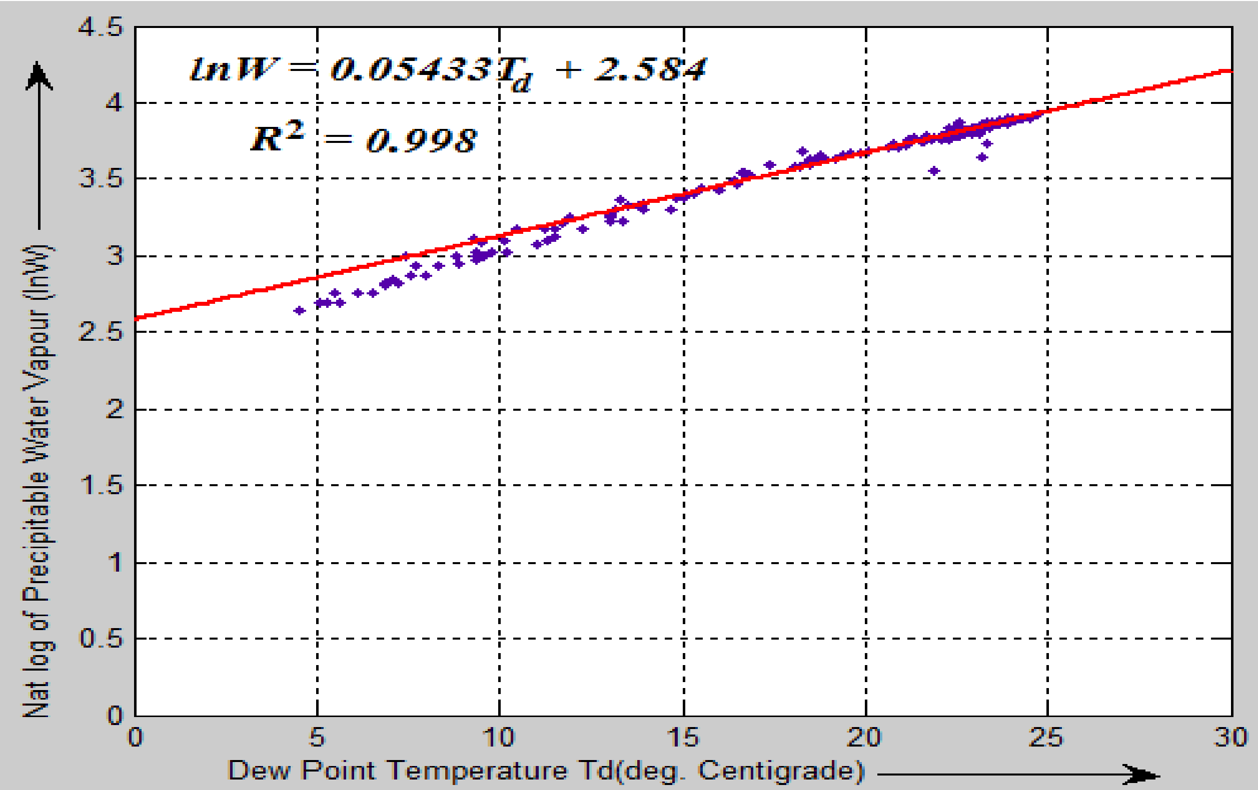

Figure 2: Combined plot of natural log. of precipitable water vapour (lnW) against dew-point temperature (T_d) for Ilorin and Yola.

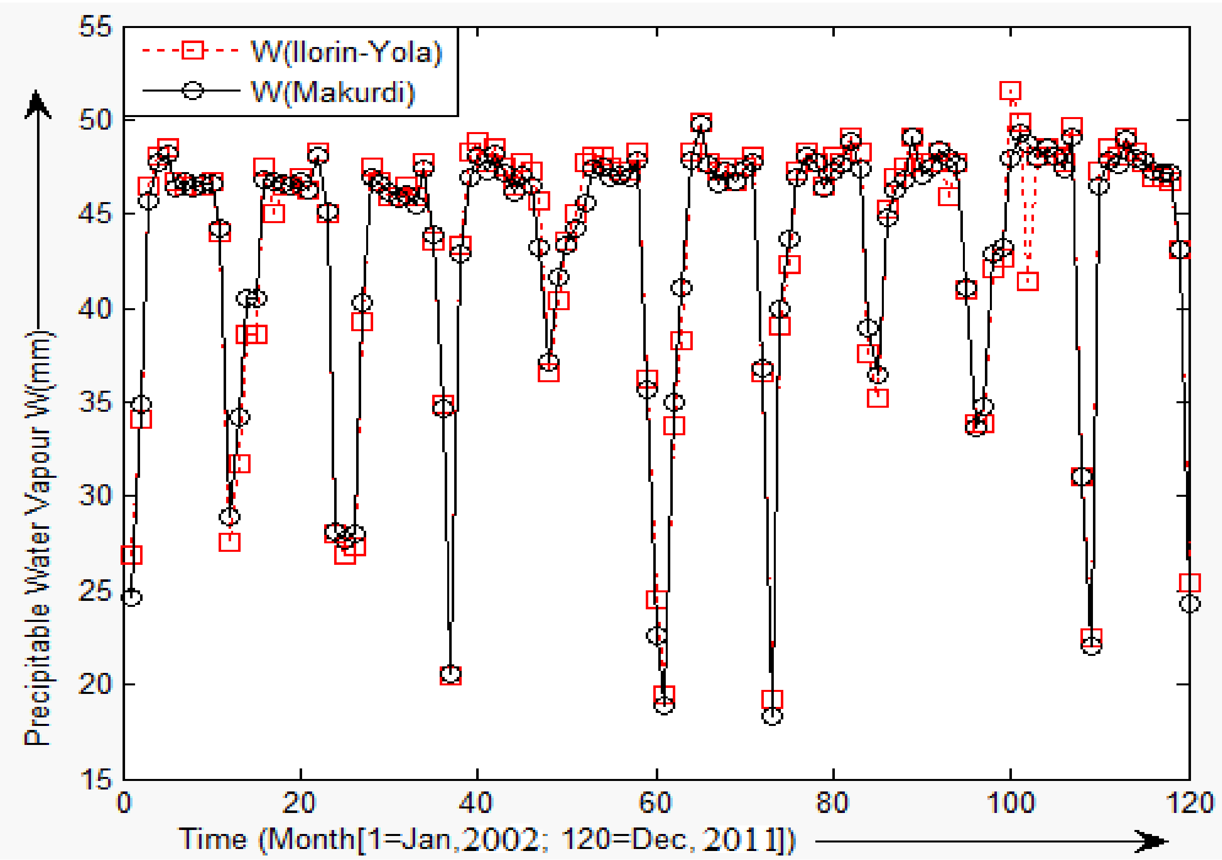

Figure 3: Time series plot of precipitable water vapour for Ilorin-Yola combined and Makurdi.

Modelling Precipitable Water Vapour with Relative Humidity and Ambient Temperature

Plots of W against RH are shown in Figs. 4 and 5, with logarithm and quadratic fits shown respectively. The fits gave the logarithm and quadratic models given in Eqns. 5 and 6.

$$W = 27.71\ln(RH) - 75.25 \quad (5)$$

$$W = -0.007276(RH)^2 + 1.365(RH) - 16.4 \quad (6)$$

The goodness-of-fit statistic was found for Eqn. 5 as SSE = 4654.05, RMSE = 4.6418 and R^2 = 0.808, while that for Eqn. 6 was found as SSE = 4240.00, RMSE = 4.4407 and R^2 = 0.825.

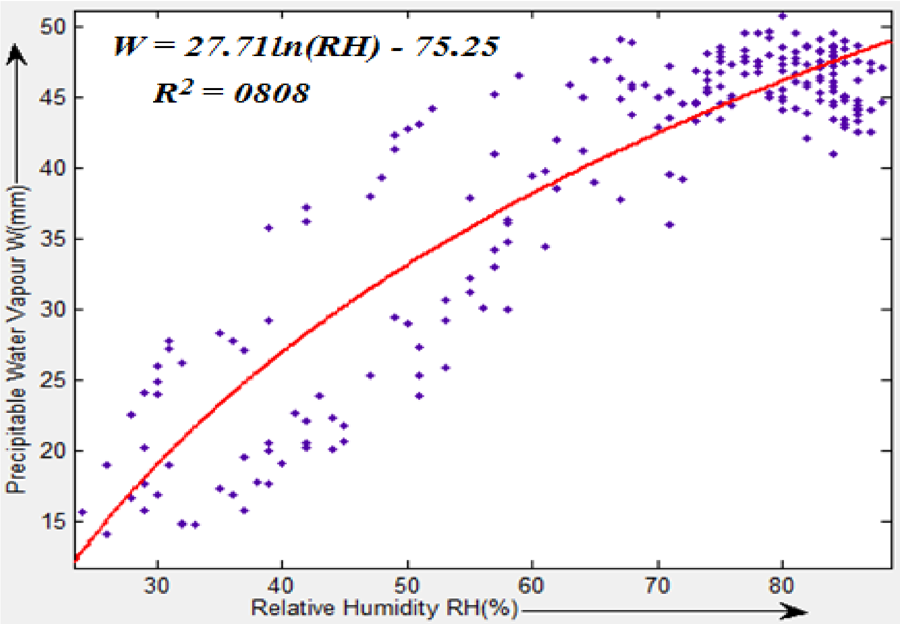

Figure 4. Regional plot of Precipitable Water Vapour against Relative Humidity, showing a logarithm fit.

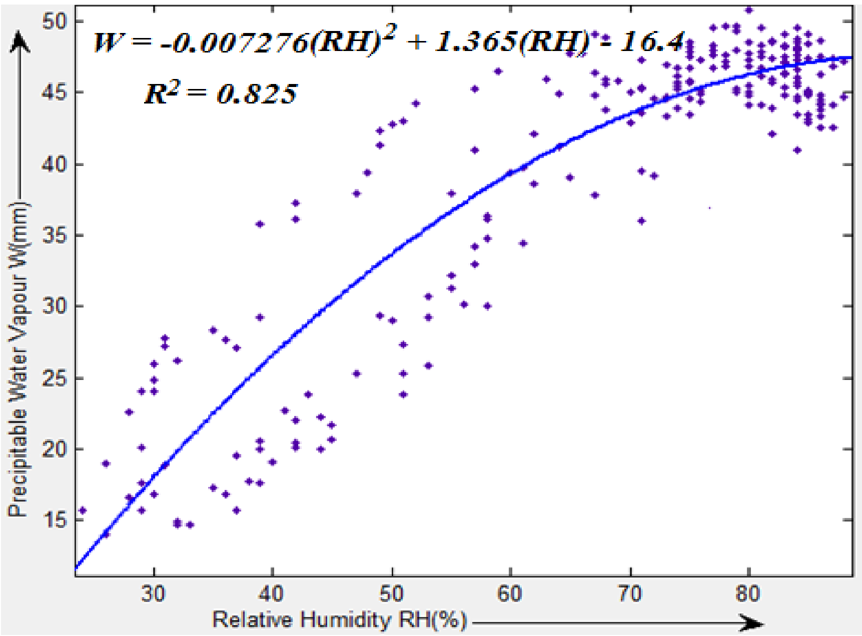

Figure 5. Regional plot of Precipitable Water Vapour against Relative Humidity, showing a quadratic fit.

A time series comparison of the models in Eqns. 5 and 6 with the Makurdi data is shown in Fig. 6, while the MATLAB® K-S test returns h = 1 for both models and p = 1.3537×10^{-12} for the logarithm model as well as p = 6.558×10^{-14} for the quadratic model.

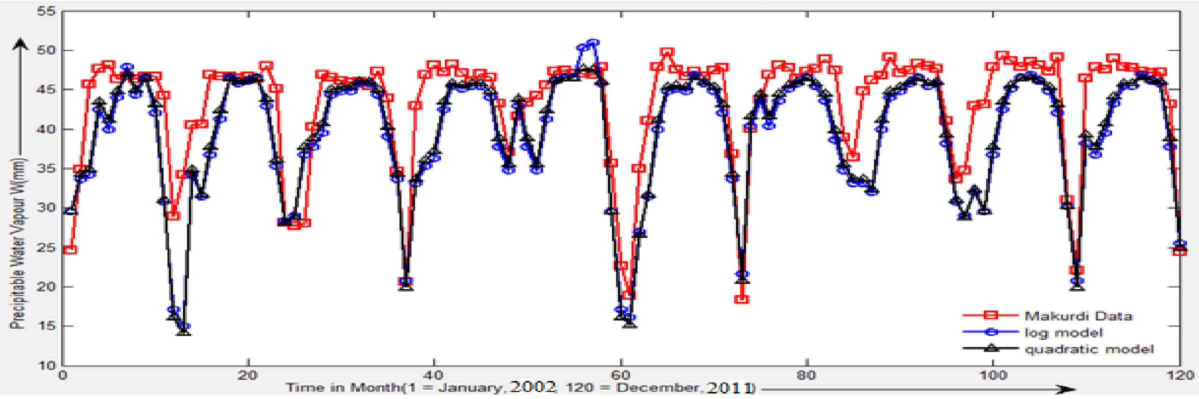

Figure 6: Time series comparison of the logarithm and quadratic models with the Makurdi data.

A scatter plot of precipitable water vapour against relative humidity divided by the surface ambient temperature (RH/T) is shown in Fig. 7. A linear fit to the scatter plot gave the model of Eqn. 7, with goodness-of-fit statistic given as SSE = 6.127, RMSE = 0.1658 and R^2 = 0.7563. A power fit to the scatter plot also gave the model of Eqn. 8 with the following goodness-of-fit statistic: SSE = 4.638, RMSE = 0.1445 and R^2 = 0.8155. The quadratic fit as shown on Fig. 7 presents a goodness-of fit statistic of SSE = 1.296, RMSE = 0.0764 and R^2 = 0.9485. The quadratic model is given in Eqn. 9.

$$lnW = 4.448\left(\frac{RH}{T}\right) + 2.646 \quad (7)$$

$$lnW = -0.5643\left(\frac{RH}{T}\right)^{-0.5457} + 4.988 \quad (8)$$

$$lnW = -48.74\left(\frac{RH}{T}\right)^2 + 25.95\left(\frac{RH}{T}\right) + 0.3902 \quad (9)$$

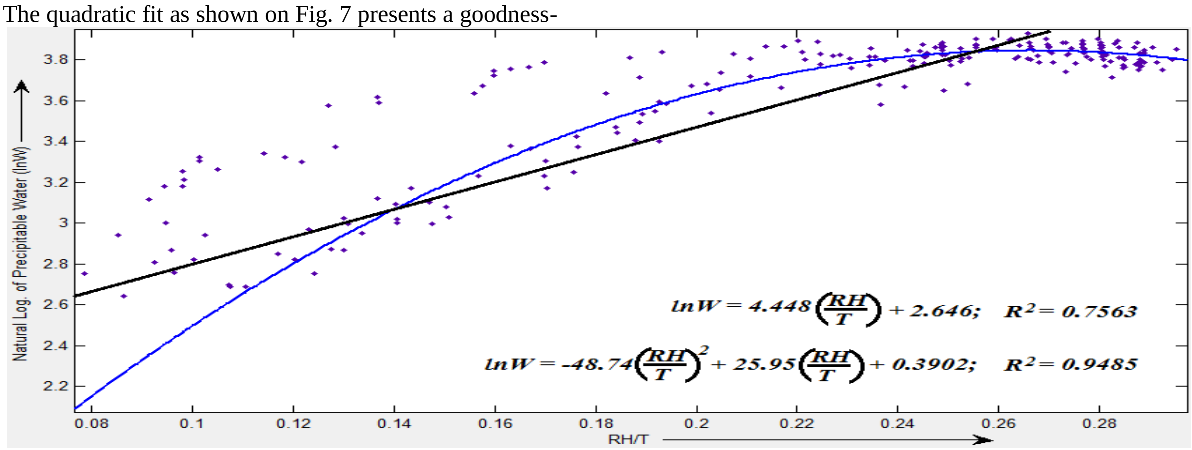

Figure 7: Scatter plot of natural logarithm of precipitable water against relative humidity divided by surface ambient temperature, showing a quadratic fit.

Time series comparison plot of the models in Eqns. 7, 8 and 9 with the precipitable water vapour data in Makurdi is shown in Fig. 8. MATLAB® K-S test returns h =1 for all the models (Eqns. 7, 8 and 9) with p-values of 2.31×10^{-14}, 7.9965×10^{-15} and 3.5875×10^{-12}, for the linear, power and the quadratic models, respectively.

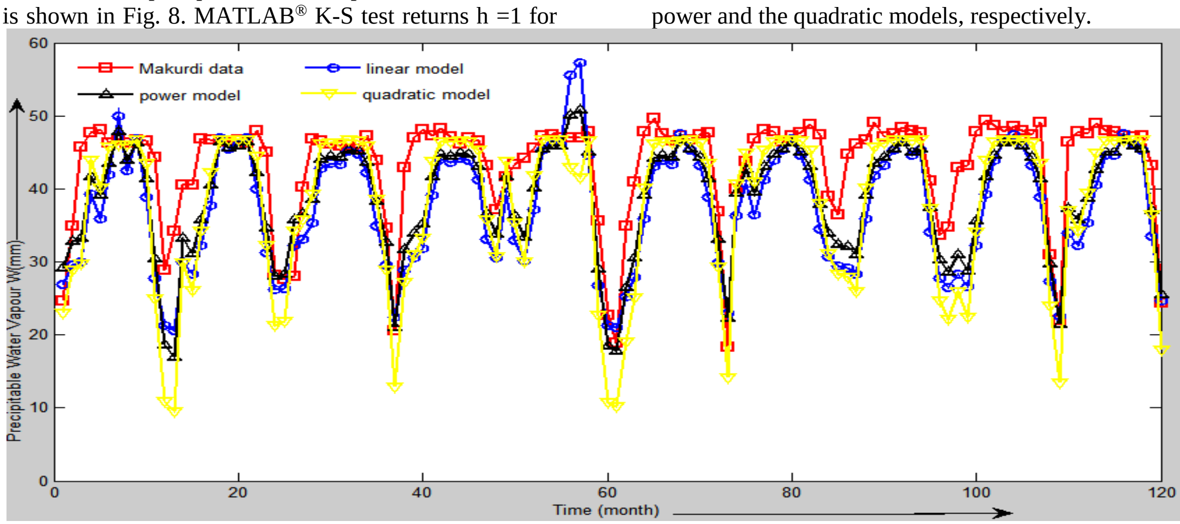

Figure 8:Time series comparison of precipitable water of Makurdi data with linear, power and quadratic models.

Seasonal Analysis

The seasons in the central region of Nigeria have been divided into wet and dry seasons, forthe purpose of this work, based on the rainfall pattern observed in this region. The wet season has been taken to be in the months of April, May, June, July, August, September and October while the dry season has been taken to be in the months of November, December, January, February, and March.

The seasonal models during the dry and wet seasons, together with the results of their goodness-of-fit, are presented in Eqns. 10 to 19:

Wet Season

$$lnW = 0.05464T_d + 2.576 \quad (10)$$

SSE = 0.007987 RMSE = 0.007868 R^2 = 0.988

$$W = -0.01129(RH)^2 + 1.644(RH) - 12.38 \quad (11)$$

SSE = 441.7 RMSE = 1.858 R^2 = 0.616

$$W = 7.185\ln(RH) + 14.94 \quad (12)$$

SSE = 674.4 RMSE = 2.286 R^2 = 0.414

$$lnW = -1.206 \times 10^{-5}\left(\frac{RH}{T}\right)^{-4.912} + 3.848 \quad (13)$$

SSE = 0.2395 RMSE = 0.04326 R^2 = 0.642

$$lnW = -21.33\left(\frac{RH}{T}\right)^2 + 10.32\left(\frac{RH}{T}\right) + 2.612 \quad (14)$$

SSE = 0.2014 RMSE = 0.03967 R^2 = 0.699

Dry Season

$$lnW = 0.06315T_d + 2.414 \quad (15)$$

SSE = 0.1639 RMSE = 0.04292 R^2 = 0.986

$$W = 0.003606(RH)^2 + 0.2067(RH) + 9.301 \quad (16)$$

SSE = 1734 RMSE = 4.389 R^2 = 0.825

$$W = 27.31\ln(RH) - 75.56 \quad (17)$$

SSE = 2306 RMSE = 5.034 R^2 = 0.767

$$lnW = 5.869\left(\frac{RH}{T}\right)^{0.987} + 2.324 \quad (18)$$

SSE = 2.999 RMSE = 0.1816 R^2 = 0.755

$$lnW = -2.756\left(\frac{RH}{T}\right)^2 + 6.888\left(\frac{RH}{T}\right) + 2.261 \quad (19)$$

SSE = 2.963 RMSE = 0.1804 R^2 = 0.758

DISCUSSION

Precipitable Water Vapour with Dew-point Temperature

The model of Eqn. 4 gave a statistically very good estimate of precipitable water W at the central region of Nigeria as could be seen in Table 2 which compares the statistical behaviour of all the models obtained in this work. The suitability of Eqn. 4 is also confirmed by the result of the MATLAB®K-S test, which shows a p-value (0.1653) that is greater than the α-value (0.05).

As could be seen in Table 2, the slope of Eqn. 4 compares very well with the slopes of other similar models obtained elsewhere and as was pointed out by Utah and Abimbola (2006) that the intercept could be used as a measure of the moisture burden of the location or the region for which the model describes, it could then be observed that the intercept of Eqn. 4 is slightly less than that of Jos but more than that of Sokoto. This is in order, as the intercept in this work is an average for several locations, while Jos value by Utah and Abimbola (2006) is for a single location. The intercept of Eqn. 4, being more than that of Sokoto also show that Sokoto has less moisture burden than the central region of Nigeria.

Table 2: Slope and Intercept Values for W vs. T_d at Different Locations.

Author(s)	Year	Location	Slope(/°C)	Intercept (cm)
Reitan(1963)	1963	U.S.A	0.06138	0.1102
Won(cited by Okulov et. al., 2002)	1977	Canada	0.05454	-0.4539
Maduekwe and Ogunmola(1997)	1997	Sokoto, Nigeria	0.06480	0.0546
Utah and Abimbola(2006)	2006	Jos, Nigeria	0.06381	0.2979
This work	2014	Central Region of Nigeria	0.05433	0.2584

Precipitable Water Vapour (W) with Relative Humidity (RH) and Ambient Temperature (T)

The summary of the statistical behaviour of the models are given in Table 3, it will be observed that even though the MATLAB®K-S test reject the models of Eqn. 5 to 9, the goodness-of-fit statistic shows that the model of Eqn. 9 (the third model in Table 3) will give a good estimate of precipitable water, therefore it could be said that as an alternative to Eqn. 4, Eqn. 9 could be used, with caution for the estimate of precipitable water vapour at the central region of Nigeria.

Table 3: Statistical Behaviour of Various Models Obt 174 **Work.**

Models	R^2	SSE	RMSE
$lnW = 0.05433T_d + 2.584$	0.998	0.04848	0.01465
$lnW = 4.448\left(\frac{RH}{T}\right) + 2.646$	0.756	6.127	0.1658
$lnW = -0.5643\left(\frac{RH}{T}\right)^{-0.5457} + 4.988$	0.816	4.638	0.1445
$lnW = -48.74\left(\frac{RH}{T}\right)^2 + 25.95\left(\frac{RH}{T}\right) + 0.3902$	0.949	1.296	0.0764
$W = 27.71\ln(RH) - 75.25$	0.808	4654.05	4.6418
$W = -0.007276(RH)^2 + 1.365(RH) - 16.4$	0.825	4240.00	4.4407

Seasonal models

It could be seen from the analysis of the seasonal models that the wet season usually presents better model statistically; this could be as a result of the presence of more or increase in atmospheric moisture during the wet season. Besides, the intercept of Eqn. 10 (2.576) could be seen to be more than that of Eqn. 15 (2.414), further affirming the assertion of Utah and Abimbola (2006) that the intercept could be used to compare moisture burden of a place.

Decade Average of Precipitable Water

A ten-year average of precipitable water vapour for the central region, combining the data from Ilorin, Yola and Makurdi for the period 2002 to 2011, is shown on Figure 9. The minimum value of W for this region was found in January with the value of 24.88±7.82mm, Utah and Abimbola (2006) obtained a minimum value of 15mm in February for Jos, while Utah (1993) obtained 10mm for the same month and location.Meanwhile, as could be seen on Figure 9, two distinct maxima were observed during the months of May and October with values of 46.79±7.82mm and 47.48±7.82mm respectively.

Observation of two distinct maxima in W is not a characteristic of this region of Nigeria but of the southern region. This observation could be as a result of data obtained from few stations in this region and hence further study is needed to confirm or refute this result.

Figure 10, shows the time series variation of the average precipitable water vapour for the central region. On the figure is shown the moderate *elniño* (ME), weak *el niño* (WE), strong*la niña* (SL), moderate *la niña* (ML) and weak *la niña* (WL) events. It would be observed that the WE events corresponds to atmospherically dryer periods as compared to the ME event period and it could be inferred, from the observation of the *la niña* periods, that occurrence of strong *el niño* events will bring high moisture burden to the central Nigeria region, thereby causing more rain and hence likelihood of flooding!

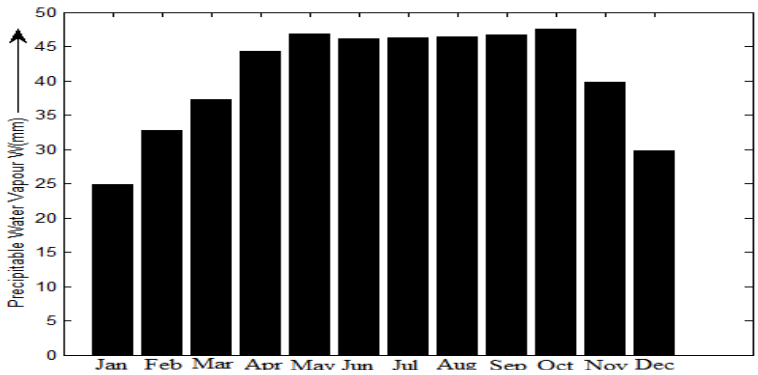

Figure 9: Monthly Decade Average for the Central Region of Nigeria.

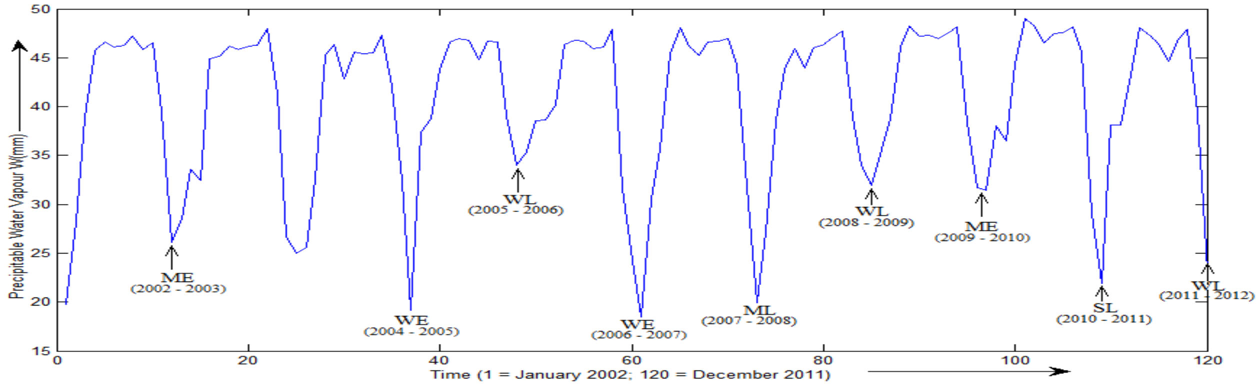

Figure 10. Time series plot of the precipitable water vapour for the region, showing some *el niño* and *la niña* events (M = moderate; W = weak; S = strong; E = *elniño*; L = *la niña*).

CONCLUSION

In this work, a suitable empirical model relating the precipitable water vapour (W) to dew-point temperature (T_d) was found for the central region of Nigeria, the model was found to compare well with similar models found elsewhere. Another model for estimating W, using relative humidity and surface ambient temperature as input parameters was also found, but the dew-point temperature model performs statistically better!

It was found that the dryer periods at the studied region corresponds to a period of weak*el niňo* events while the wetter periods corresponds to the strong *el niňo* events. The ten-year average minimum of W for the region was observed to be 24.88±7.82*mm* (see Figure 9) in the month of January while two maxima were observed in the months of May and October as 46.79±7.82 *mm* and 47.48±7.82 *mm*, respectively (see Figure 9).

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