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Estimation of Reference Evapotranspiration Using Penman-Monteith Equation and Time Series Model in some Selected States in Northern Nigeria

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Abstract

Based on the problem of climate change which greatly affects agriculture and water management in Northern Nigeria, this study estimates reference evapotranspiration using Penman-Monteith equation and time series models in some selected states in Northern Nigeria. The study covered 16 states in Northern Nigeria which were selected using purposive sampling techniques. The materials used for the study consist of secondary data of daily mean records of air temperature, wind speed, solar radiation, and relative humidity from 1st January 1984 to December 2022. From the data, the daily reference evapotranspiration were computed using Penman-Monteith equation. Based on this, daily and mean annual reference evapotranspiration was obtained. From the result obtained on the daily and annual mean reference evapotranspiration, the time series models were plotted. The time series models plotted consist of daily reference evapotranspiration against time and mean annual reference evapotranspiration against time. The time series plots provided a random, nonlinear trend plot which is aperiodic. The plot of the mean and variance of reference evapotranspiration of states against latitudinal trend showed that R^2 >0.60, which indicated that the mean and variance of reference evapotranspiration has a strong relationship with latitudinal trend of the states and thus can be used for predictive purpose. This latitudinal trend behavior of the mean and variance of reference evapotranspiration is further supported using spatial distribution map of Northern Nigeria which showed that the lowest mean reference evapotranspiration is location within FCT-Abuja and Jos while the highest mean reference evapotranspiration is located within Sokoto, Kebbi and Gusau.

Keywords: Evapotranspiration, Penman-Monteith equation, solar radiation, time series model

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Introduction

Evapotranspiration is a natural phenomenon which consists of the movement of water from the soil (evaporation) and the movement of water through leaves of plants (transpiration). Evaporation and transpiration are combined to form evapotranspiration because these processes occur simultaneously. In physics, Evapotranspiration is the directional change of water to vapor and its movement to the atmosphere [1, 2]

Evapotranspiration is one of the greatest factors in hydrology. It is considered when calculating hydrologic water balance, distribution of water system, establishing irrigation system and assessing changing climate problem [3]. When assessing climate change, evapotranspiration is considered because it gives the trends of water deficit and the period it mostly occurred. In northern Nigeria, the major problem of climate change is aridity because it affects crop yield due to insufficient rainfall. Climate variation and the problem it brings is of great concern and is a topic of interest in today's research trend [4]. Climate change is viewed to change water cycle and evapotranspiration globally [5]. Also, there is reasonable evidence to suggest that the water cycle has been changing with climate change [6]. Climate change which has direct relationship with evapotranspiration also had relationship with climate variables, because temperature rise affects vapor pressure deficit, sunshine duration, evapotranspiration, precipitation, wind speed and relative humidity.

The direct measurement of evapotranspiration is done using lysimeter. This direct measurement of evapotranspiration is very difficult because it takes a long time and involves large areas. As a result of this, it makes the research work to be very expensive and time-consuming. As a result of this, the Food and Agriculture Organization (FAO) recommended the use of localized areas and reference evapotranspiration equation to estimate reference evapotranspiration (ETo) [7].

ETo is defined as the frequency of evapotranspiration from a localized area that have a crop height of 0.12 m, a crop surface resistance factor of 70 secm^{-1}, and an albedo factor of 0.23 [7]. They further said that localized crop consists of an extensive surface of green grass cover that have the same height. ETo can be computed from several ETo equations using recorded weather variables such as radiation, air temperature, air humidity and wind speed among others [8].

The several ETo computing equations consisting of Penman-Monteith equation, Priestley-Taylor equation, Hargreave-Samani equation, Adjusted Hargreaves equation etc. However, the most used equation is the Penman-Monteith equation [9]. They further explained that Penman-Monteith equation did not need local calibration and can be used to provides ETo values for a uniform grass reference surface worldwide.
Time series model is referred to as a reference frame of ETo in a space time, which is the motion of vaporized water in the atmosphere. The vaporized water particles are measured by calculating the rate of evapotranspiration using time series of daily mean record of weather variables. This computation of ETo gives the daily time series of ETo which is then used to analyze the characteristics of ETo. Furthermore, [10] remarked that characterizing ETo using time series can be used to make observations and predictions for future strategic decisions making.
Estimating and characterizing ETo using time series model is highly required for the provision of weather information which can be used for water and irrigation management mostly in the arid region. It is in view of this that this study investigated reference evapotranspiration and time series model in some selected states in Northern part of Nigeria.

Model equation for reference evapotranspiration

The model equation used in computing reference evapotranspiration is Penman-Monteith equation. The formula for Penman-Monteith equation is given by:

$$ET_{o,pm} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_k}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \ (mm/day) \quad (1)$$

The parameters and formulae for Penman-Monteith equations consist of:

a. Mean air temperature, T:

Mean air temperature, $T = \frac{T_{min} + T_{max}}{2}$ (2)

Absolute temperature, $T_k = T + 273.16$ (3)

b. Psychrometric constant, γ [9]:

$$\gamma = \frac{C_p P}{\varepsilon\lambda} = 0.665 \times 10^{-3} \quad (kPa/°C) \quad (4)$$

Where; C_p = specific heat capacity of surrounding air at constant pressure
= $1.013 \times 10^3 \ MJ/kg°C$
ε = ratio of molecular weight of water vapor to dry air = 0.622
λ = latent heat of vaporization = 2.45 MJ/k

c. Saturated water vapor pressure,(e_s) [9]:

$$e_s(T) = 0.6108 \ exp\left(\frac{17.27\ T}{T + 237.3}\right) \quad (kPa) \quad (5)$$

T = average air temperature (°C)

d. Actual water vapor pressure, (e_a) [9]:

$$e_a(T_{dew}) = 0.6108 \ exp\left(\frac{17.27\ T_{dew}}{T_{dew} + 237.3}\right) \quad (kPa) \ (6)$$

Where; T_{dew} = dew point temperature which is computed from the relative humidity (RH) using the expression [11]:

$$T_{dew} = \left(\frac{RH}{100}\right)^{\frac{1}{8}}(112 + 0.9T) + 0.1T - 112 \quad (7)$$

Vapor pressure deficit = $e_s - e_a$

e. Slope of saturated water vapor pressure (Δ)[9]

$$\Delta = 4098\frac{e_s}{(T_k)^2} \quad (8)$$

f. Net shortwave radiation, R_{ns}:

$$R_{ns} = (1 - \alpha)R_s(MJ/m^2day) \quad (9)$$

R_s is the incident solar radiation and α is the albedo whose value is 0.23 [9].

g. Net longwave radiation, R_{nl}:

Net long wave radiation is defined as the net energy flux that comes out from the earth's surface. It is a function of the Stefan-Boltzmann's law with some correction from the relative humidity and cloud cover which acts as absorbers of longwave radiation and is expressed as [9]:

$$R_{nl} = \sigma\left[\frac{T^4_{max,k} + T^4_{min,k}}{2}\right](0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right)(MJ/m^2day) \quad (10)$$

Where σ = Stefan-Boltzmann's constant = $4.903 \times 10^{-9}\ MJK^{-4}m^{-2}day^{-1}$

h. Net radiation, R_n:

$$R_n = R_{ns} - R_{nl} \quad (11)$$

i. Wind speed relation:

The wind speed (U_2) was determined at 2 m height above the ground (Novak, 2014). Hence the height x is 2m above the ground:

$$U_2 = \frac{4.87}{\ln(67.8x - 5.42)} \quad (km/hr) \quad (12)$$

j. Soil heat flux density, G:

The soil heat flux compared to net radiation R_n is small. The reason is because the soil surface is covered by crop. Therefore, $G \approx 0$ [9].

Materials and Methods

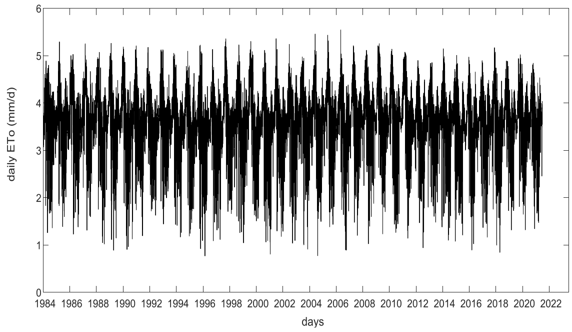
The study covered Northern States in Nigeria. Northern Nigeria is located at latitudes 10° 30' 59.99" North of the equator and longitude 7° 25' 59.99" East of the Greenwich Meridian. It shared borders to the North with Niger, to the East with Chad and Cameroon and to the West with Benin Republic. In this study, 16 states from the 20 Northern states were selected using purposive sampling technique. The state capitals of these 16 states were investigated as reference locations and they consist of: of Makurdi, Dutse, Jos, Minna, Sokoto, Katsina, Kaduna, Bauchi, FCT-Abuja, Maiduguri, Jalingo, Yola, Gusau, Damaturu, Birnin-Kebbi and Kano.
The materials used for analyses consist of secondary data obtained from Modern Era Retrospective Analysis for Research and Application (MERRA-2). These data consist of daily mean records of air temperature, wind speed, solar radiation and relative humidity for selected locations in Northern Nigeria from 1st January 1984 – 31st December 2022.

The information from this data was inputted into MATLAB (R2020a) software after coding the Penman-Monteith equations formular and parameters into the software. The result obtained from MATLAB (R2020a) gives the rate of reference evapotranspiration within the reference location.

Results and Discussion

Daily and annual mean variation of reference evapotranspiration

The result of the computation of daily reference evapotranspiration was computed using the daily record of climates variables in each of the 16 Northern states. Another result computed consists of average daily reference evapotranspiration across the entire duration of 1984-2024. These entire durations were then reduced into a single annual duration using averages. The daily and annual mean variation time series of reference evapotranspiration was then plotted as presented in Figs 1 and 2, respectively.



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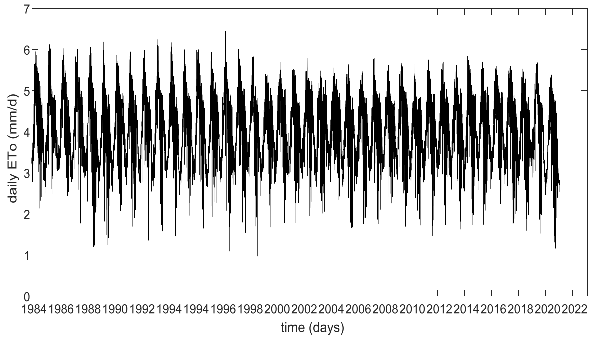

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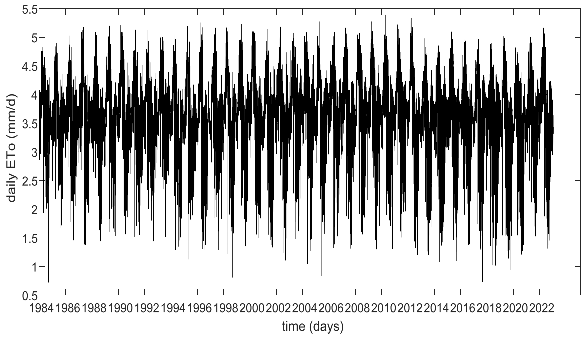
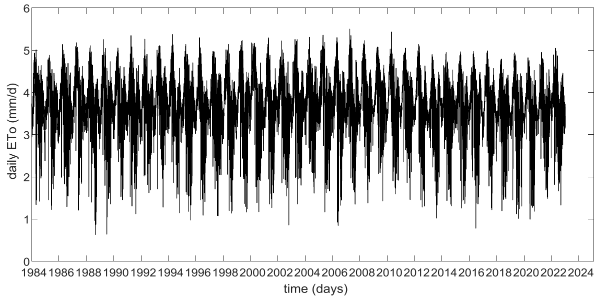
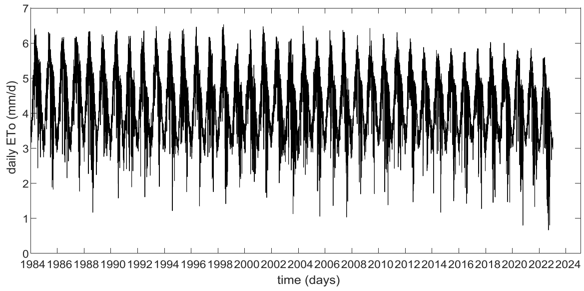


(c) Jos



(d) Minna



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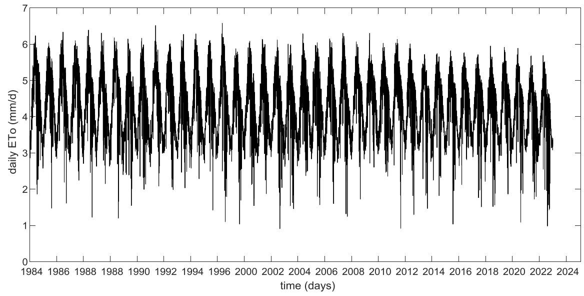

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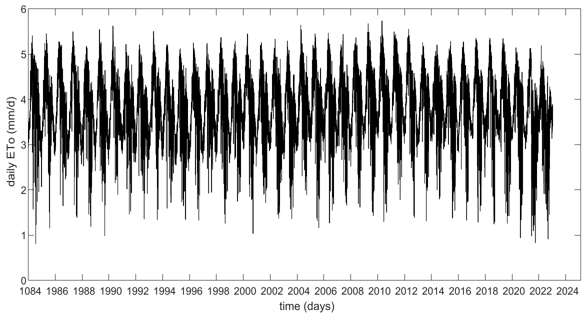

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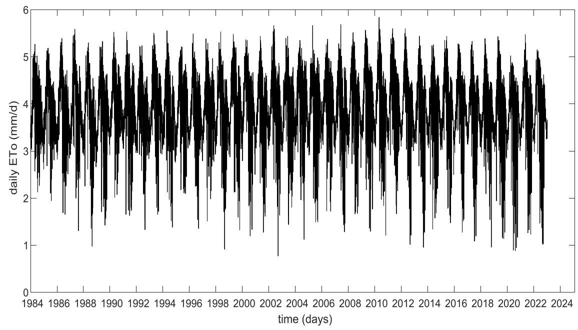

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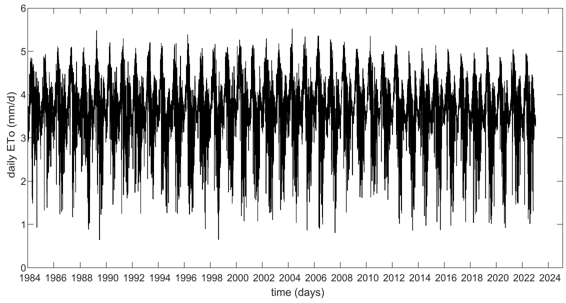

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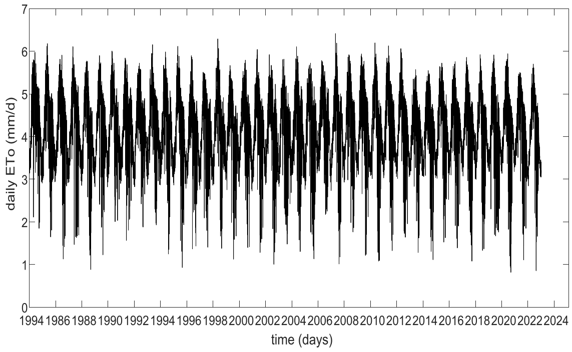

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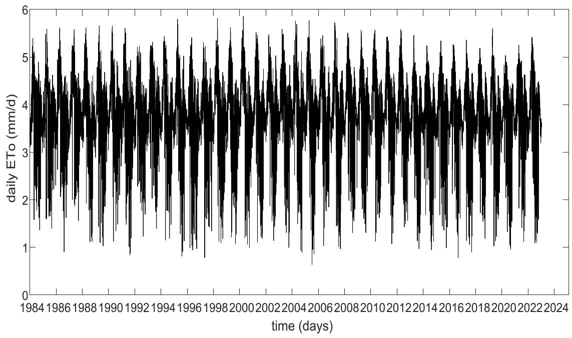

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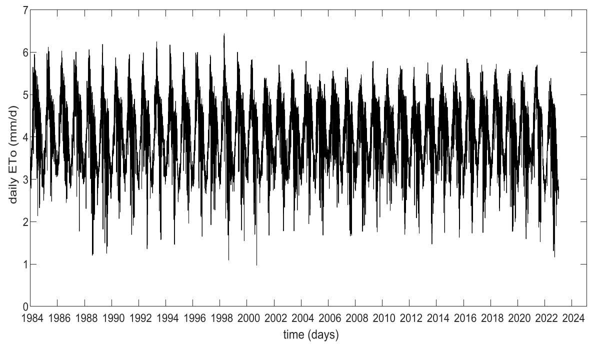

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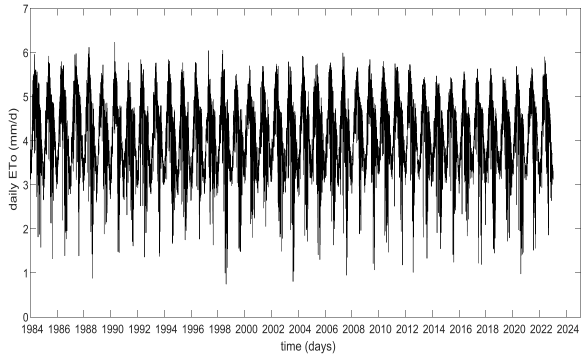

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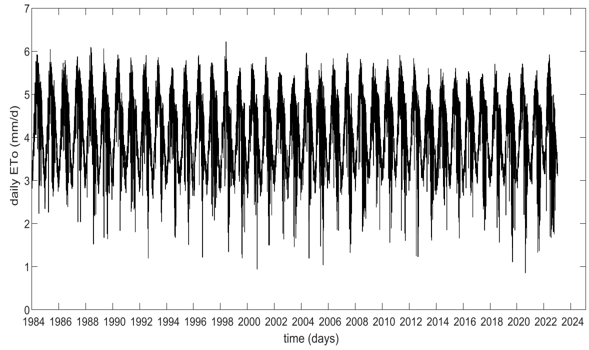

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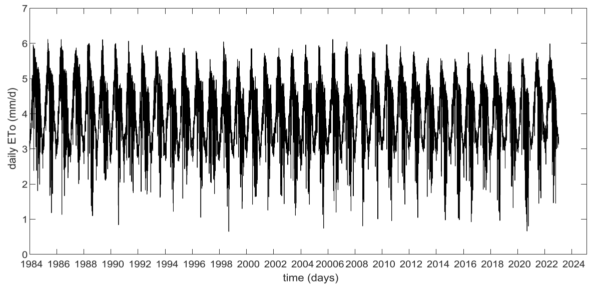
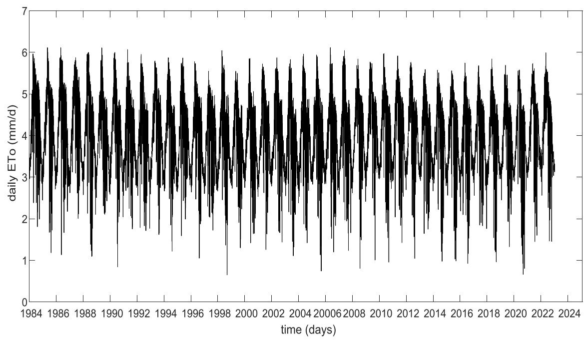


(o) Birnin Kebbi

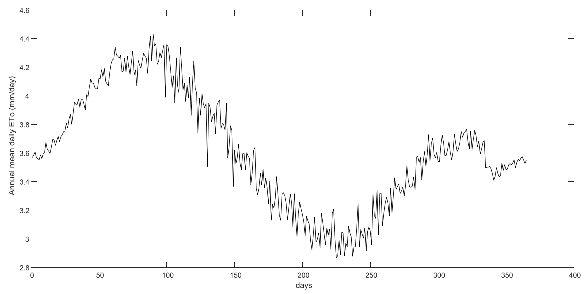


(p) Kano

Figure 1: Plots of daily reference evapotranspiration from 1984-2022

The above plots of the daily ETo against daily time series in the 16 states from 1984 to 2022 portrayed a random irregular and non-periodic shape due to seasonal variation as seen in all the 16 states. These irregular shapes showed a degree of chaotic behavior, which indicates that the reference evapotranspiration throughout the period in each state cannot be predicted because seasonality plays a great role in determining the pattern of reference evapotranspiration. From the plot, during rainy season, there is a high rate of evapotranspiration due to high level of water in the soil. Whereas during dry season, there rate of evapotranspiration reduces due to low level of water in the soil which may be due to the high temperature which is mostly prevalent during dry seasons. This chaotic behavior agrees with that of [7] and [10].

The above plot of annual mean variation time series of reference evapotranspiration in each of the 16 states was computation from the mean of each year daily reference evapotranspiration for the period of 38 years. This computation resulted in a single annual reference evapotranspiration. The plot of annual reference evapotranspiration against the annual time series portrayed a random irregular and non-periodic shape due to seasonal variation as seen in all the 16 states. The annual daily reference peaking in April and November during the dry season was as a result of the availability of moisture and low atmospheric relative humidity while the daily reference evapotranspiration peaking in August and September during the rainy season was due high relative humidity and excess soil moisture due to heavy rainfall.



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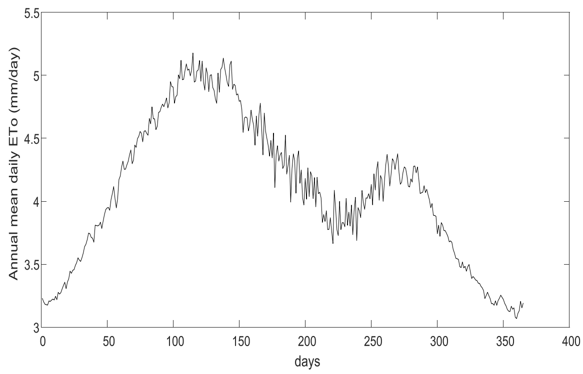

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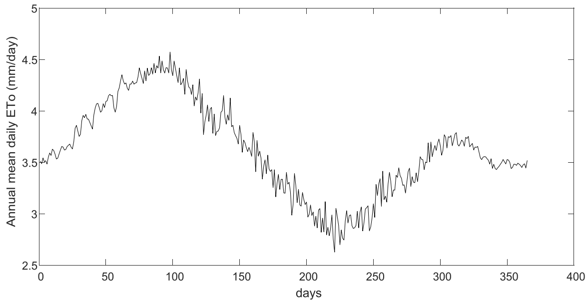
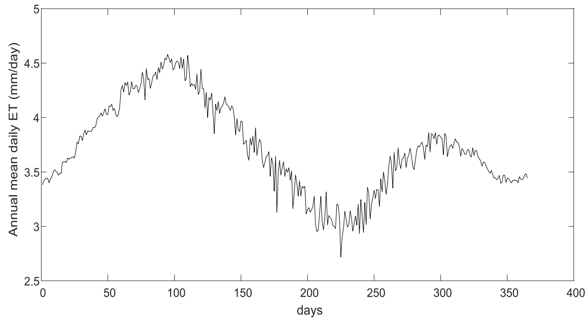


(c) Jos



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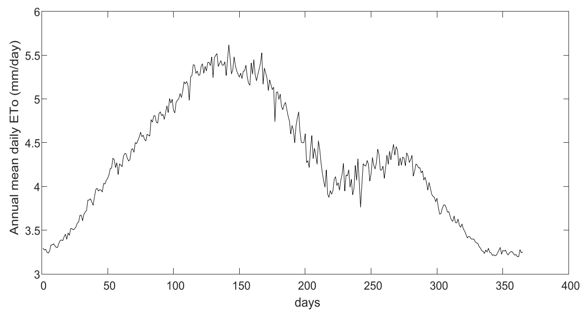

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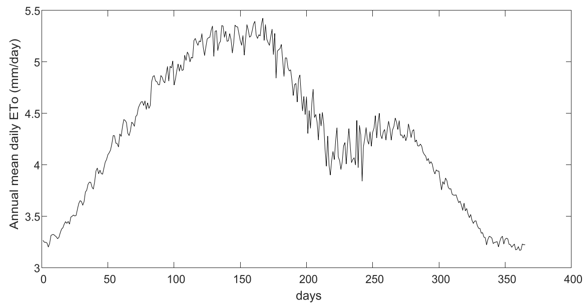

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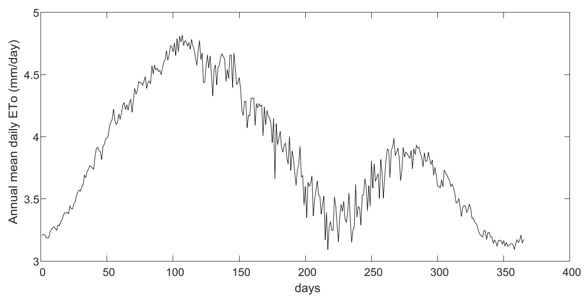

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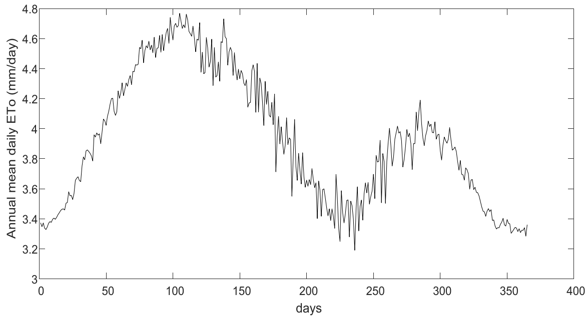

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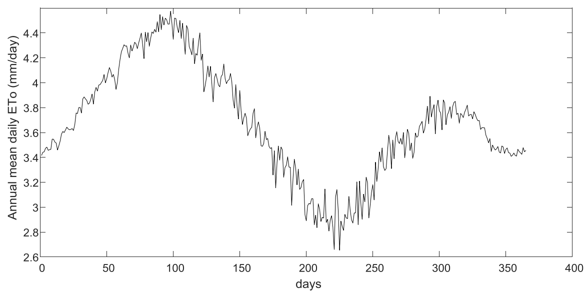

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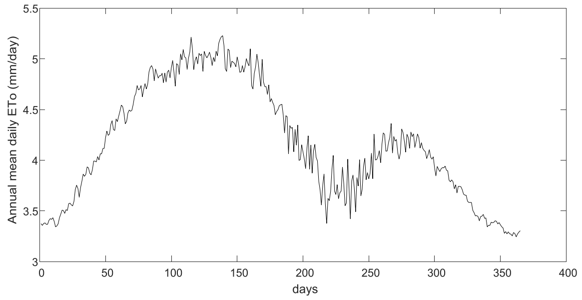

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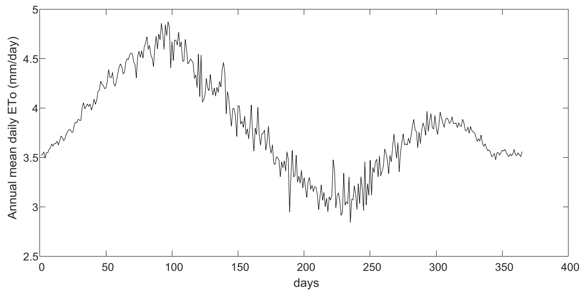

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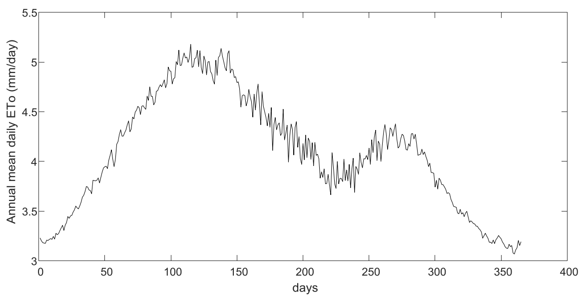

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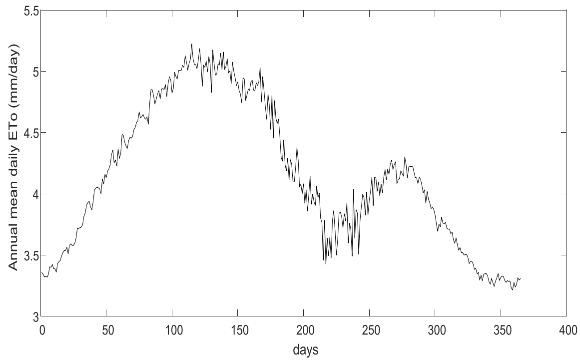

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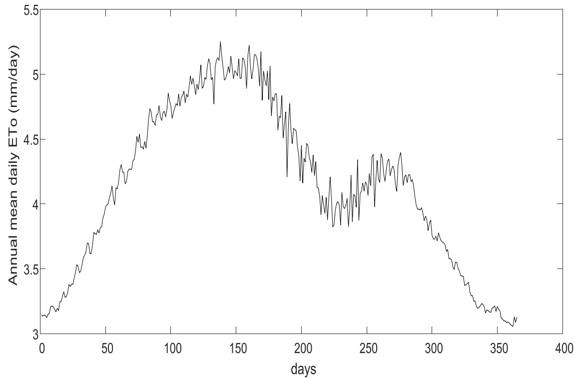

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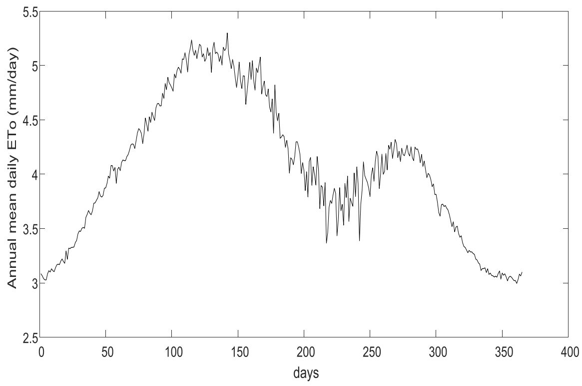

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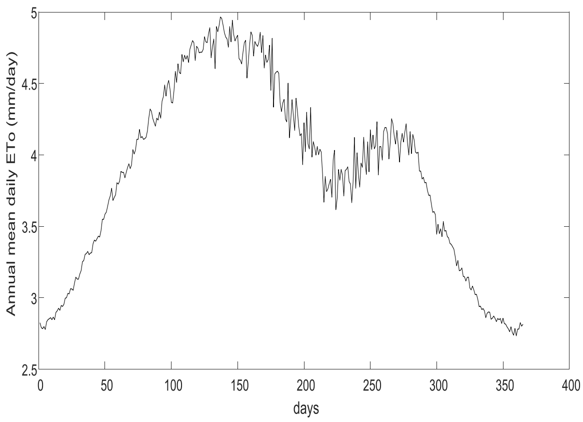

(p) Kano

Figure 2: Plot of annual mean variation time series of reference evapotranspiration from 1984-2022

Mean of reference evapotranspiration and latitudinal/longitudinal trend

The mean of reference evapotranspiration of each state was computed and then plotted against the latitudinal/longitudinal coordinates of each selected Northern state in Nigeria. From the plot, the regression analysis was done to calculate the coefficient of determination to examine the trend of the plot. The plot of mean reference evapotranspiration against the latitudinal/longitudinal trend is presented in Figs 3 and 4.

From the plot, the coefficient of determination of the mean of reference evapotranspiration against latitudinal trend was 0.6572, whereas the coefficient of determination of the mean of reference evapotranspiration against longitudinal trend was 0.000005. This result showed that the coefficient of determination of the mean of reference evapotranspiration against latitudinal trend has a strong relationship between them and can be used for predictive purpose to show the weather pattern as we migrate from south to north in the selected Northern states in Nigeria. Whereas the coefficient of determination of the mean of reference evapotranspiration against longitudinal trend has a very weak relationship and thus cannot be used for predictive purpose.

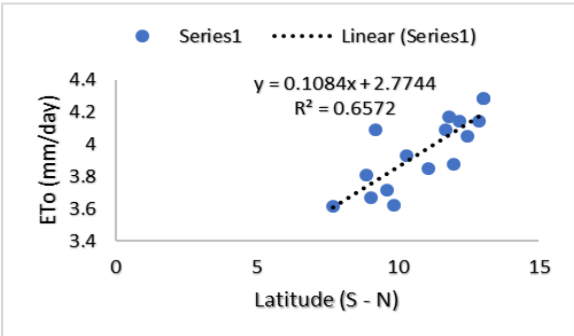

Figure 3: Mean reference evapotranspiration against latitudinal trend across 16 Northern states in Nigeria

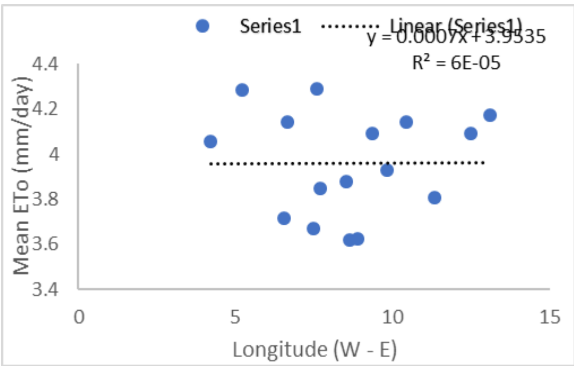

Figure 4: Mean reference evapotranspiration against longitudinal trend across Northern Nigeria

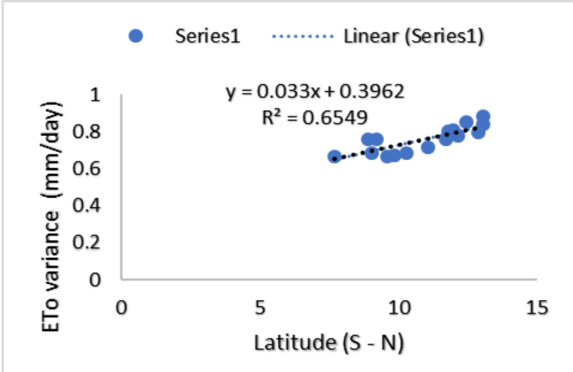

Figure 5: Variance reference evapotranspiration against latitudinal trend across 16 Northern states in Nigeria

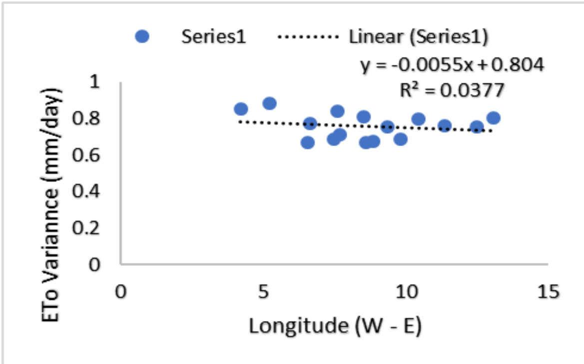

Figure 6: variance reference evapotranspiration against longitudinal trend across 16 Northern states in Nigeria

Variance of reference evapotranspiration and latitudinal/longitudinal trend

The variance of reference evapotranspiration of each state was computed and then plotted against the latitudinal/ longitudinal coordinates of each selected Northern state in Nigeria. From the plot, the regression analysis was done to calculate the coefficient of determination to examine the trend of the plot. The plot of mean of reference evapotranspiration against the latitudinal/ longitudinal trend is presented in Figs 5 and 6.

From the plot, the coefficient of determination of the variance of reference evapotranspiration against latitudinal trend was 0.6549, whereas the coefficient of determination of the variance of reference evapotranspiration against longitudinal trend was 0.0377. This result showed that the coefficient of determination of the variance of reference evapotranspiration against latitudinal trend has a strong relationship between them and can be used for predictive purpose to show the weather pattern as we migrate from south to north in the selected Northern states in Nigeria. Whereas, the coefficient of determination of the variance of reference evapotranspiration against longitudinal trend has a very weak relationship and thus cannot be used for predictive purpose.

Spatial distribution of reference evapotranspiration

The spatial distribution of reference evapotranspiration presented in Fig. 7 showed the range of mean reference evapotranspiration across the 16 states in Nigeria.

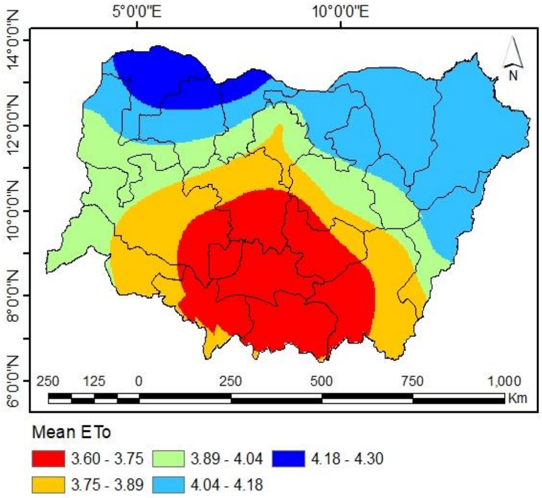

Fig. 7: Spatial distribution of mean ETo across Northern Nigeria

From the distribution, the lowest mean reference evapotranspiration is location within FCT-Abuja and Jos. The increment in the mean evapotranspiration moves from south to north across the 16 Northern states in Nigeria. The peak of mean reference evapotranspiration lies within Sokoto, Kebbi and Gusau, and these states are part of the Sahel region which is gradually approaching desertification.

Conclusion

Based on the findings from the study, it is concluded that estimating the reference evapotranspiration using Penman-Monteith method and time series method in sixteen locations across northern Nigeria is unstable and chaotic. This finding was based on the random motion of the mean reference evapotranspiration across each of the 16 Northern states in Nigeria. The regression analyses showed that the coefficient of determination strongly agrees the latitudinal trend which shows an upward increment of reference evapotranspiration that is greater than 0.6. As a result of this, the weather pattern can be predicted from south to north latitudinal trend. This result is also collaborated using spatial distribution map of mean reference evapotranspiration of the 16 states in Northern Nigeria.

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