Asian Journal of Advances in Research

Volume 7, Issue 1, Page 524-556, 2024; Article no.AJOAIR.2874

Interconnection of Climate Parameters and Reference Evapotranspiration over Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://prh.mbimph.com/review-history/2874

Original Research Article

Received: 09/10/2023
Accepted: 13/12/2023
Published: 14/10/2024

ABSTRACT

This study investigated temporal variations in reference evapotranspiration (ETo) and its interconnection with climate parameters across four climatic regions in Nigeria over a 42-year period (1979-2021). The ETo datasets were collected from the Archive of ECMWF-ERA-5 at a resolution of 0.25° by 0.25° grid system over Nigeria. The interconnection analyses between ETo and climate parameters (air temperature, relative humidity, wind speed and net radiation) were conducted using the cross-correlation test, Mann-Kendall tests, and four homogeneity tests at a 5% significance level. The results demonstrated strong correlations between ETo and relative humidity (RH) in the Sahel, Guinea Savannah, and Coastal regions, with R^2 values of 0.7343, 0.8418, and 0.7662, respectively. Trend analysis using the Mann-Kendall test indicated significant increasing trends in ETo for the Sahel, Guinea Savannah, and Rainforest regions, while the Coastal region exhibited a significant decreasing trend. Change point analyses using the four homogeneity tests revealed that ETo experienced significant changes primarily in 1999 in the Sahel and Guinea Savannah regions, 1996 in the Rainforest region, and 2006 in the Coastal region. In conclusion,

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Cite as: *Ogolo, E. O., O. S. Ojo, and M. Idahosa. 2024. "Interconnection of Climate Parameters and Reference Evapotranspiration over Nigeria". Asian Journal of Advances in Research 7 (1):524-56. https://jasianresearch.com/index.php/AJOAIR/article/view/482.*

relative humidity emerged as the most sensitive parameter to ETo, with immediate response time lags observed in the Sahel and Guinea Savannah regions, and a one-month response time lag in the Rainforest and Coastal regions of Nigeria.

Keywords: Reference evapotranspiration; interconnection; climate change; homogeneity; mann-kendall; Nigeria.

1. INTRODUCTION

According to several studies [1,2,3,4,5,6], evapotranspiration—the process of combining evaporation and transpiration—is an essential component of the hydrological cycle and regulates the movement of moisture from the Earth's surface to the atmosphere. After precipitation, it is the second-most crucial hydrologic factor. Reference evapotranspiration (ETo) is a measurement of the rate of evapotranspiration from a reference crop under ideal conditions, with certain parameters assumed [3]. Understanding water availability and irrigation needs in agricultural systems requires evaluating ETo. There are many ways to calculate ETo, including using lysimeters and empirical equations, but the FAO Penman-Monteith method is strongly recommended as the preferred method due to its accuracy. However, there is limited research focusing on the climatic regions of Nigeria and the correlation of ETo with meteorological variables in this area.

The effects of global climate change and human activity on hydrological processes have been highlighted in earlier studies [7,8,9,10]. These elements have affected evapotranspiration rates, increased the frequency of floods and droughts, and changed precipitation patterns [11]. Depending on climatic conditions and regional factors, there are different relationships between ETo and meteorological parameters like atmospheric temperature, vapor pressure, precipitation, and wind speed [12]. Emeka et al. [13] conducted research in Nigeria to examine how FAO Penman-Monteith reference evapotranspiration (ETo) changed in response to climatic variables under various climate types. According to the study, the maximum temperature is the factor that affects ETo the most in Maiduguri, Sokoto, Kaduna, and Jos. ETo is most sensitive to relative humidity in Port Harcourt, whereas it is most sensitive to variations in solar radiation in Enugu and Ibadan. Zhang et al. [14] looked into the effects of climate change on reference evapotranspiration, aridity index, and their temporal-spatial variations in the Yellow River Basin (YRB), China, from 1961 to 2012. The researchers found that the spatial change trends of the aridity index were widespread across the YRB and were consistent with the declining trend of reference evapotranspiration. Huo et al. [15] also looked into how climate change in China's arid region affected the aridity index (AI) and reference evapotranspiration (ETo). The study found that the annual temperature, humidity, and precipitation all exhibited rising trends over time. Radiation and wind speed both showed a downward trend. ETo and AI showed decreasing trend due to the significant decreasing trend of wind speed over 50 years than other meteorological variables leading to the alleviation of climatic drought. There are no, however, a lot of studies that are specifically concerned with the climates of Nigeria. For the region's agricultural planning and sustainable management of water resources, it is essential to comprehend ETo dynamics in Nigeria and its response to climate change.

By providing a thorough analysis of reference evapotranspiration and its correlation with meteorological variables in Nigeria's climatic regions, this study seeks to close the knowledge gap. The specific goals include calculating ETo using the FAO-PM 56 equation, looking at the relationship between ETo and meteorological variables, and looking into the seasonal and inter-annual trends of ETo. By focusing on these goals, the study will advance knowledge of the hydrological dynamics and potential effects of climate change on Nigeria's evapotranspiration patterns. The information will be useful for the region's strategies for managing water resources, planning agriculture, and adapting to climate change.

2. METHODOLOGY

2.1 Study Area

Located on the western coast of Africa between latitudes 4° and 14° N and longitudes 2° to 14° E, Nigeria has a land area of 923,769 km2, as shown in Fig. 1. According to Ojo [16] the four main climatic regions of Nigeria are the Sahel, Guinea Savannah, Rainforest, and Coastal Regions. Eludoyin et al. [17] found that three

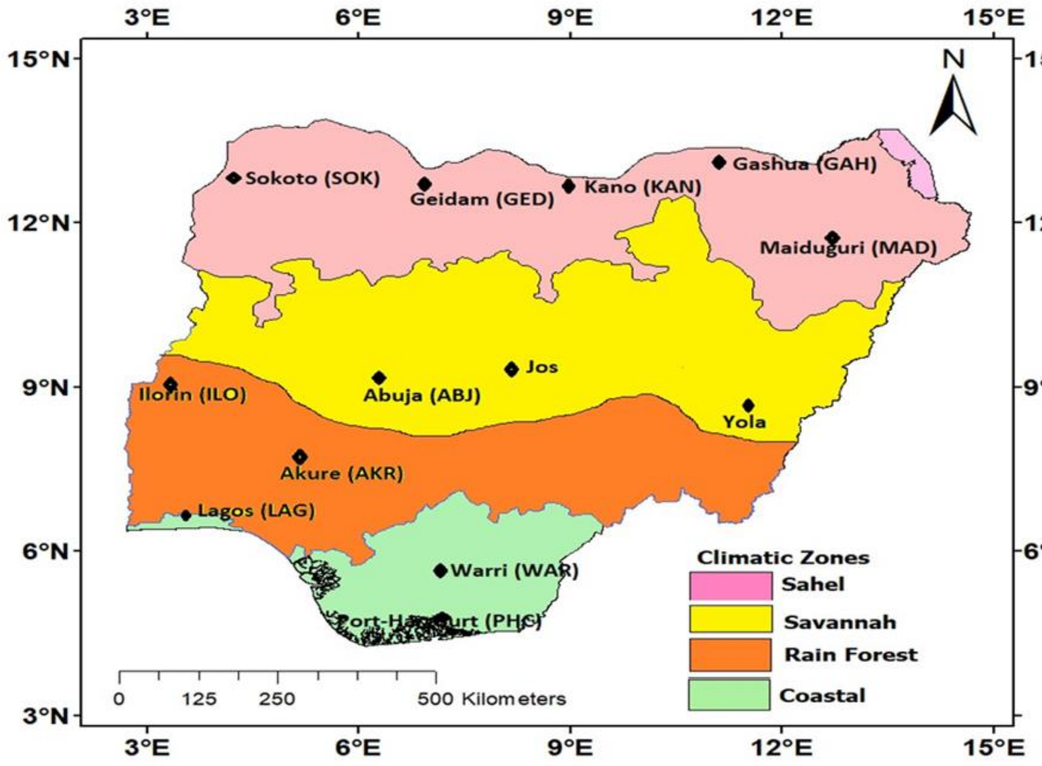


Fig. 1. Map of Nigeria showing 4 climatic regions and some selected stations [16]

atmospheric air masses—the maritime tropical (mT), continental tropical (cT), and equatorial easterlies—have an effect on Nigeria's climate. The mT and cT air masses come from the Atlantic Ocean and the Sahara Desert, respectively. The pattern and timing of rainfall are controlled by the inter-tropical discontinuity (ITD), which is where the two air masses converge [18].

Nigeria, there are two distinct seasons: wet and dry. With an average annual rainfall of 1,200–3,000 mm, the south typically experiences 8–10 months of rain, compared to the north's 2-4 months of rain and 400–1,100 mm annual average [19,20,21].

The close proximity of the Sahara Desert in the north and the Atlantic Ocean in the south is what causes the significant variation in rainfall. The south typically experiences bimodal rainfall peaks in June and September, as opposed to the north, which has a single peak in August. In the rainy season, temperatures range between 25 and 30^{o}C, while in the dry season, they are between 20 and 30^{o}C [18].

2.2 Data Acquisition and Analysis

The European Centre for Medium-Range Weather Forecasts Reanalysis version 5 database (ERA 5) archive was used in this study to obtain daily data on temperature (^{o}C), wind speed (m/s), relative humidity (%), and solar radiation (MJ/m^2 day). The data were processed into monthly and annual averages over Nigeria for the four (4) climatic regions of the Sahel, Guinea, Rainforest, and Coastal Regions over a 42-year period (1979-2021). In order to calculate ETo, FAO recommended and revised the Penman-Monteith model in 1998 [3]. It can be expressed as:

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma\frac{900}{T+273}[e_s - e_a]u_2}{\Delta + \gamma \times (1 + 0.34 \times u_2)} \quad (1)$$

where ET_o is reference evapotranspiration (mm/d); Rn is the net radiation at the crop surface (MJ/m^{2}d); G is the soil heat flux density (MJ/m^{2}d), T is the air temperature at 2m height(^{o}C), U_2 is the wind speed at 2 m height (m/s), e_s is the vapor pressure of the air at saturation (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the vapor pressure curve (kPa/C) and γ is the psychometric constant (kPa/C).

The trend in ETo was examined using the Mann-Kendall test (M-K test). The Mann-Kendall test (M-K test), also known as the Kendall's tau test, is a rank-based non-parametric test for determining the significance of a trend as a result of Mann [22] and Kendall [23]. It has been extensively used in studies that analyze climate change and hydrological trend detection [11,10,24]. The M-K test is an easy-to-use and trustworthy method for handling missing values and values that are below a detection threshold. According to Tabari et al. [19,20,21], the test is also appropriate for data that do not follow a normal distribution. The statistic S of Kendall's tau test is defined as follows:

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} sgn(x_i - x_j) \quad (2)$$

where x_i is the data value at time i, x_j is the data value at time t_j, n is the length of the data set and sign () is the sign function which can be computed as:

$$sgn\,(x_i - x_j) = \begin{cases} 1 & if (x_i - x_j) > 0 \\ 0 & if (x_i - x_j) = 0 \\ -1 & if\,(x_i - x_j) < 0 \end{cases} \quad (3)$$

The statistic S is normally distributed when n> 10. The variance (Var) of S is given by:

$$Var(S) = \frac{[n(n-1)(2n+5)] - \sum_{m-1}^{n} t_m (m-1)(2m+5)}{18} \quad (4)$$

where t_m represents the number of ties of extent m. The standardized test Z_c is calculated by:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\,S > 0 \\ 0 & if\,S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\,S < 0 \end{cases} \quad (5)$$

Zc values that are positive or negative represent an increasing or decreasing trend, respectively. When it is zero, no change in trend has been noticed.

Also**,** the point of change in time series is detected using homogeneity tests which include the Pettitt test (K), standard normal homogeneity test (T_o), Buishand test (Q) and Von Neumann ratio test (N). The Pettitt test, as proposed by Pettitt [25], is a nonparametric test that enables the identification of the point at which any significant shift occurred in time series. This method finds a significant change in a time series' mean even when the change's precise timing is unknown. In order to determine whether the two samples $x_1, \dots, x_t$ and $x_{t+1}, \dots, x_N$ are drawn from the same population, the test uses the Mann-Whitney statistic $U_{t,N}$ [11, 26]. The test statistic $U_{t,N}$ is given as:

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^{N} sgn(x_t - x_j)\; for\; t = 2, \dots, N \quad (6)$$

$$\begin{matrix} if\,(x_t - x_j) > 0 & sgn(x_t - x_j) = 1 \\ if\,(x_t - x_j) = 0 & sgn(x_t - x_j) = 0 \\ if\,(x_t - x_j) < 0 & sgn(x_t - x_j) = -1 \end{matrix} \quad (7)$$

The test statistic measures how often more first sample participants than second sample participants. In Pettitt's test, the null hypothesis is the absence of a changing point. The following are its statistic K(t) and the associated probabilities for significance testing:

$$K(t) = Max_{1 \le t \ge N} |U_{t,N}| \quad (8)$$

$$p \cong 2\; exp\left\{\frac{-6(K_N)^2}{(N^3 + N^2)}\right\} \quad (9)$$

The Standard Normal Homogeneity Test was proposed by Alexandersson [27]. The null hypothesis is same as the Pettitt test. T(k) is computed as

$$T(k) = k\overline{Z_1}^2 + (n-k)\overline{Z_2}^2, \quad k = 1,2, \dots, N \quad (10)$$

where

$$\overline{Z_1} = \frac{1}{k} \frac{\sum_{i=1}^{k} (Y_i - \bar{Y})}{s}$$

and $\overline{Z_2} = \frac{1}{n-k} \frac{\sum_{i=k+1}^{n} (Y_i - \bar{Y})}{s}$ (11)

If the break is located at the point k, T(k) reaches its maximum value at k=K. it's test statistics T_o is defined as

$$T_o = \max(T(k))\; for\; 1 \le k < n \quad (12)$$

If T_o exceeds the test statistics value, the null hypothesis is rejected

The Buishand test assumes that the data are distributed independently and randomly, which is consistent with the H0 hypothesis. This test, which is conducted by Wijngaard et al. [28], is sensitive to time series breaks in the middle and it is given by:

$$S_o^* = 0;\; S_k^* = \sum_{i=1}^{k} (X_i - \bar{X}), k = 1, 2, \dots, N \quad (13)$$

where: $\bar{X}$ is the mean of time series observations $(X_1, X_2, \dots, X_N)$

k is the number of the observation at which a break point has occurred.

Rescaled adjusted partial sums are obtained by dividing S_k^* by the sample standard deviation [29]:

$$S_K^{**} = \frac{S_k^*}{D_x},\ k = 1,2,\dots,N \quad (14)$$

$$D_x = \sqrt{\frac{\sum_{i=1}^{N}(X_i - \bar{X})^2}{N}} \quad (15)$$

Its statistics used to analyze homogeneity is expressed as follows:

$$Q = max_{0 \le k \le N}|S_k^{**}| \quad (16)$$

$Q/\sqrt{N}$ value is compared with the critical value [29]. If the calculated value is less than the critical value, the null hypothesis is accepted, otherwise it is rejected [30].

The Von Neumann ratio test (N), in accordance with Wijngaard et al. [28], does not identify a particular region where homogeneity is compromised and does not provide information regarding when homogeneity is compromised. The mean squared proportion of the variance in succession is described by N in this test [31]:

$$N = \frac{\sum_{i=1}^{n-1}(Y_i - Y_{i+1})^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \quad (17)$$

Critical values of this test are given in Wijngaard et al. [28]. If the calculated N value exceeds the critical N value, H0 hypothesis is considered homogeneous.

The coefficient of determination (R^2) was used as a statistical indicator, which is a measure of the utility of regression equation. It ranged between 0 and 1, with the highest value indicating less error useful for predictions and the lowest value indicating high error and is not useful for making prediction [32]. The magnitude of the relationship between variables by coefficient of determination was taken in this study as:

$$R^2 < 0.09 = Very\ Weak$$
$$0.09 < R^2 > 0.25 = Weak$$
$$0.25 < R^2 > 0.49 = Moderate$$
$$R^2 < 0.49 = Strong$$

The coeffiecient of determination (r) was used to give a descriptive measure of the strength of the linear relationship of the variables [33] Correlation values close to unity is desirable because they depict the good relationship between the variables and this maybe positive or negative implying that the variables have direct or inverse relationship.

In order to evaluate the sensitivity and responsiveness of the reference evapotranspiration and aridity index time-lagged relationships, the cross-correlation function was also used. According to Ojo et al. [32], responsiveness is measured by the CCF peak's lag, whereas sensitivity is determined by the CCF peak's cross-correlation strength. According to Boyd, the ratio of covariance to root-mean variance can be used to express how closely the time series Y and X are correlated:

$$\rho_{y,x} = \frac{\Upsilon_{y,x}}{\sqrt{\sigma_y^2 \sigma_x^2}} \quad (18)$$

where *ρ* is the cross-correlation function of the two time-series, *γ* is the covariance of the two time-series, σ is the standard deviation of time-series *Y* and *X*. The covariance between *Y* and *X* time-series is given by:

$$\Upsilon_{y,x} = \frac{1}{N}\sum_{i=0}^{N}(Y - X)(X - Y) \quad (19)$$

In this study, Y would stand for the climate parameters time-series and X would stand for the reference evapotranspiration time-series between 1979 and 2021. Cross-correlations are dimensionless, with values ranging from -1.0 to +1.0.

3. RESULTS AND DISCUSSION

3.1 Correlation of Meteorological Variables with Reference Evapotranspiration

The scattergrams presented in Figs. 2 – 5 (a-f) demonstrate the correlations between reference evapotranspiration (ET_o) and its six climate parameters in Nigeria's climatic regions. Amongst all the parameters: mean temperature (TN), maximum temperature (TX), minimum temperature (TM), relative humidity (RH), wind speed (U2), and net radiation (RN), the findings revealed that ET_o in the Sahel, Guinea, and Coastal regions was strongly influenced by relative humidity (RH), with R^2 values of 0.7343, 0.8418, and 0.7662, respectively. The negative slopes of the downward trend lines indicated an inverse relationship, that is, a decrease in relative humidity would lead to an increase in reference evapotranspiration, and vice versa. This correlation highlights the impact of the dry and hot atmospheric conditions prevalent in those regions, which result in increased water loss to the atmosphere. Conversely, a moister atmosphere leads to a lower rate of water loss. These findings align with previous studies and emphasize the importance of considering relative humidity when assessing evapotranspiration in those regions. Furthermore, in the Rainforest region, ET_o exhibits a strong positive correlation with net radiation (RN), with an R^2 value of 0.8400. This implies that an increase in net radiation contributes to higher evapotranspiration in this region. The implications of this correlation suggest that variations in net radiation, influenced by factors such as cloud cover and solar radiation, play a significant role in regulating evapotranspiration rates in the Rainforest region. The findings are valuable for understanding and managing water resources in different climatic zones within Nigeria.

3.2 Seasonal Variations of ET_o and Meteorological Variables

Figs. 6-9 (a-f) show the seasonal variations for ETo and meteorological variables in all regions. The Sahel region (Fig. 6) showed that reference evapotranspiration fell to minimum between April and September, which are transition months from the dry season to rainy months and from wet season to dry season. It rose from October to March, which are the dry season months. On the other hand, air temperature (TM, TN, and TX) followed the same pattern of increase in dry months and fall on the rainy months. The rate of evapotranspiration would therefore rise as air temperature rises, which demonstrates how a rise in temperature influences ETo by raising the air's ability to hold water vapor [3]. With r-value of 0.7752 though, it did have a strong correlation with wind speed. In the rainy and dry seasons, respectively, the relative humidity increased. At the beginning of the rainy (April) and dry (Oct) months, the net radiation (RN) experienced two peaks. The warm air rising in the atmosphere during these times may be the cause of this.

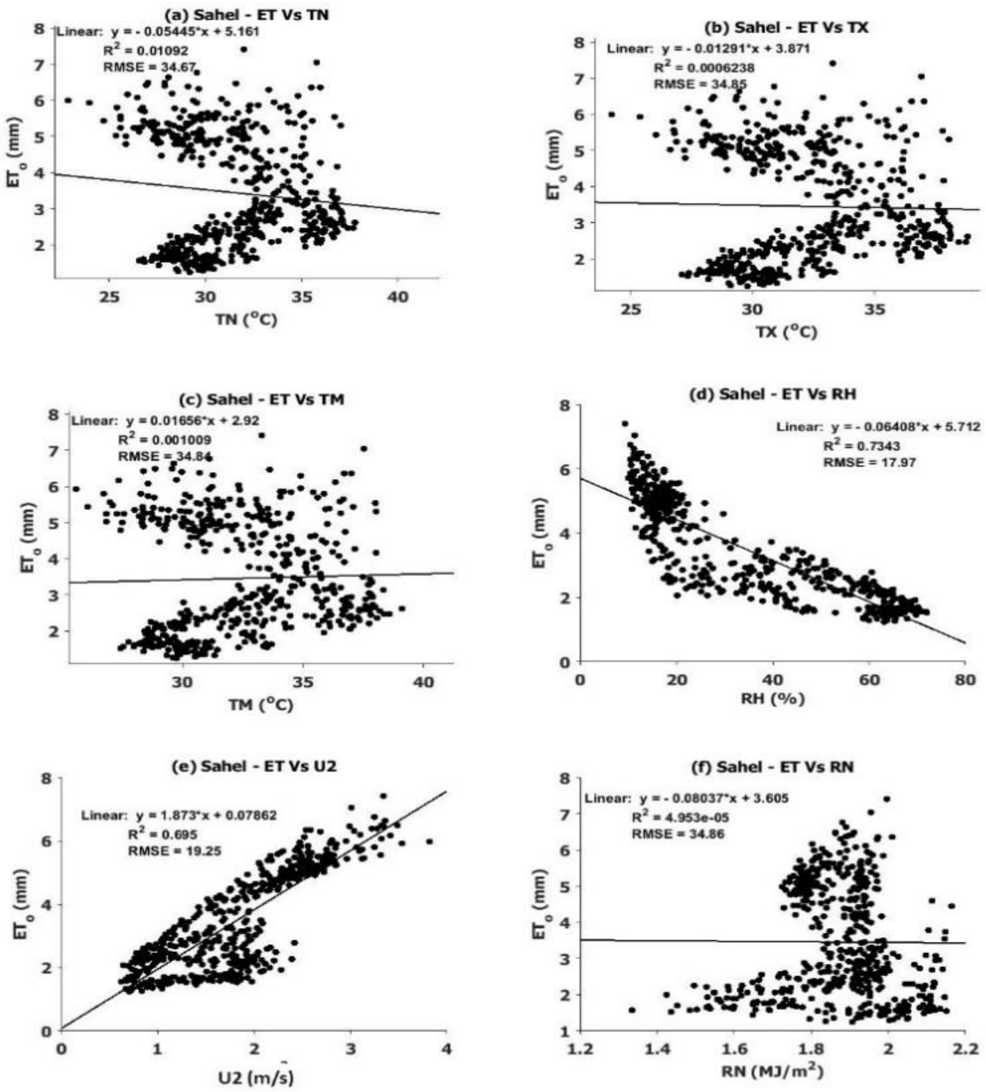


Fig. 2. Scattergrams of Correlation between reference evapotranspiration and its constituents climate parameters in the Sahel region

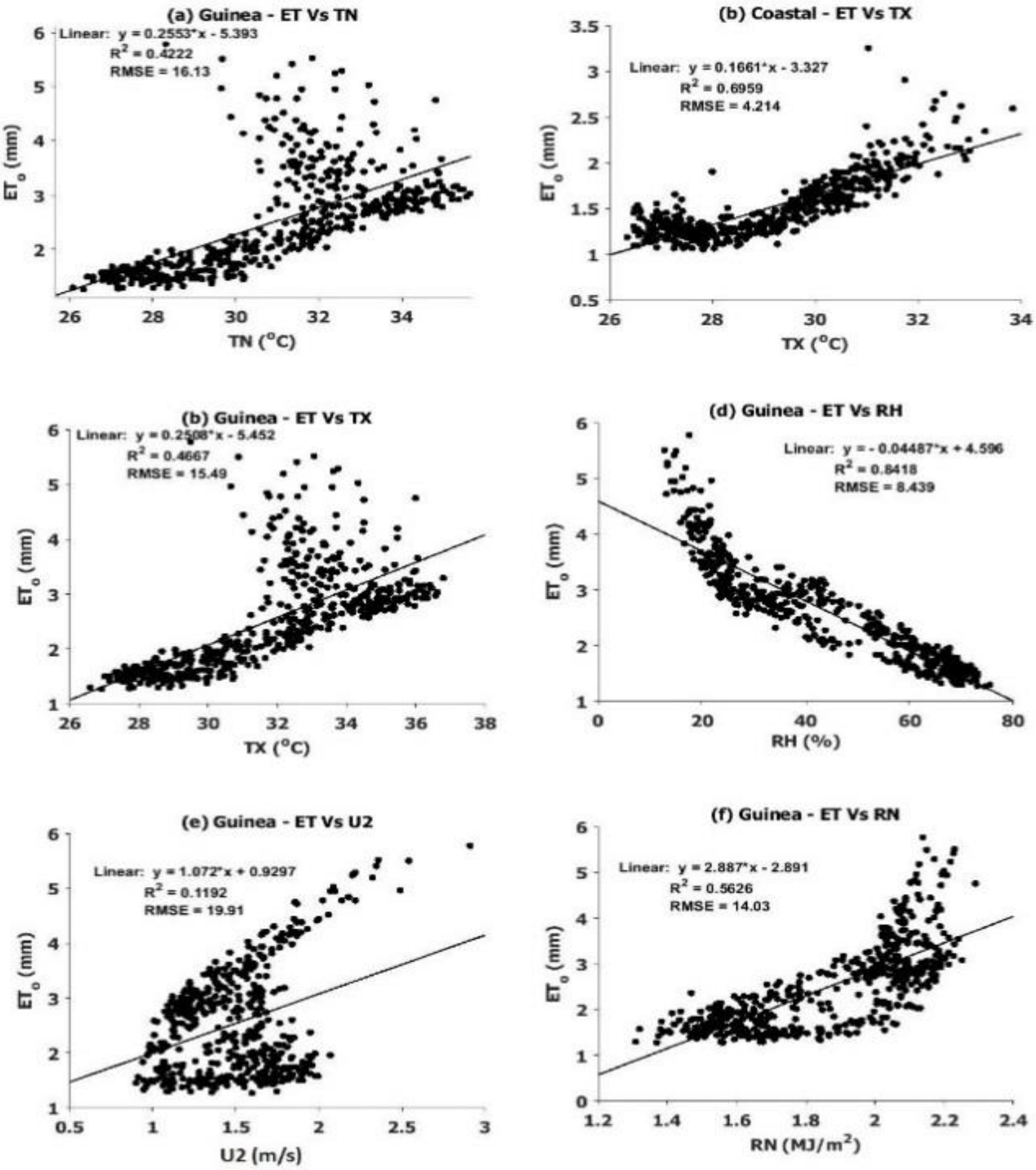


Fig. 3. Scattergrams of Correlation between reference evapotranspiration and its constituents climate parameters in the Guinea region

This was also true for the Guinea region (Fig. 7), which had strong correlation with RH as r = 0.95, implying that relative humidity affected the monthly variations of ET_o. In the Rainforest region (Fig. 8), reference evapotranspiration was on the increase between the months of March to October, which are the rainy months, with a rapid fall in the month of August (owing to the August break), its value was closely related with net radiation RN as r = 0.9922. The values of temperature and net radiation dropped during the rainy month and found to be rising in the dry months while relative humidity was on the rise by the rainy months and fell during the dry months as expected. This shows that the more humid the atmosphere, the average temperature condition and net radiation would be decreasing.

The reference evapotranspiration in the Coastal regions (Fig. 9) was found to fall during the rainy months (April to Oct) and was rising during the dry months with its peak at March, this pattern was found to be true for temperature and net radiation with stronger relation on maximum temperature as r = 0.8393. While wind speed U2 was observed to have two peaks at the rainy season; at the onset (April) and at the core rainy month (August) and then it dropped, while relative humidity was on the increase in the rainy months and fell in the dry months. Therefore, ET_o in Nigeria exhibits seasonal variations, with low values observed during the core rainy month of August due to the prevalence of rain-bearing clouds that diminish solar radiation reaching the Earth's surface [34, 35]. The reduced ET_o during

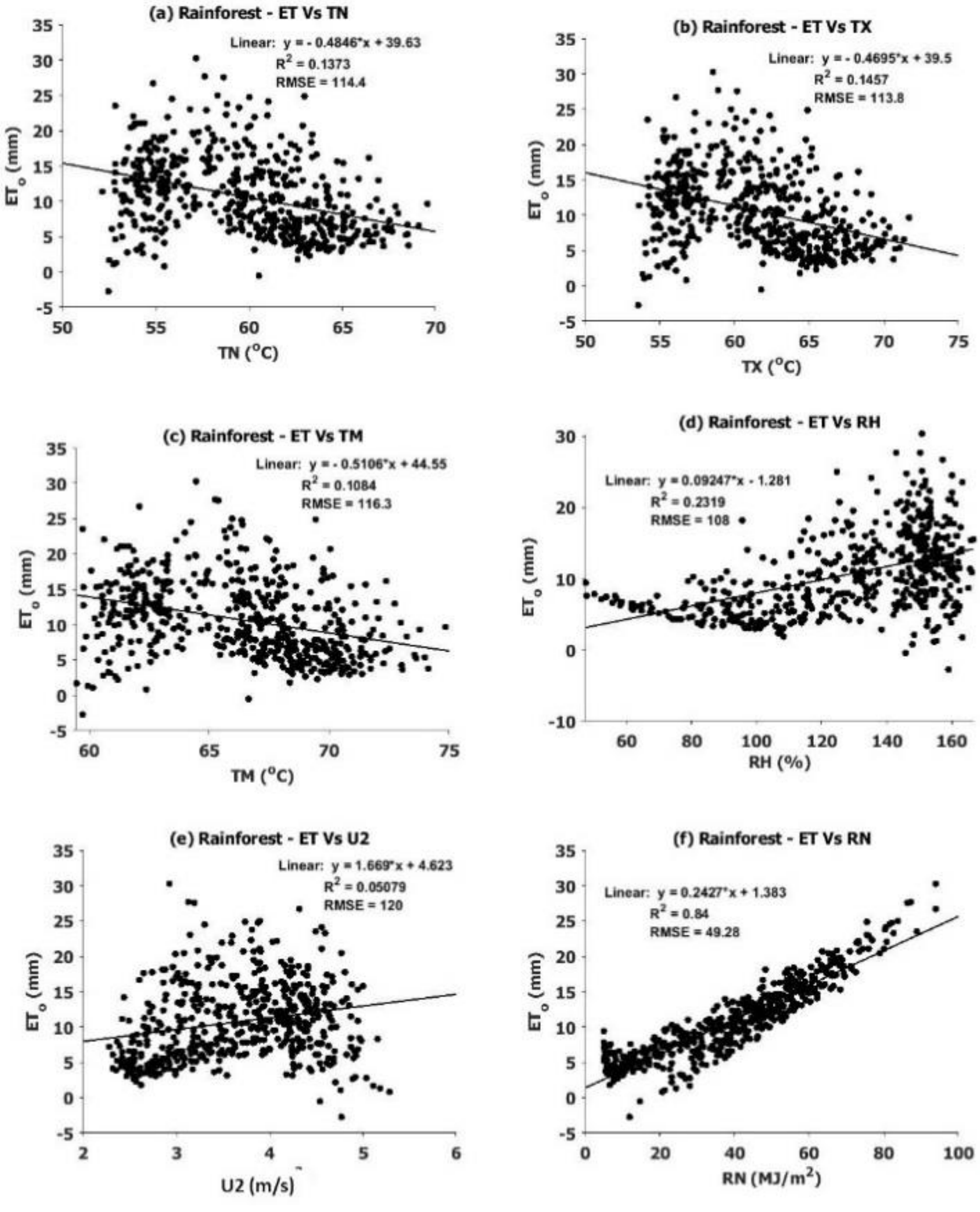


Fig. 4. Scattergrams of Correlation between reference evapotranspiration and its constituents climate parameters in the Rainforest region

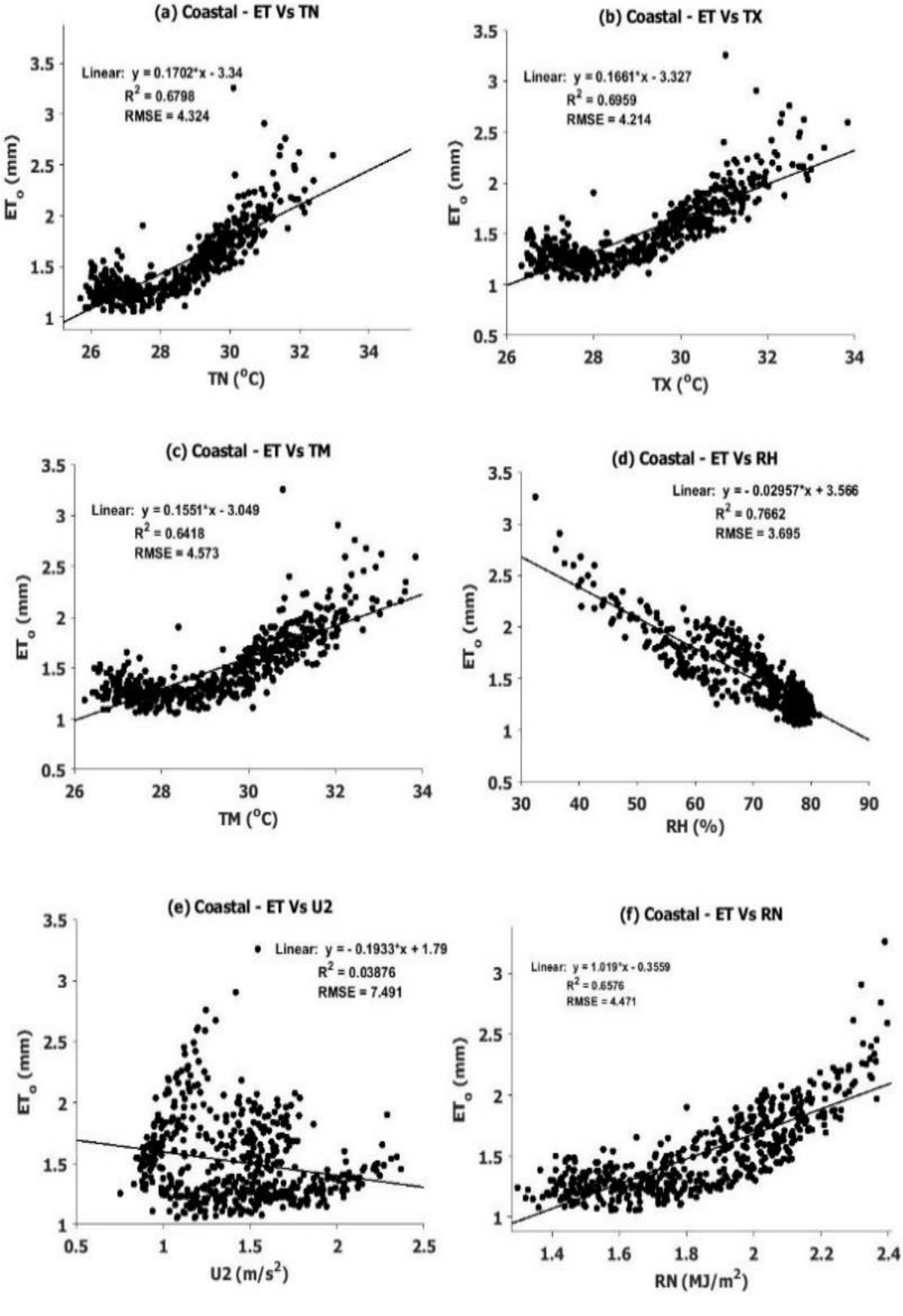
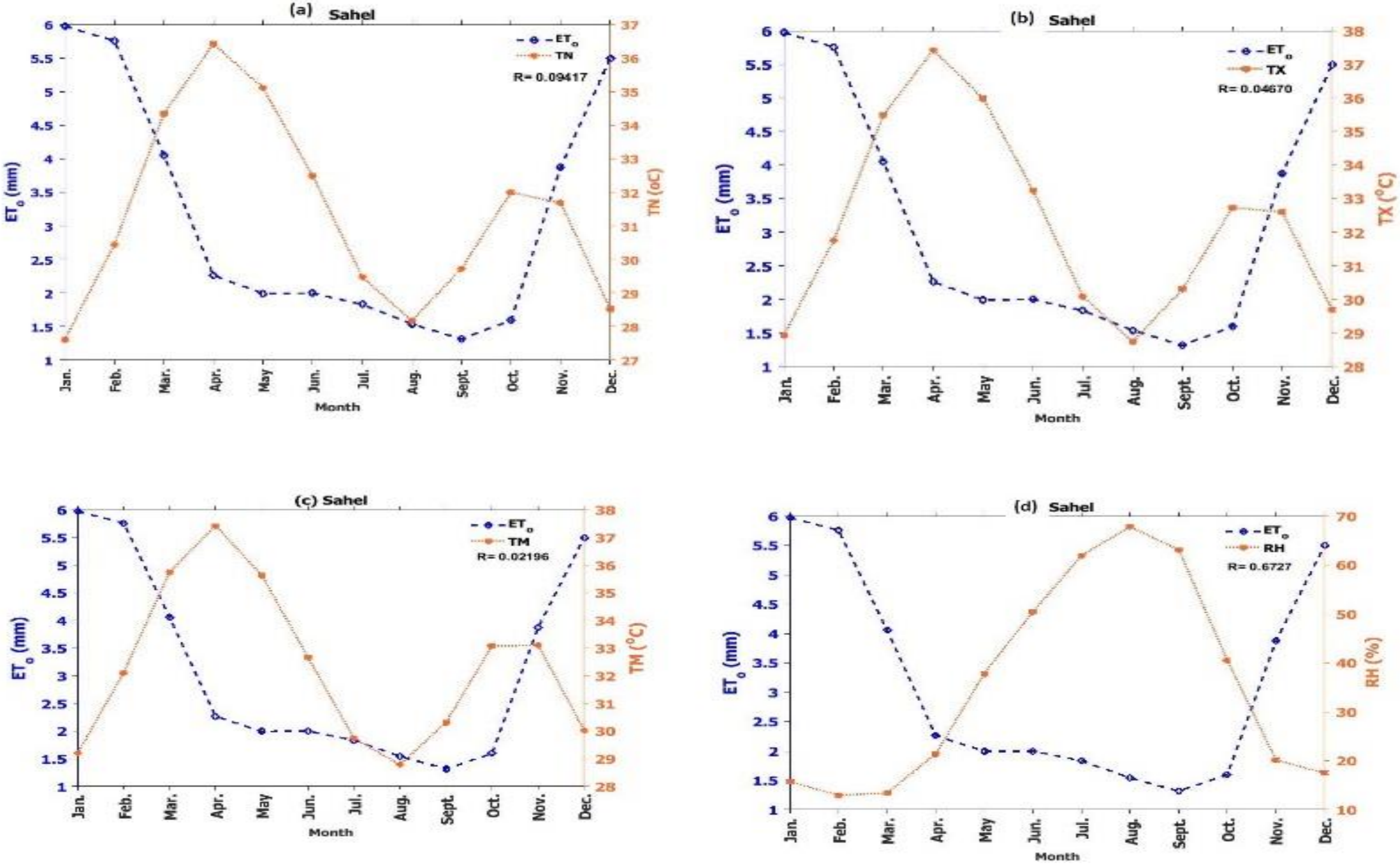


Fig. 5. Scattergrams of Correlation between reference evapotranspiration and its constituents climate parameters in the Coastal region


(a) Sahel
ET$_o$
TN
R= 0.09417
ET$_o$ (mm)
TN (oC)
Month
(b) Sahel
ET$_o$
TX
R= 0.04670
ET$_o$ (mm)
TX (°C)
Month
(c) Sahel
ET$_o$
TM
R= 0.02196
ET$_o$ (mm)
TM (°C)
Month
(d) Sahel
ET$_o$
RH
R= 0.6727
ET$_o$ (mm)
RH (%)
Month

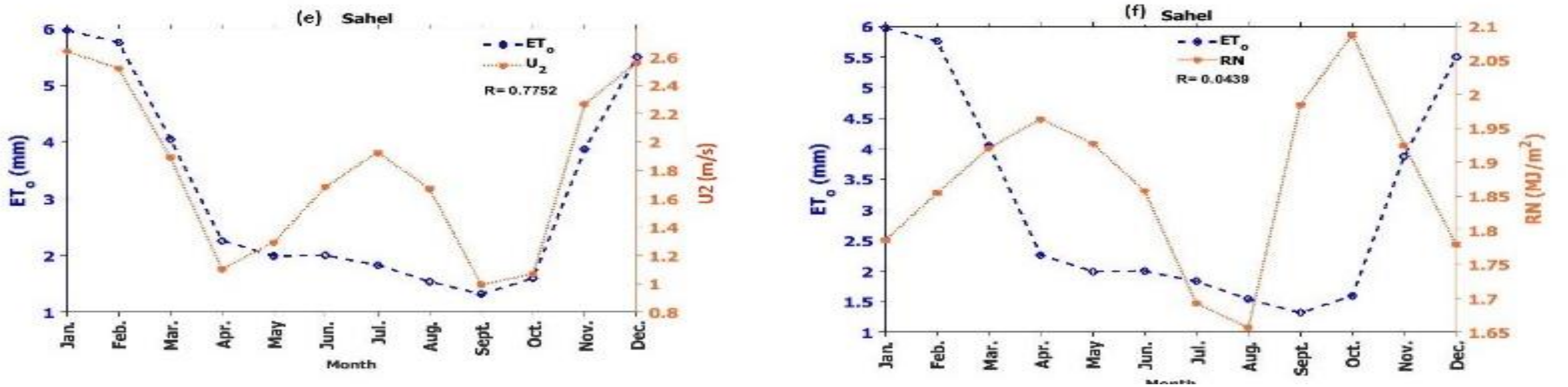
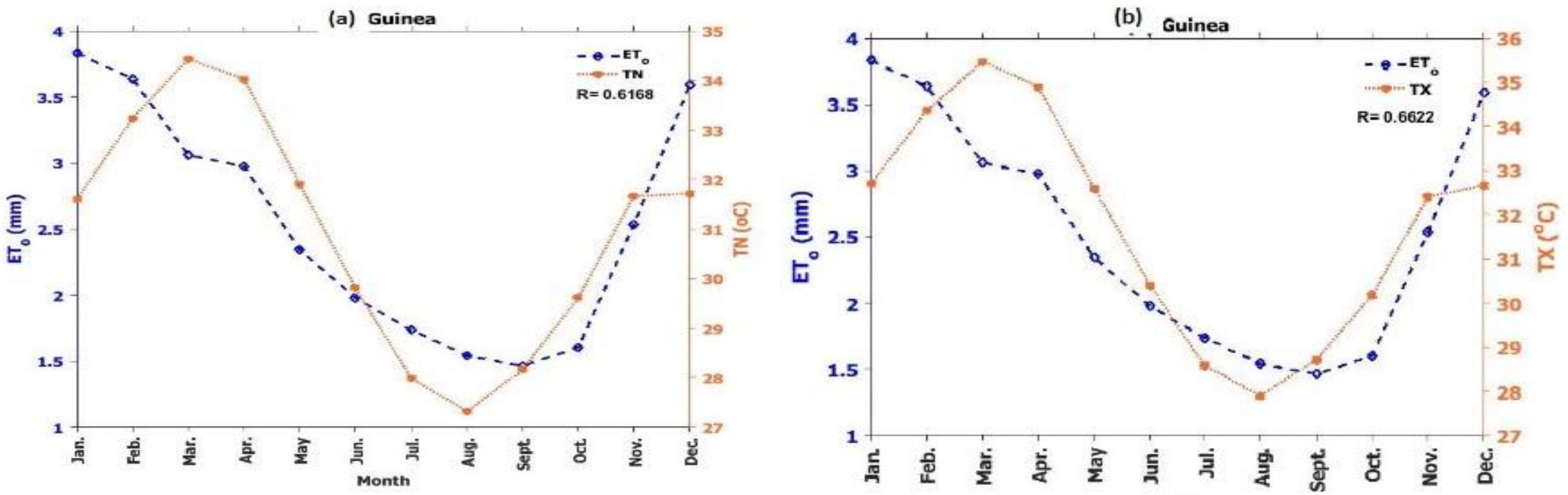


Fig. 6. Seasonal variation of reference transpiration and climate variables in the Sahel



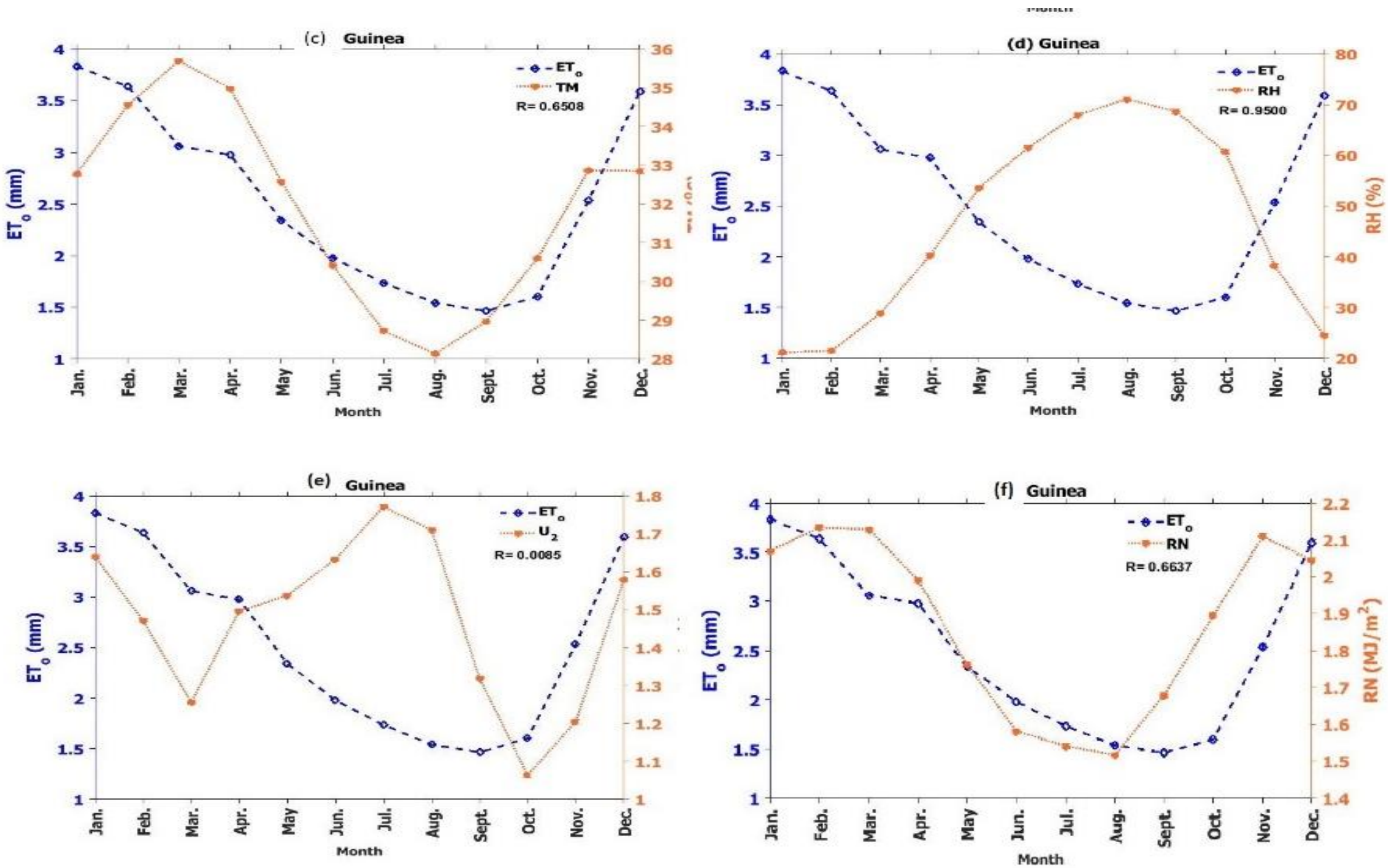
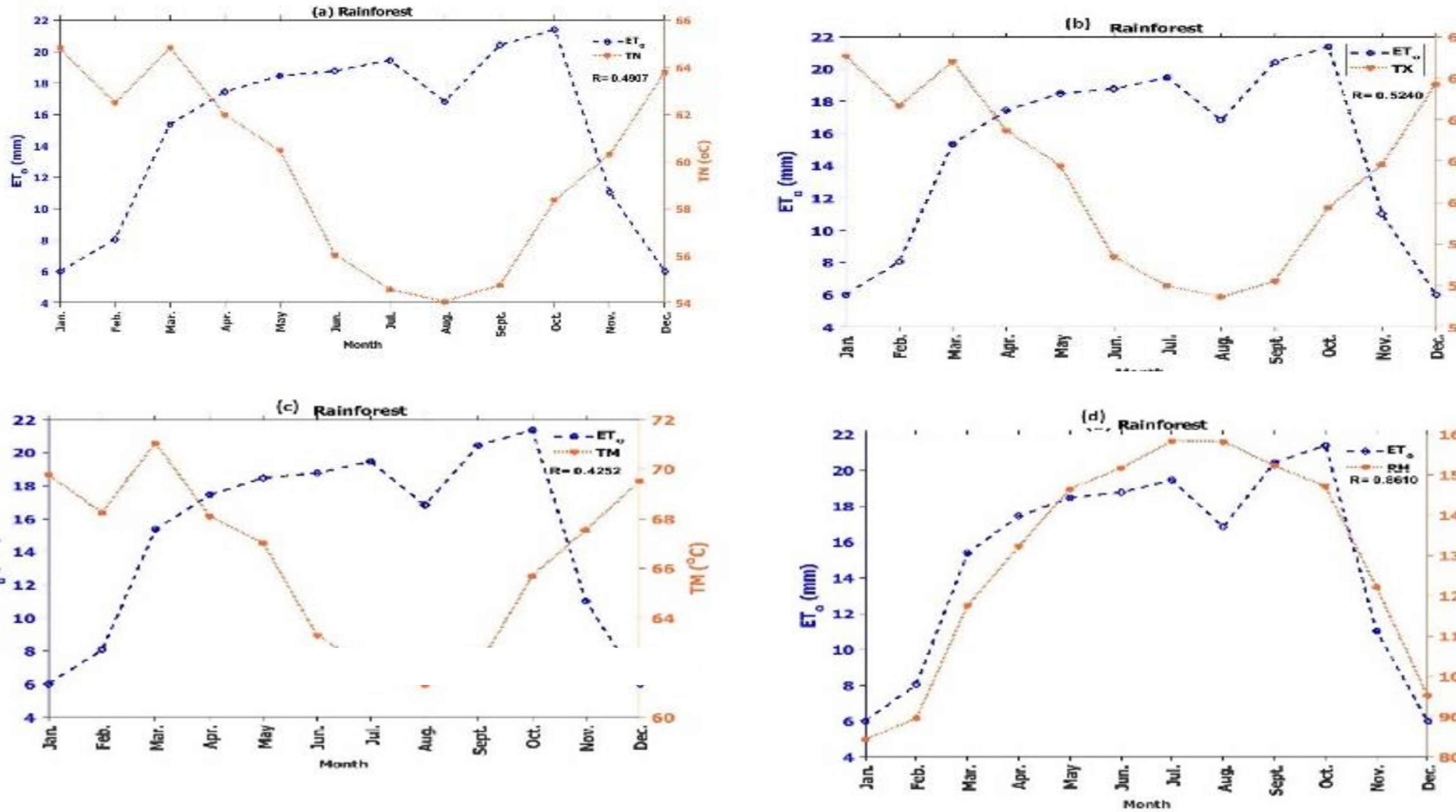


Fig. 7. Seasonal variation of reference transpiration and climate variables in the Guinea


(a) Rainforest
ETo (mm)
TN (oC)
R= 0.4907
Month
(b) Rainforest
TX (°C)
R= 0.5240
(c) Rainforest
TM (°C)
R= 0.4252
(d) Rainforest
RH (%)
R= 0.8610
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.

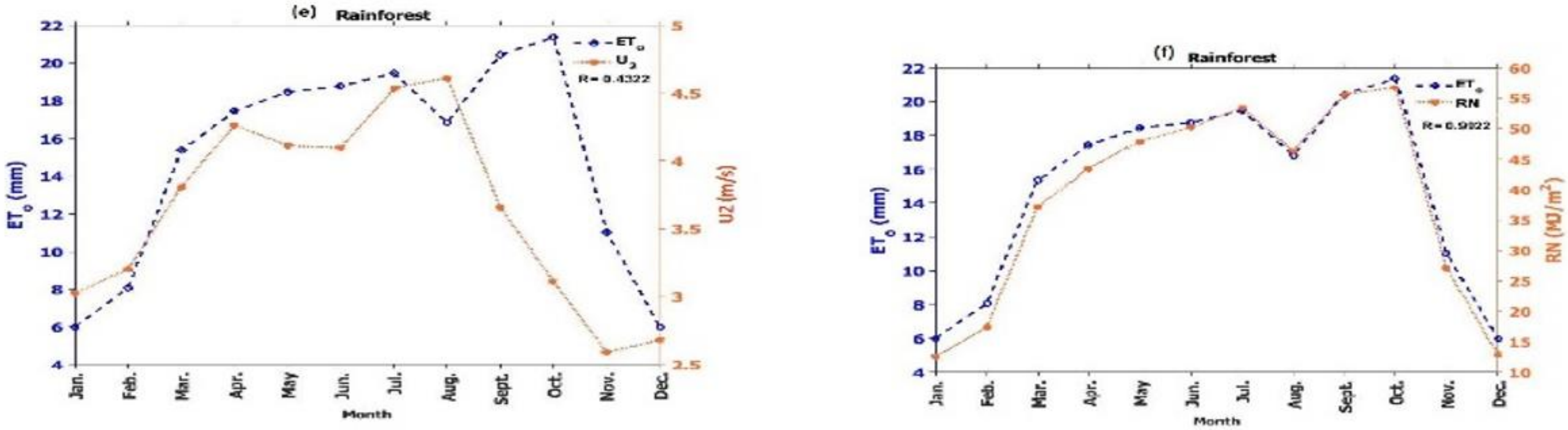
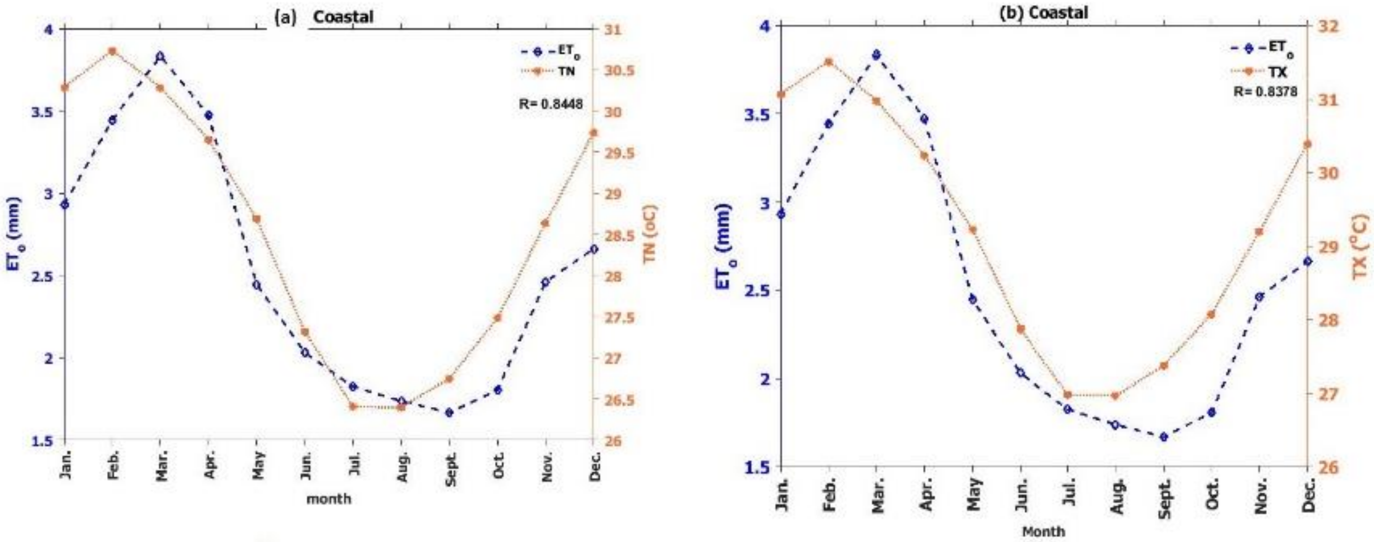


Fig. 8. Seasonal variation of reference transpiration and climate variables in the Rainforest



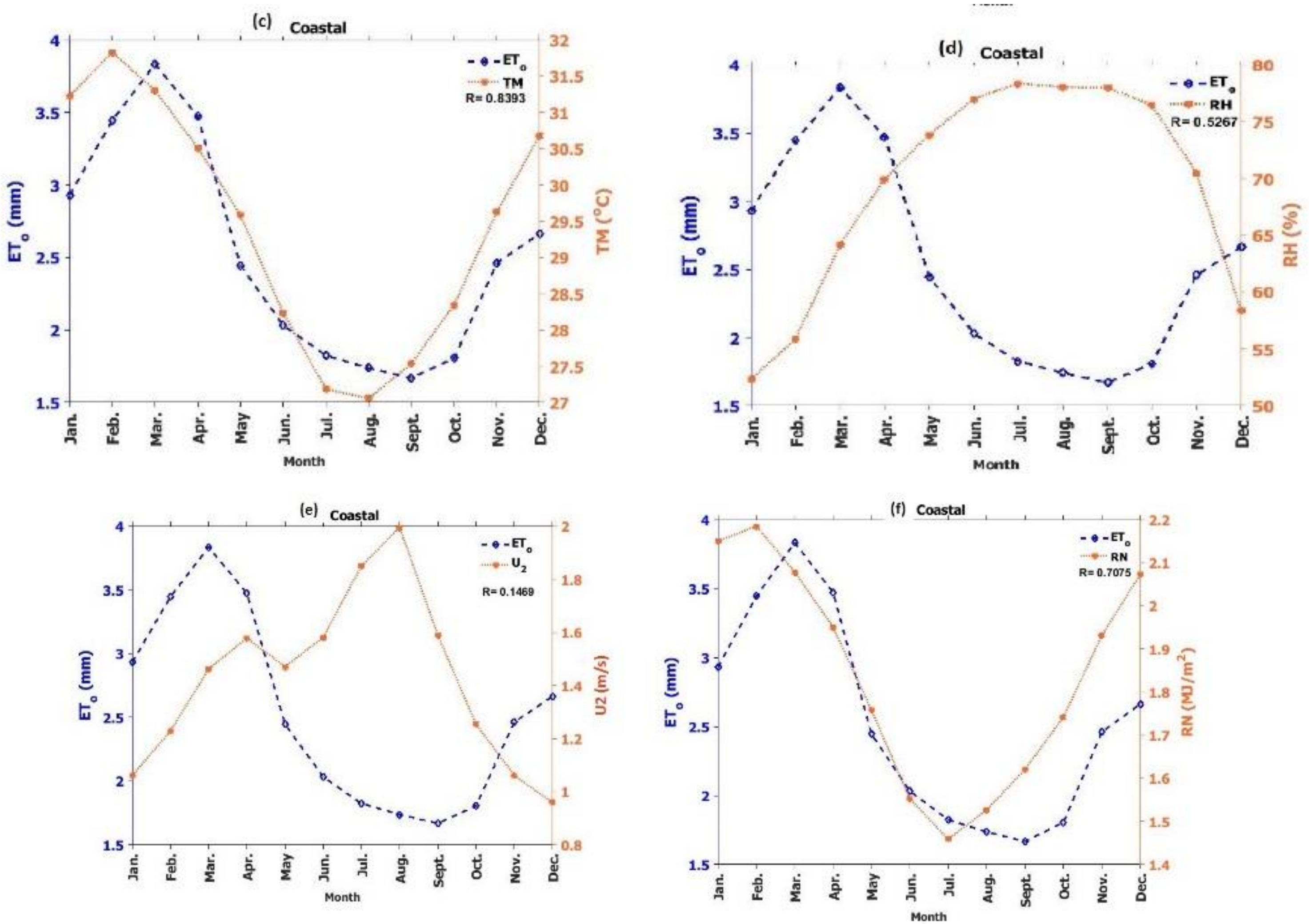


Fig. 9. Seasonal variation of reference transpiration and climate variables in the Coastal

this period has implications for water resource management and agriculture. Conversely, evapotranspiration increases during dry months, driven by higher temperatures, net radiation, and wind, which promote water transport and uptake.

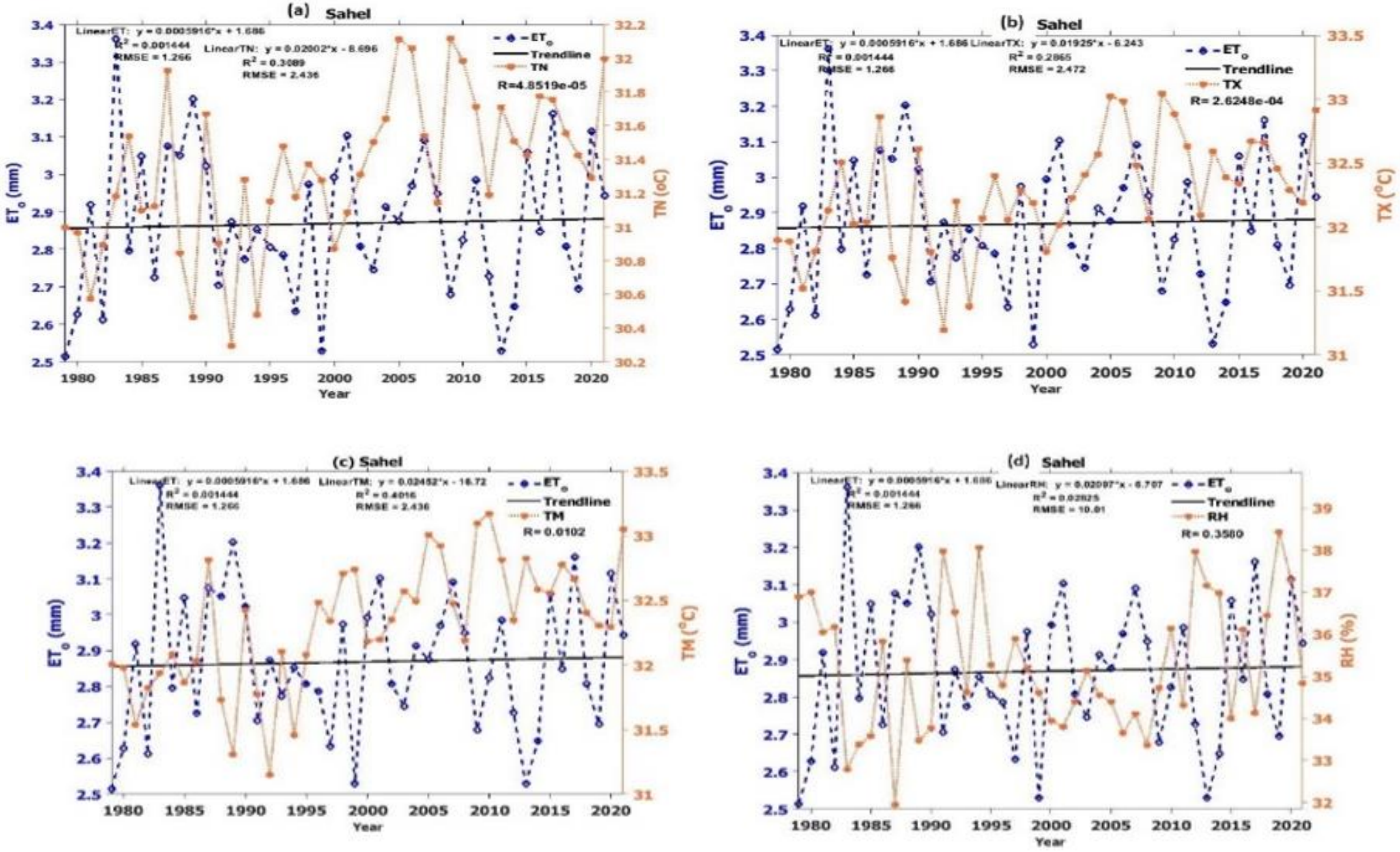
Cloud cover plays a significant role in the amount of solar radiation reaching the surface, with cloudless skies resulting in warmer temperatures and cloudy skies leading to cooler temperatures [36,37]. Understanding these seasonal variations and their influencing factors is crucial for effective water management and climate change impact assessments in Nigeria. Generally, in all regions, reference evapotranspiration decreased during the rainy months with relative humidity being highly correlated in those months. This is due to the fact that lower evapotranspiration rates occur in humid weather due to both the high air humidity and the presence of clouds. This was consistent with studies by Isikwue et al. [36] and Akinsanola and Ogunjobi [38].

3.3 Inter-annual Variation of ET_o and Meteorological Variables

Figs. 10-13 (a-f) depict the interannual variations of Evapotranspiration (ET_o) and its six constituent variables across four climatic regions in Nigeria from 1979 to 2021. The analysis of interannual variations of Evapotranspiration (ET_o) and its constituent variables in different climatic regions of Nigeria from 1979 to 2021 reveals distinct patterns. In the Sahel region (Fig. 10), mean temperature (TM), maximum temperature (TX), and minimum temperature (TN) experienced substantial increasing rates of 0.02452/year, 0.02002/year, and 0.01925/year, respectively, compared to the relatively lower rate of ET_o increase at 0.0005916/year. The correlation coefficient between ET_o and wind speed (U2) of 0.836 indicates a positive relationship, suggesting that the rise in U2, coupled with increasing temperatures due to climate change, leads to higher evapotranspiration rates by introducing drier winds and additional heat energy to the evapotranspiration site [39,40]. Moving to the Guinea region (Fig. 11), the increasing rates of TX, TN, and TM at 0.02095/year, 0.02081/year, and 0.02058/year, respectively, outpaced the rate of ET_o increase, which stood at 0.001447/year. Additionally, rainfall (RN) exhibited an increasing trend with a rate of 0.001783/year, while both wind speed (U2) and relative humidity (RH) displayed decreasing trends at rates of 0.001302/year and 0.005602/year, respectively. These variations suggest that factors beyond temperature, such as rainfall, wind speed, and relative humidity, contribute to the interannual variability of ET_o in the Guinea region. In the Rainforest regions (Fig. 12), ET_o exhibited a decreasing trend at 0.04681/year, despite the increasing rates of TM, TN, and TX at 0.5927/year, 0.5299/year, and 0.526/year, respectively owing to the offset created by decreasing trend of windspeeed, net readiation and relative humidity. The high correlation coefficient of 0.9987 between ETo and rainfall (RN) indicates a strong relationship, highlighting the significant influence of rainfall on ET_o variation within the Rainforest region. This finding aligns with studies conducted in other regions, such as Northeast China [41] and the Qilian Mountains of China [42] where wind speed, relative humidity, and other factors contributed to decreased ET_o. The role of wind speed (U2) and relative humidity (RH) in the Rainforest region is evident with correlation coefficients of 0.0040 and 0.2627, respectively, further emphasizing their contribution to the ET_o variation. In the Coastal region (Fig. 13), ETo displayed a relatively low increasing rate of 0.00137/year, while TM, TX, and TN exhibited increasing rates of 0.02437/year, 0.01608/year, and 0.01536/year, respectively. Notably, relative humidity (RH) and rainfall (RN) demonstrated decreasing trends at rates of 0.0262/year and 0.003619/year, respectively, while wind speed (U2) displayed a slight increasing trend of 0.0004197/year. These observations suggest that in the Coastal region, factors such as temperature and wind speed play a role in ET_o variation, while relative humidity and rainfall have contrasting effects. Generally, the analysis highlights the region-specific characteristics in the interannual variations of ET_o and its constituent variables in Nigeria. The findings emphasize the influence of various climatic factors, including temperature, wind speed, relative humidity, and rainfall, on the observed trends of ET_o.

3.4 Trend analysis and Homogeneity Test

Tables 1 – 4 display Mann-Kendall trends and homogeneity tests of ETo across four climatic regions in Nigeria. The value of Z indicates the strength of the increasing trend (positive Z value) or decreasing trend (negative Z value) in ET_o trend, with higher values implying stronger ETo in the respective area at a significance level of


(a) Sahel
LinearET: y = 0.0005916*x + 1.686
R^2 = 0.001444
RMSE = 1.266
LinearTN: y = 0.02002*x - 8.696
R^2 = 0.3089
RMSE = 2.436
ET_o
Trendline
TN
R=4.8519e-05
ET_o (mm)
TN (oC)
Year
(b) Sahel
LinearET: y = 0.0005916*x + 1.686
LinearTX: y = 0.01925*x - 6.243
R^2 = 0.001444
RMSE = 1.266
R^2 = 0.2865
RMSE = 2.472
ET_o
Trendline
TX
R= 2.6248e-04
ET_o (mm)
TX (°C)
Year
(c) Sahel
LinearET: y = 0.0005916*x + 1.686
LinearTM: y = 0.02452*x - 16.72
R^2 = 0.001444
RMSE = 1.266
R^2 = 0.4016
RMSE = 2.436
ET_o
Trendline
TM
R= 0.0102
ET_o (mm)
TM (°C)
Year
(d) Sahel
LinearET: y = 0.0005916*x + 1.686
LinearRH: y = 0.02097*x - 6.707
R^2 = 0.001444
RMSE = 1.266
R^2 = 0.02825
RMSE = 10.01
ET_o
Trendline
RH
R= 0.3580
ET_o (mm)
RH (%)
Year

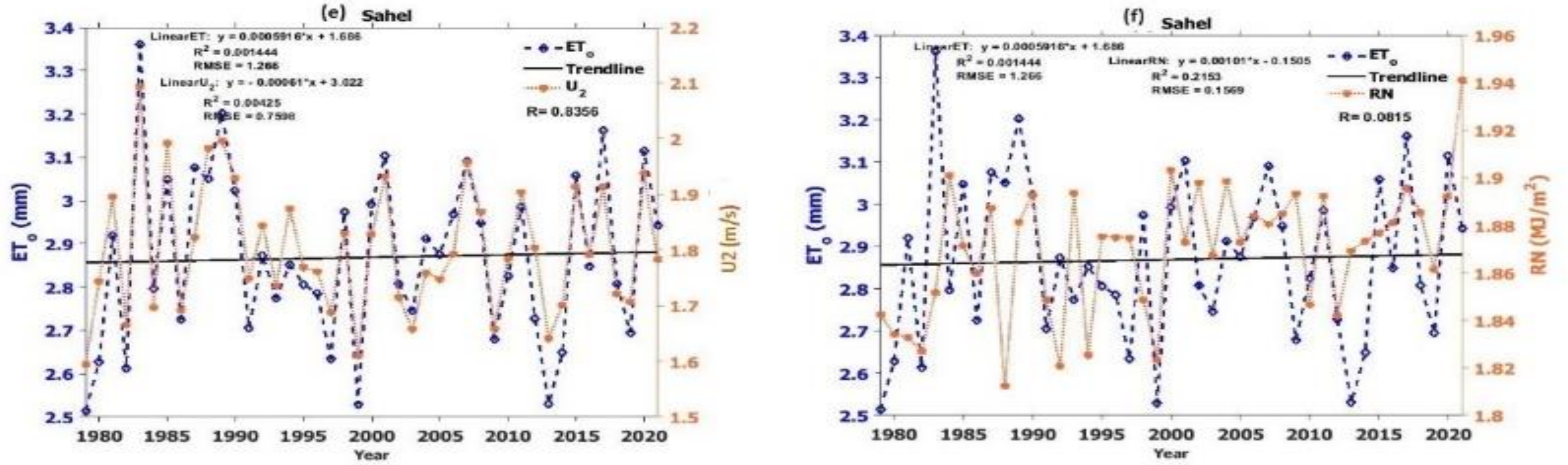
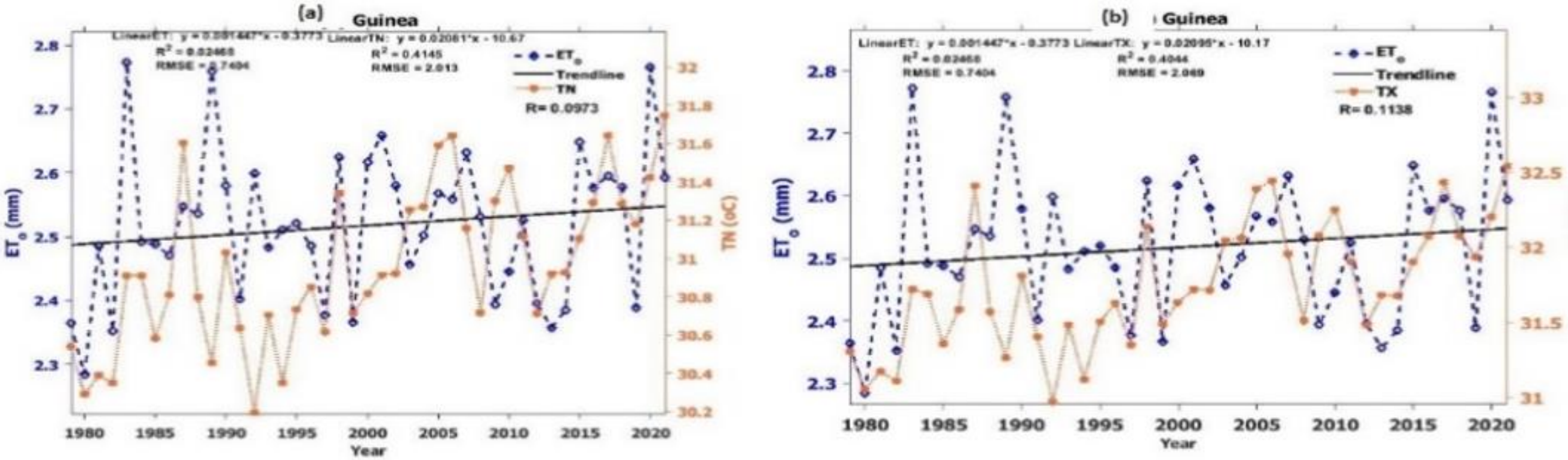


Fig. 10. Inter-annual variation of reference transpiration and climate variables in the Sahel region, Nigeria



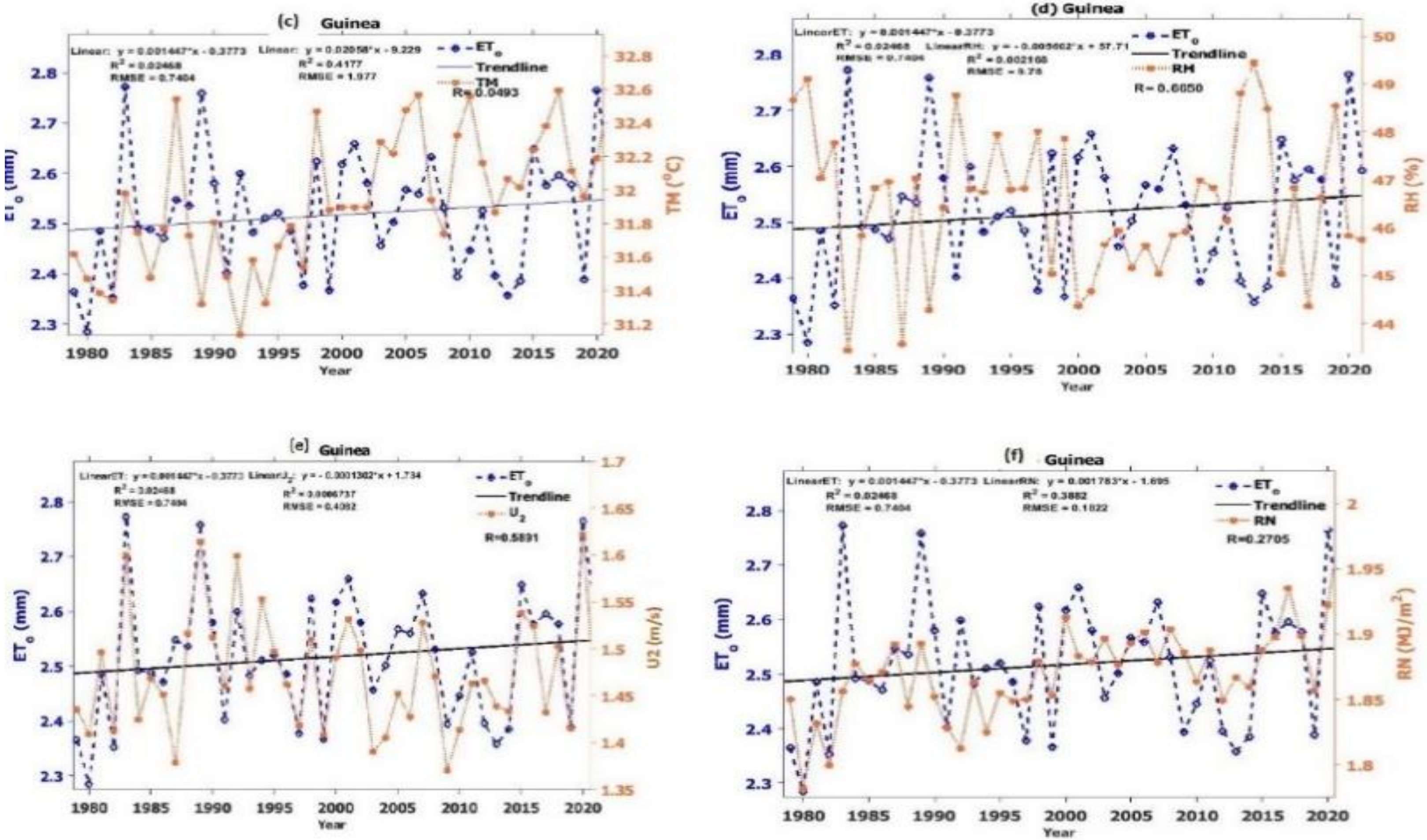
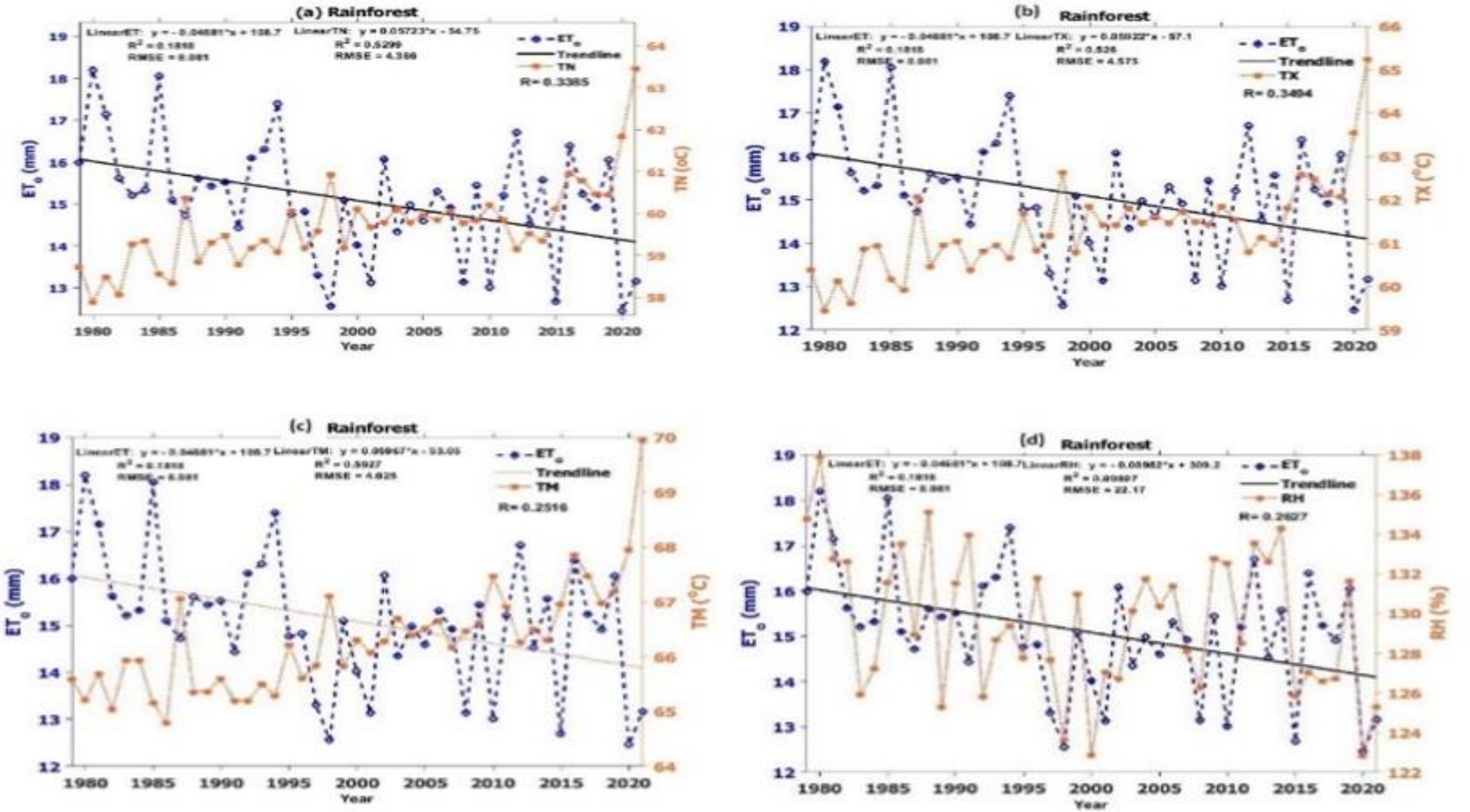


Fig. 11. Inter-annual variation of reference transpiration and climate variables in the Guinea Savannah region, Nigeria


(a) Rainforest
ET$_o$ (mm)
TN (oC)
Year
R= 0.3385
(b) Rainforest
ET$_o$ (mm)
TX (°C)
Year
R= 0.3494
(c) Rainforest
ET$_o$ (mm)
TM (°C)
Year
R= 0.2516
(d) Rainforest
ET$_o$ (mm)
RH (%)
Year
R= 0.2627
Trendline

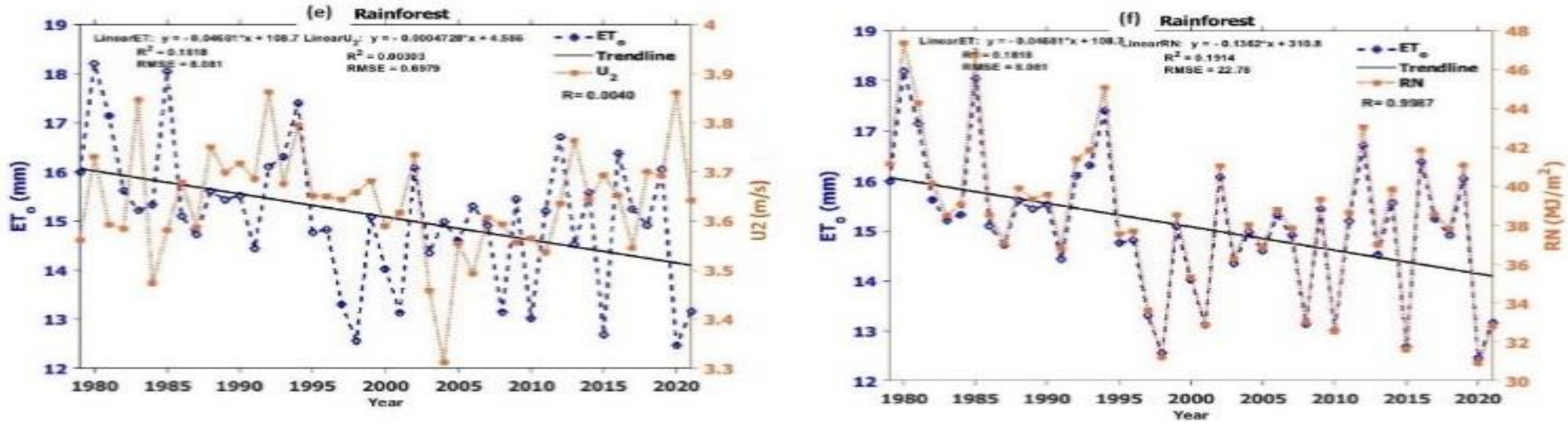
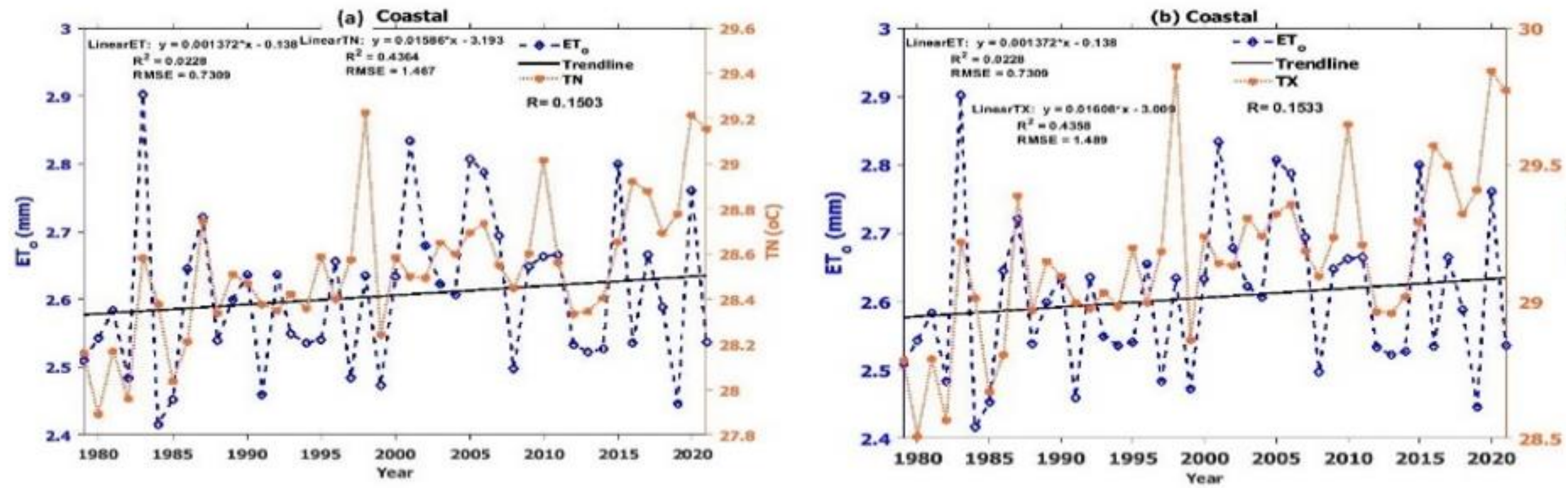


Fig. 12. Inter-annual variation of reference transpiration and climate variables in the Rainforest region, Nigeria



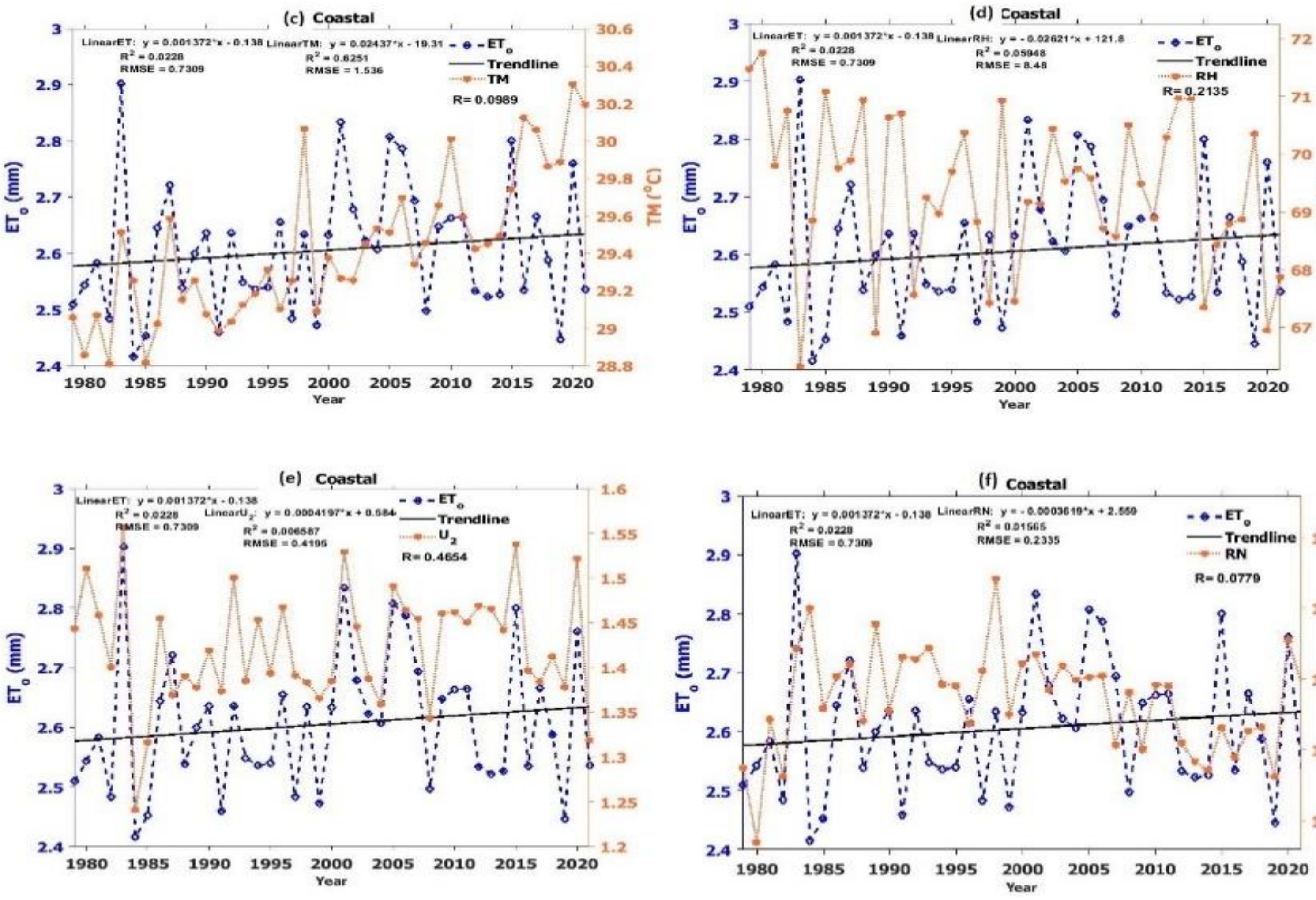


Fig. 13. Inter-annual variation of reference transpiration and climate variables in the Coastal region, Nigeria

P<0.05 (alpha level). Moreover, K, To, Q, and N represent the strength of change points in ETo using the Pettit, Standardized Normal Homogeneity Test (SNHT), Buishand, and Von-Neumann ratio, respectively. A significant change point (year) signifies inhomogeneity, indicating a sudden shift in ETo variability in a particular area. In the Sahel region (Table 1), all ten stations demonstrated an increasing trend in ETo. However, Sokoto, Katsina, and Dutse exhibited non-significant trends, as indicated by their P-values exceeding the alpha level of 0.05. The increasing trends detected in Sahel region, being a region with limited rainfall, can lead to drier conditions, which may result in reduced vegetation cover, increased risk of drought stress, and changes in ecosystem composition. Based on the study's criteria of being supported by at least two out of three change point tests, 1999 was established as the year of homogeneous/inhomogeneous change in ETo in nine out of ten stations. Only Katsina experienced a change in ETo starting from 1983. Among the stations, Maiduguri recorded the highest values of Z, K, To, Q, and N, indicating the most pronounced and significant trends and change points in the region. In the Guinea region (Table 2), ten out of eleven stations exhibited significant increasing trends in ETo. Jos was the only station with an insignificant trend, as indicated by a P-value greater than the alpha level of significance (0.05). As previously established, six out of the eleven stations had their change points in the year 1999, while Makurdi, Minna, Lafia, and Lokoja had their change points established as 1997. Only Bauchi had its change point in 2002. Abuja and Bauchi recorded the highest values of Z, K, To, Q, and N, indicating strong significant trends and change points in these locations. In the Rainforest region (Table 3), ETo exhibited an increasing trend overall, although Ewekoro and Shagamu had insignificant trends with P-values exceeding the alpha level of significance (0.05). The study revealed that three out of ten stations experienced change points in the year 1996. Ilorin and Akure had their change points in 1999, Akure and Ado-Ekiti in 1994, while Ewekoro and Shagamu exhibited inhomogeneous change points in 1982. Only Benin experienced a change point in 2006.

Ilorin recorded the strongest significant trend and change point, as it displayed the highest values of Z, K, To, Q, and N. In the Coastal region (Table 4), eight stations exhibited an insignificant decreasing trend in ETo, while only Bonny displayed a significant decreasing trend. Ikeja, Enugu, and Asaba showed insignificant increasing trends. Seven out of twelve stations experienced homogeneous/inhomogeneous change points in ETo in 2006, whereas Yenagoa and Okpe had their inhomogeneous change points in 2008. Ikeja and Enugu also exhibited inhomogeneous changes in 1982, while Asaba experienced inhomogeneous change in ET_o in 1996. Calabar and Port-Harcourt recorded the highest values of Z, K, To, Q, and N, indicating the strongest insignificant decreasing trend and change point in the Coastal region. Generally, changes in ET_o can have socio-economic consequences. For example, shifts in agricultural productivity can affect food security, livelihoods of farmers, and rural economies. Additionally, variations in water availability due to ET_o changes can impact hydropower generation, water-dependent industries, and human settlements reliant on consistent water supplies.

3.5 Cross Correlation of ET_o and Meteorological Variables

Figs. 14 - 17 (a-f) illustrate the cross-correlation plots between evapotranspiration (ET_o) and meteorological variables in different climatic regions of Nigeria. The left and right sides of the plots indicate the degree of sensitivity, with correlation values between 0-0.4 considered as weak sensitivity, 0.45-0.65 as moderate sensitivity, and 0.7-1 as strong sensitivity. The time response of each parameter (in months) is provided at the bottom of the plots. In the Sahel region (Fig. 14 (a-f)), ET_o demonstrated moderate sensitivity with a correlation value of 0.65 and a one-month lead response time with TN, TX, and TM. ETo and RH exhibited a strong negative sensitivity with a correlation value of 0.7 at an immediate response time lag. ETo and U2 displayed moderate positive sensitivity with a correlation value of 0.55 and a one-month response time lag. ETo and RN also showed moderate positive sensitivity with a correlation value of 0.5 and a four-month lead response time. These results indicate that ETo tends to increase with higher values of TN, TM, TX, and U2, while decreasing with reduced RH and RN in the Sahel region. In the Guinea Savannah region (Fig. 15 (a-f)), ETo exhibited a strong positive sensitivity with a correlation value of 0.98 and no significant response time lag with TN, TX, and TM.

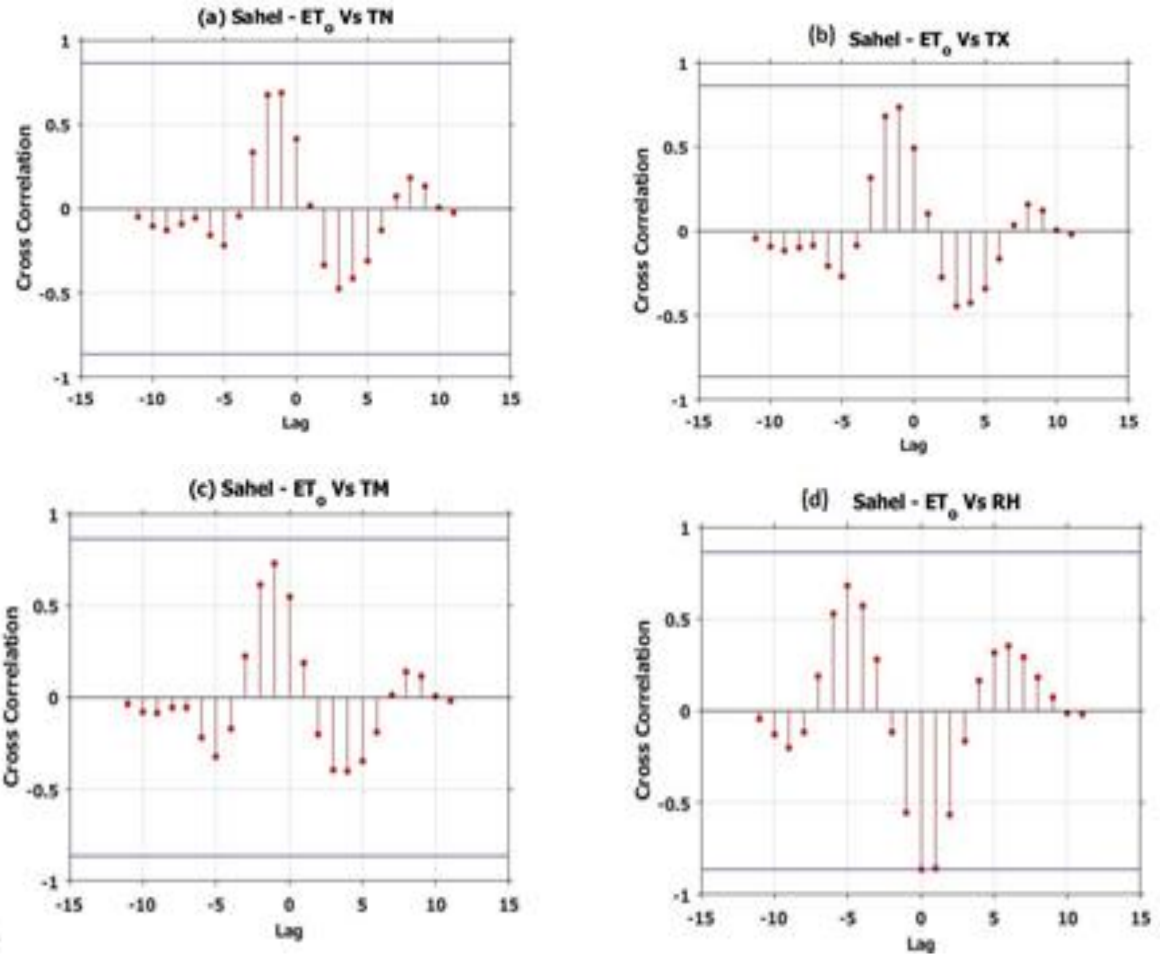
Table 1. Mann-Kendall Trend and Homogeneity test for the Sahel and Guinea Savannah Region

STATION	TREND			PETTITT			SNHT			BUISHAND			VON-NEUMANN	
	Z	B	P	K	CP	P	To	CP	P	Q	CP	P	N	P
MAIDUGURI	**3.9**	0.001	**0.000**	**412**	**1999**	**< 0.0001**	**21.9**	**1999**	**< 0.0001**	**15.5**	**1999**	**< 0.0001**	**1.2**	**0.0**
GOMBE	**3.0**	0.001	**0.005**	**286**	**1999**	**0.003**	**12.6**	**1999**	**0.004**	**11.8**	**1999**	**0.002**	**1.5**	**0.1**
SOKOTO	1.9	0.001	0.079	158	1999	0.442	**11.0**	**1982**	**0.007**	7.4	1999	0.108	1.9	0.4
KATSINA	1.0	0	0.368	136	1983	0.780	5.6	1983	0.205	5.0	1983	0.478	2.3	0.8
KADUNA	**4.5**	0.002	**< 0.0001**	**334**	**1999**	**< 0.0001**	**14.4**	**1999**	**0.000**	**12.6**	**1999**	**0.000**	**1.1**	**0.0**
BIRNIN-KEBBI	**2.7**	0.001	**0.011**	**238**	**1999**	**0.031**	**8.5**	**1999**	**0.035**	**9.3**	**1999**	**0.020**	1.1	0.2
GUSAU	**2.8**	0.001	**0.008**	180	1999	0.228	**9.7**	**1983**	**0.018**	8.2	1999	0.054	1.6	0.1
DAMATURU	**3.1**	0.01	**0.004**	**340**	**1999**	**< 0.0001**	**16.3**	**1999**	**0.000**	**13.4**	**1999**	**< 0.0001**	**1.4**	**0.0**
DUTSE	0.6	0	0.586	92	1999	0.373	2.6	1999	0.704	5.3	1999	0.400	2.4	0.9
SAHEL	**3.4**	0.001	**0.001**	**296**	**1999**	**0.001**	**13.3**	**1999**	**0.002**	**12.1**	**1999**	**0.001**	1.6	0.1

Table 2. Mann-Kendal Trend and Homogeneity Tests of the Guinea Savannah Region

STATION	TREND			PETTITT			SNHT			BUISHAND			VON-NEUMANN	
	Z	B	P	K	CP	P	To	CP	P	Q	CP	P	N	P
YOLA	**4.4**	0.002	**< 0.0001**	**328**	**1999**	**< 0.0001**	**16.6**	**1999**	**0.000**	**13.5**	**1999**	**< 0.0001**	**1.1**	**0.0**
BAUCHI	**4.5**	0.022	**< 0.0001**	**390**	**2002**	**< 0.0001**	**20.4**	**2002**	**< 0.0001**	**14.9**	**2002**	**< 0.0001**	**1.0**	**0.0**
MAKURDI	**3.3**	0.002	**0.002**	**282**	**1997**	**0.004**	**11.4**	**1997**	**0.005**	**11.1**	**1997**	**0.002**	**1.4**	**0.0**
MINNA	**4.4**	0.002	**< 0.0001**	**342**	**1997**	**0.000**	**14.3**	**1997**	**0.003**	**12.5**	**1999**	**< 0.0001**	**0.9**	**< 0.0001**
BIDA	**4.2**	0.002	**< 0.0001**	**330**	**1999**	**< 0.0001**	**15.1**	**2019**	**0.002**	**11.7**	**1999**	**0.000**	**0.9**	**< 0.0001**
JALINGO	**4.1**	0.002	**0.000**	**296**	**1999**	**0.002**	**14.2**	**1982**	**0.001**	**11.9**	**1999**	**0.001**	**0.8**	**< 0.0001**
ABUJA	**5.2**	0.002	**< 0.0001**	**394**	**1999**	**< 0.0001**	**18.9**	**2015**	**0.000**	**13.7**	**1999**	**< 0.0001**	**0.6**	**< 0.0001**
JOS	1.6	0.001	0.137	**170**	**1999**	**0.327**	5.6	1999	0.223	7.8	1999	0.072	2.1	0.6
LAFIA	**2.7**	0.001	0.013	**256**	**1997**	**0.015**	**10.1**	**2014**	**0.019**	**10.2**	**1997**	**0.007**	**1.3**	**0.0**
LOKOJA	**3.9**	0.002	**0.000**	**264**	**1997**	**0.008**	**11.5**	**2015**	**0.006**	**10.5**	**1997**	**0.002**	**1.2**	**0.0**
GUINEA	**4.1**	0.000	**0.000**	**342**	**1999**	**0.000**	**15.2**	**1999**	**< 0.0001**	**12.9**	**1999**	**< 0.0001**	**1.0**	**< 0.0001**

ETo and RH showed a strong negative sensitivity with a correlation value of 0.85 and a one-month response time lag. ETo and U2 displayed moderate positive sensitivity with a correlation value of 0.6 and a four-month lead response time. However, the sensitivity between ETo and RN was insignificant, despite a strong correlation value of 0.85 and a one-month response time lag. These findings suggest that ETo tends to increase with higher values of TN, TM, TX, U2, and RN, while decreasing with reduced RH in the Guinea Savannah region. Similarly, in the Rainforest region (Fig. 16 (a-f)), ETo showed strong positive sensitivity with a correlation value of 0.85 and no response time lag with TN, TX, and TM. ETo and RH exhibited a strong negative sensitivity with a correlation value of 0.85 and a one-month response time lag. ETo and U2 displayed strong positive sensitivity with a correlation value of 0.75 and a four-month lead response time. ETo and RN also showed a strong negative sensitivity with a correlation value of 0.75 and a one-month response time lag. These results indicate that ETo tends to increase with higher values of TN, TM, TX, and U2, while it decreased with reduced RH and RN in the Rainforest region. In the Coastal region (Fig. 16 (a-f)), ETo exhibited an insignificant response time lag and a strong positive sensitivity of 0.9 with TN, TX, and TM. ETo and RH showed a strong negative sensitivity with a correlation value of 0.85 and a one-month response time lag. ETo and U2 demonstrated strong positive sensitivity with a correlation value of 0.7 and a four-month lead response time. ETo and RN also displayed strong positive sensitivity with a correlation value of 0.85 and a one-month response time lag. These findings suggest that ETo tends to increase with higher values of TN, TM, TX, RN, and U2, while decreasing with reduced RH in the Coastal region. Generally, these results indicate that variations in ETo are largely influenced by changes in TN, TM, TX, U2, RH, and RN in their respective climatic regions. Understanding these sensitivities and response times between ETo and meteorological variables can have relevant implications for water resource management, agriculture, and climate adaptation strategies in different regions of Nigeria.



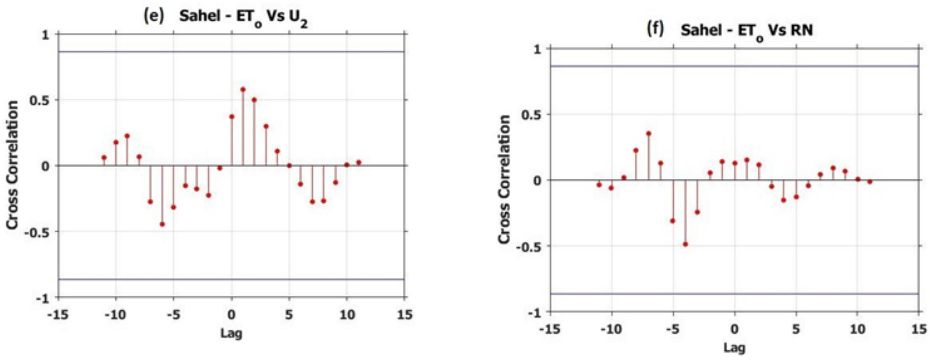


Fig. 14. Cross correlation of reference evapotranspiration and climatic variables in the Sahel Region

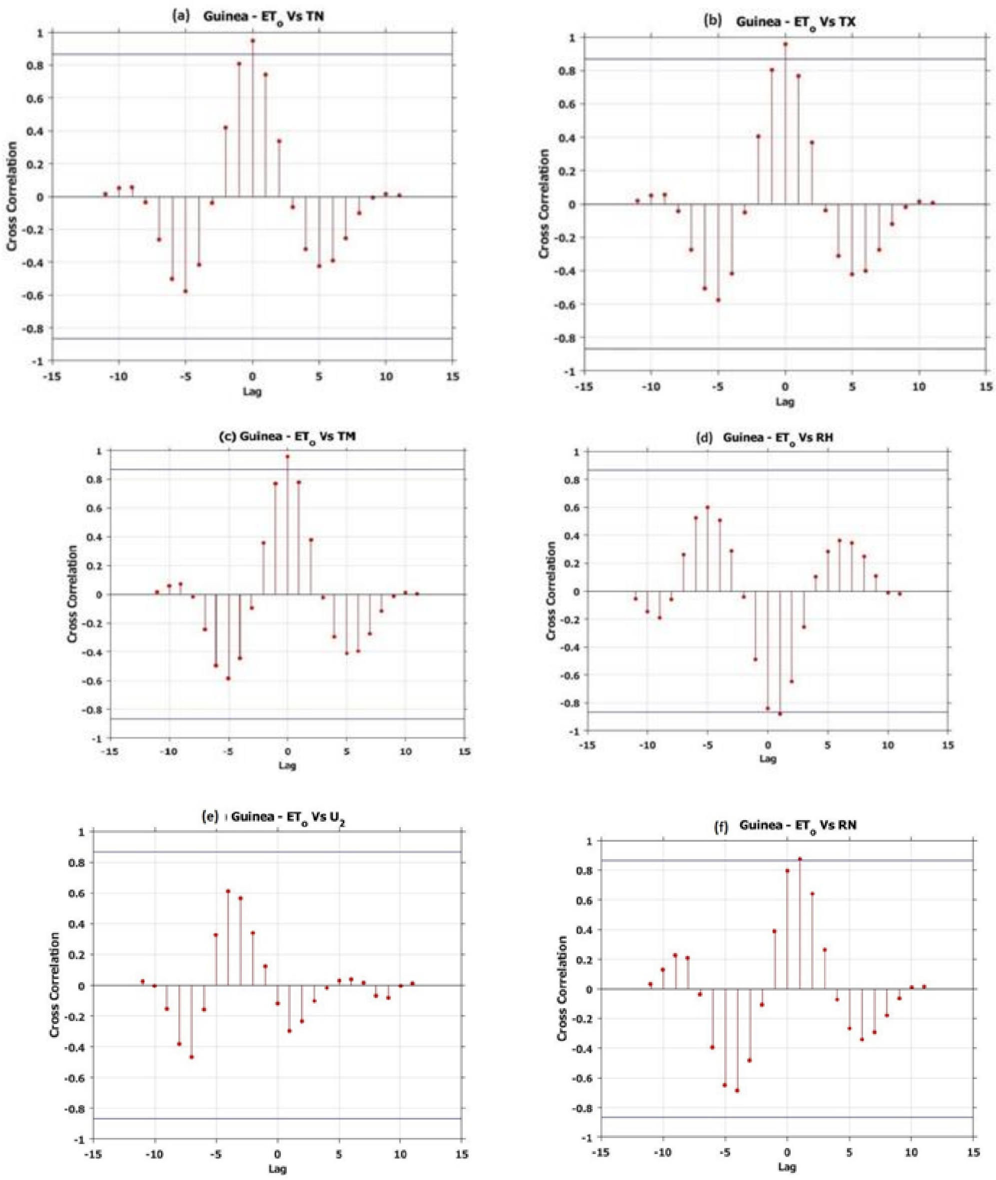


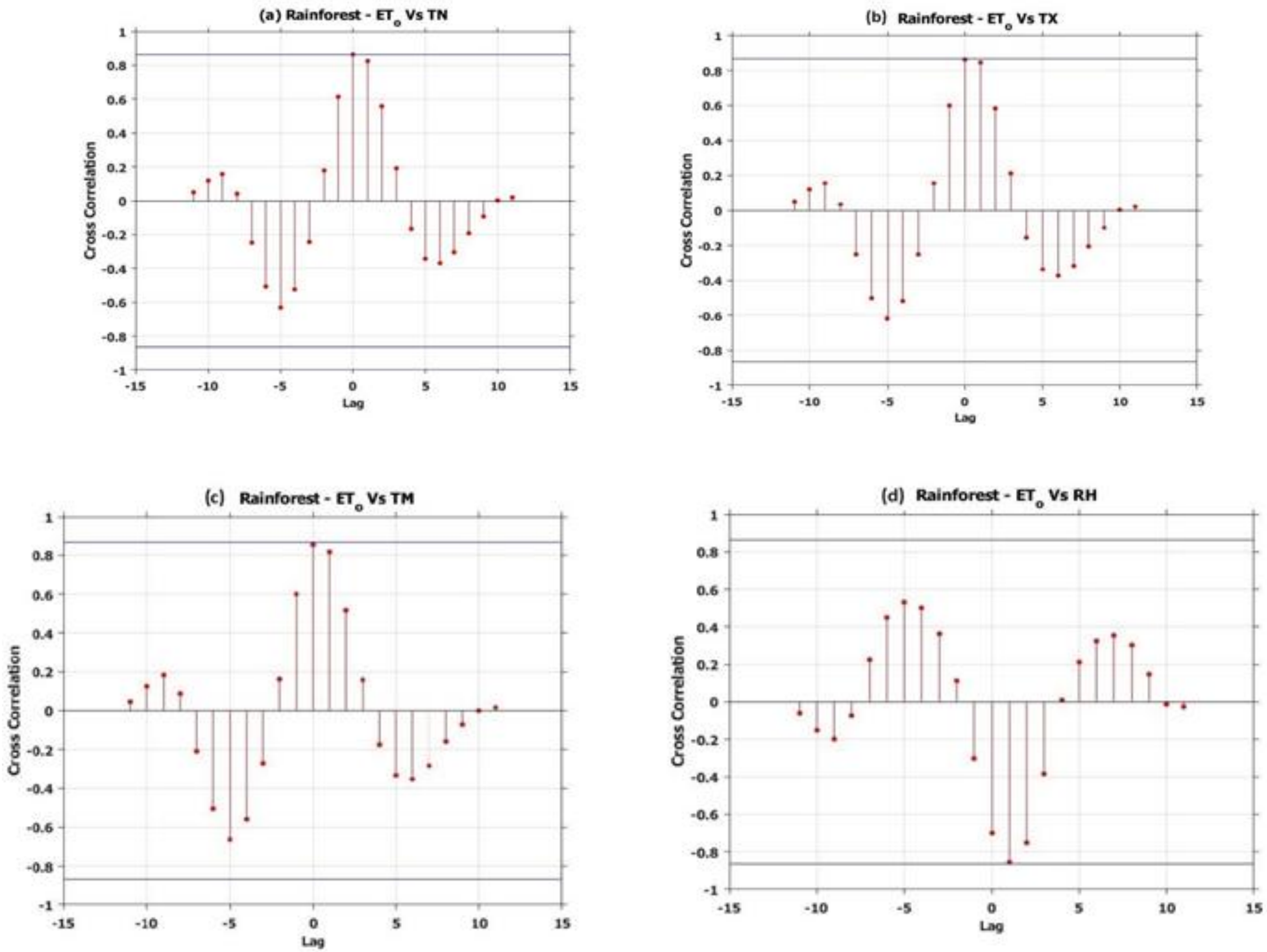
Fig.15. Cross correlation of reference evapotranspiration and climatic variables in the Guinea Savannah Region

Table 3. Mann-Kendall Trend and Homogeneity test for the Rainforest Region

STATION	TREND			PETTITT			SNHT			BUISHAND			VON-NEUMANN	
	Z	B	P	K	CP	P	To	CP	P	Q	CP	P	N	P
ILORIN	4.8	0.003	< 0.0001	372	1999	< 0.0001	17.6	1998	< 0.0001	13.9	1999	< 0.0001	1.0	< 0.0001
AKURE	3.0	0.002	0.005	284	1994	0.003	12.5	1983	0.002	10.9	1994	0.001	1.1	0.0
ABEOKUTA	4.4	0.002	< 0.0001	284	1999	0.002	8.7	1999	0.033	9.8	1999	0.011	1.7	0.2
ADO-EKITI	3.4	0.002	0.002	310	1994	0.001	13.0	1994	0.001	11.6	1996	0.000	1.1	0.0
OSHOGBO	3.9	0.889	0.000	310	1996	0.001	14.3	1994	0.000	12.3	1996	0.000	1.2	0.0
BENIN	3.2	0.001	0.003	286	2006	0.002	12.7	2006	0.002	11.3	2006	0.002	1.8	0.2
IBADAN	3.4	0.002	0.001	284	1996	0.002	12.2	1996	0.004	11.4	1996	0.001	1.6	0.1
EWEKORO	1.9	0.001	0.072	166	1989	0.356	21.8	1982	< 0.0001	9.0	1982	0.021	1.3	0.0
SHAGAMU	1.3	0.001	0.209	160	1983	0.425	20.5	1982	0.000	8.7	1982	0.032	1.4	0.0
RAINFOREST	3.7	0.004	0.001	300	1996	0.001	13.4	2019	0.003	11.6	1996	0.000	1.1	0.0

Table 4. Mann-Kendall Trend and Homogeneity test for the Coastal Region

STATION	TREND			PETTITT			SNHT			BUISHAND			VON-NEUMANN	
	Z	B	P	K	CP	P	To	CP	P	Q	CP	P	N	P
IKEJA	1.9	0.001	0.069	168	1989	0.333	21.9	1982	< 0.0001	9.0	1982	0.023	1.3	0.0
CALABAR	-1.4	-0.001	0.180	258	2006	0.015	11.5	2011	0.006	10.5	2006	0.006	1.2	0.0
ENUGU	0.9	0	0.414	132	1982	0.832	11.1	1982	0.010	6.4	1982	0.214	1.6	0.2
BONNY	-2.1	-0.001	0.044	264	2006	0.007	9.1	1980	0.025	9.3	2006	0.017	1.1	0.0
PORT-HARCOURT	-2.1	-0.001	0.054	258	2006	0.013	9.3	2006	0.024	9.6	2006	0.012	1.3	0.0
IKOT-EPENE	-1.9	-0.001	0.079	238	2006	0.029	8.1	2011	0.039	9.0	2006	0.025	1.3	0.0
UYO	-0.2	-0.001	0.112	256	2006	0.011	11.1	2011	0.006	10.2	2006	0.007	1.2	0.0
YENAGOA	-1.2	-0.001	0.267	208	2008	0.097	7.1	1980	0.083	8.1	2008	0.060	1.5	0.0
ASABA	2.0	0.001	0.060	222	1996	0.056	12.6	1982	0.001	9.2	1996	0.016	1.3	0.0
OWERRI	-1.6	-0.001	0.137	204	2006	0.114	6.3	1982	0.136	7.3	2006	0.120	1.8	0.3
OKPE	-1.0	0	0.357	174	2008	0.288	8.6	1982	0.037	6.4	2008	0.216	1.5	0.1
COASTAL	-1.8	-0.001	0.098	230	2006	0.041	10.0	1982	0.015	7.6	2006	0.089	1.4	0.0


(a) Rainforest - ET$_o$ Vs TN
(b) Rainforest - ET$_o$ Vs TX
(c) Rainforest - ET$_o$ Vs TM
(d) Rainforest - ET$_o$ Vs RH
Cross Correlation
Lag

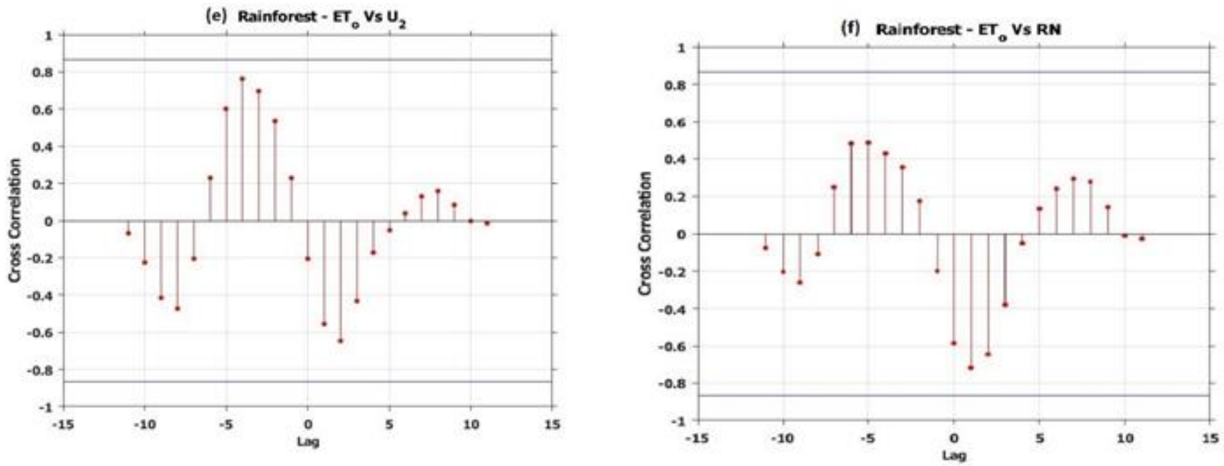
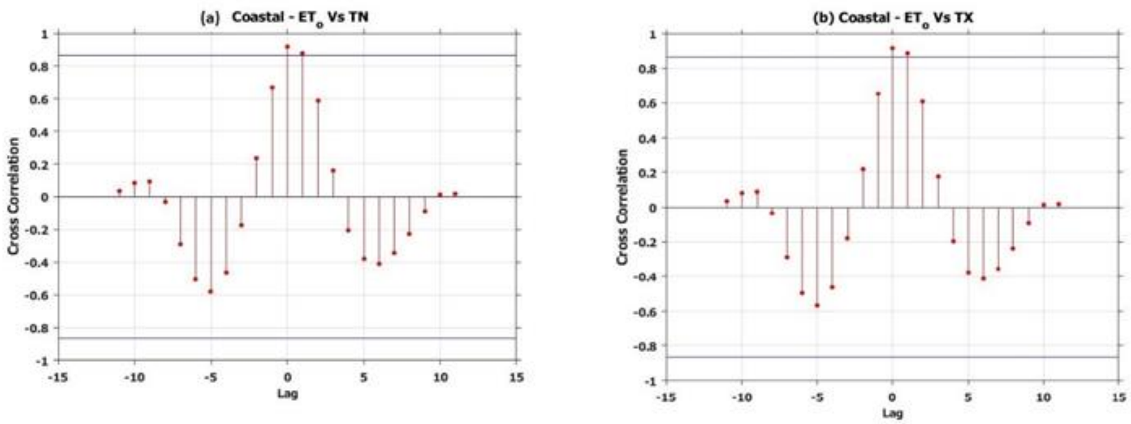


Fig. 16. Cross correlation of reference evapotranspiration and climatic variables in the Rainforest Region



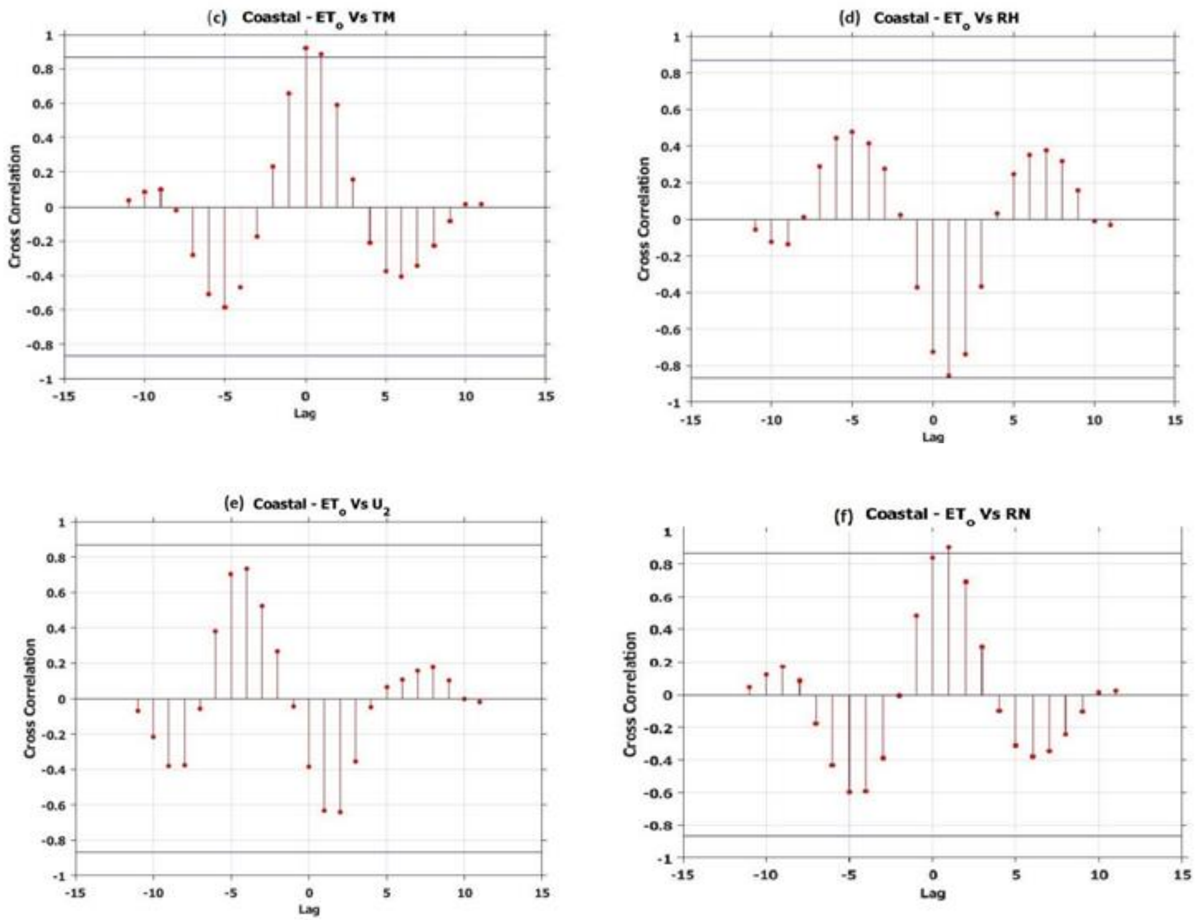


Fig. 17. Cross correlation of reference evapotranspiration and climatic variables in the Coastal Region

4. CONCLUSION

In this study, a comprehensive analysis of the interconnection between reference evapotranspiration and meteorological variables during 1979-2021 in climatic regions over Nigeria was carried out. The quantitative contributions of the meteorological variables revealed that ET_o was strongly negatively correlated in the Sahel, Guinea and Coastal regions to relative humidity (RH) with values of R^2 as 0.7343, 0.8418, and 0.7662 respectively. The analysis of trends, homogeneity, and cross-correlation in different climatic regions of Nigeria reveals insightful findings. In the Sahel region, most stations exhibited an increasing trend in Evapotranspiration (ET_o), although some trends in Sokoto, Katsina, and Dutse were non-significant. The year 1999 was identified as the year of homogeneous/inhomogeneous change in ETo for most stations, except for Katsina, which experienced a change in 1983. Strong significant trends and change points were observed in Maiduguri. Similarly, the Guinea region displayed a significant increasing trend in ET_o across most stations, with Abuja and Bauchi showing prominent trends and change points. The Rainforest region exhibited an overall increasing trend in ET_o, with Ilorin displaying the strongest significant trend and change point. In the Coastal region, most stations had insignificant decreasing trends, while Calabar and Port-Harcourt showed the strongest insignificant decreasing trends and change points. The cross-correlation analysis revealed that ET_o in the Sahel, Guinea, Rainforest, and Coastal regions was influenced by various meteorological variables. Temperature variables (TN, TX, TM) exhibited positive sensitivity, while relative humidity (RH) showed negative sensitivity. Wind speed (U2) and rainfall (RN) displayed both positive and insignificant sensitivities. Understanding these patterns can assist in water resource management, agriculture, and climate adaptation strategies tailored to the specific climatic regions of Nigeria. Future studies could also consider examining the relationships between ET_o and other climatic indices, such as the North Atlantic Oscillation (NAO) or El Niño-Southern Oscillation (ENSO), to assess any potential teleconnections and improve climate prediction models. Lastly, considering the potential effects of climate change on ETo patterns in these regions and projecting future trends under different climate scenarios would be valuable for adaptation planning and policy formulation.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

DATA AVAILABILITY

The data and codes used for this study are available on request.

ACKNOWLEDGEMENT

The authors appreciates the European Centre for Medium-Range Weather Forecasts Reanalysis version 5 database (ERA 5) for making their data available for this study.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://prh.mbimph.com/review-history/2874