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On the Relationship between Equivalent Potential Temperature (theta-e) and Convective Rain over Nigeria and Togo

Michael C. Ochei*

Abstract

Convective precipitation is a key feature of West Africa's climate, driven by the West African monsoon system. Accurate forecasting of convective storms is challenging but essential for disaster mitigation in the region. This study investigates the ability of using equivalent potential temperature (theta-e) for predicting convective rainfall events in West Africa. Theta-e combines the thermodynamic effects of moisture and temperature to represent total energy available for convection. Daily rainfall and meteorological data over 15 years (2003–2017) from Nigeria and Togo were analyzed. Theta-e was estimated and correlated to rainfall occurrences using linear regression. Results demonstrate coherent increasing theta-e trends over time across the region. Seasonal cycles show peak rainfall corresponding to reduced theta-e during rainy months. Correlation analyses find theta-e and convective rainfall are moderately to weakly inversely related on monthly scales. Daily time-series indicate lower theta-e values accompany major convective rainfall event. The study concludes that while theta-e shows skill for identifying convective condition in West Africa, relationships are complex and non-linear. Thresholds of 340–370 K seem most favourable for intense rainfall events. However, theta-e value must exceed 355K 2-3 days before strong convective rain is observed at a station. Incorporating theta-e alongside other stability parameters into forecast models could enhance early warnings for flooding, lightning, hail and thunderstorms events. Overall, theta-e shows the predictive ability of using it as a parameter for characterizing environments conducive to severe convective rainfall development across West Africa.

Keywords: Equivalent potential temperature; convective rain; abuja; lagos; dapaong; lome

INTRODUCTION

Convective rainfall, characterized by its localized and intense nature, often leads to significant meteorological events such as thunderstorms, hail, and flash floods. This type of rainfall accounts for a substantial portion of total precipitation in many regions around the world. Its occurrence is closely linked to convective processes driven by atmospheric instability, moisture availability, and other meteorological factors. It occurs when the energy from the sun heats the earth's surface and causes water to evaporate changing to water vapour. Convective rainfall is a common feature of the West African climate, which is majorly driven by the West African monsoon. It is one of the world's most interesting regions in terms of weather and climate, but it is poorly understood.

A study by Grist and Nicholson (2001) highlights the significance of the West Africa monsoon as a

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major factor of convective activity. The West African monsoon can be described by its seasonal shifts, which bring a change in wind patterns and temperature gradients that are directly related to the formation of convective systems (Sultan et al., 2005) [1].

Accurate prediction of convective rain in West Africa is challenging due to the region's complex topography, diverse land cover, and the influence of large-scale climate systems. There are uncertainties and restrictions in the lead time of predictions because conventional forecasting models frequently fail to capture the complex processes that lead to convective rainfall. Therefore, there is a growing need for more advanced and refined forecasting techniques that can better capture the specific dynamics of convective events in West Africa. One of the key parameters that can be used in predicting convective rain is the equivalent potential temperature (theta-e). Fink *et al.,* (2006) [2] applied linear regression to predict hourly rainfall rates from radiosonde theta-e measurements. Also, modern reanalysis datasets have enabled detailed mapping of theta-e fields across West Africa. For example, (Vischel *et al.,* 2011) [3] calculated theta-e from ERA-Interim data to examine moisture transport pathways.

Equivalent potential temperature (theta-e) is a thermodynamic parameter that combines the effects of both temperature and humidity, thereby providing information about the stability condition of the atmosphere. It measures the energy available in the atmosphere for the development and intensification of convective systems. It is also a fundamental meteorological parameter that evaluates the thermodynamic instability of the atmosphere. It measures the potential energy available for the development of severe weather events. Higher values of equivalent potential temperature (theta-e) indicate greater instability and the potential for convective activity with higher severity of heavy rainfall as supported by studies conducted by Ali *et al.* (2021) [4] and Fowler *et al.* (2021) [5]. However, Theta-e alone neglects other stability and triggering factors, meaning not all high theta-e regions develop heavy rain. Large-scale dynamical influences from African easterly waves can focus or inhibit convection (Poan *et al.,* 2015) [6]. More recently, machine learning methods like random forests allow for non-linear relationships and interactions between multiple predictors (Richards *et al.,* 2022) [7].

Convective instability is usually investigated through the use of equivalent potential temperature (theta-e) whereas its saturation value is used to study conditional instability (Adefolalu, 1972; Akinsanola and Ogunjobi, 2013) [8, 9]. Theta-e has gained recognition in recent years as a valuable tool for assessing the stability of the atmosphere, and critical factors in the initiation and intensity of convective systems (Smith *et al.*, 2018) [10]. Several studies have shown a distinct signal whereby high theta-e air is co-located with subsequent convective development in West Africa (Jones *et al.,* 2019; Smith *et al.,* 2021) [11, 12]. Despite the proven effectiveness of theta-e in other contexts, research on its application for rainfall prediction in West Africa remains limited. Existing studies on West African Monsoon prediction have predominantly focused on parameters such as sea surface temperature or the African Easterly Jet (Moufouma-Okia and Rowell, 2009) [13]. While some investigations have delved into instability indices like Convective Available Potential Energy (CAPE) (Guichard *et al.,* 2004) [14].

This study evaluated the equivalent potential temperature as a predictive tool, estimated the variations and trends of parameter (theta-e) in convective rainfall, and thus identify the theta-e thresholds for severe convective rain formation; thereby contributing to a more accurate and region-specific forecasting, aiding meteorological agencies, disaster management authorities, and other stakeholders in making an informed decision.

METHODOLOGY

Study Area

This study examines four urban locations across two West African countries: Lomé and Dapaong in Togo, and Lagos and Abuja in Nigeria (Figure 1). Lomé and Lagos are southern coastal cities situated along the Gulf of Guinea, whereas Dapaong and Abuja are inland locations positioned in the northern sectors of their respective countries, representing more continental climatic regimes.

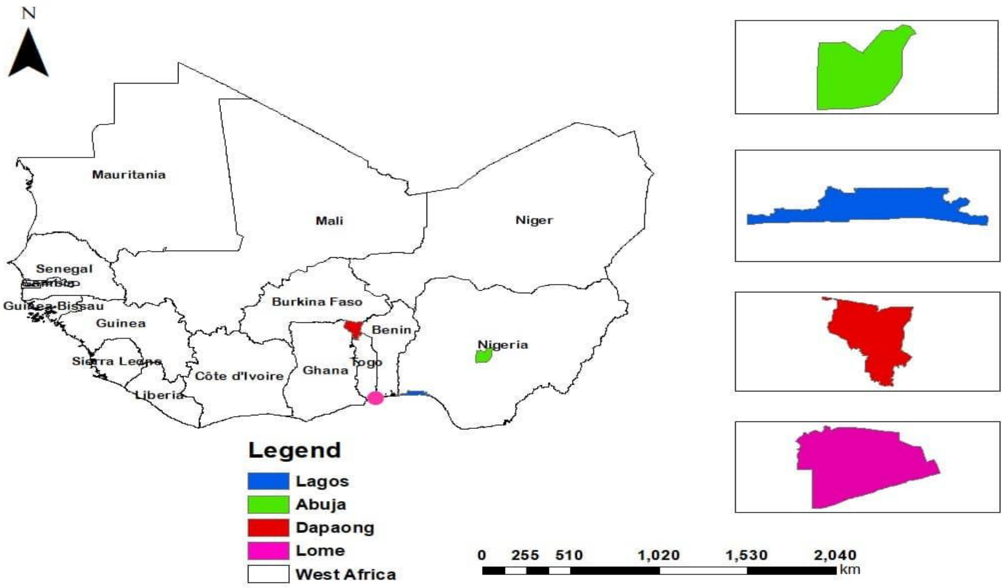


Figure 1. Map of West Africa showing the urban locations within the countries under study.

The broader West African region is geographically bounded by the Gulf of Guinea to the south, the Atlantic Ocean to the west, the Lake Chad Basin and Cameroon to the east, and by the Sahara Desert and the Sahelian belt to the north. Ecologically, the region is commonly classified into three principal zones: the humid Guinea zone, the sub-humid Savannah zone, and the semi-arid Sahel zone (Abiodun and Omotosho, 2007) [15]. These ecological gradients correspond closely with latitudinal variations in rainfall, vegetation, and atmospheric thermodynamics.

The climate of the selected study locations is primarily governed by the seasonal interaction of two dominant air masses: the moist maritime tropical (mT) air mass associated with the southwesterly monsoon flow from the tropical Atlantic, and the dry continental tropical (cT) air mass transported by the northeasterly trade winds from the Sahara Desert. The meridional oscillation of the boundary between these air masses—referred to as the Inter-Tropical Discontinuity (ITD)—controls the seasonal distribution of rainfall, convective activity, and atmospheric instability across the region (Adefolalu, 1984) [16]. The northward advance of the ITD during boreal summer (rainy season) facilitates moisture advection and enhanced convection, while its southward retreat during boreal winter (dry season or harmattan) promotes dry, stable conditions over much of inland West Africa.

Estimation of Equivalent Potential Temperature (Theta-e)

This study utilizes historical meteorological observations, including air temperature and atmospheric pressure, to estimate the equivalent potential temperature (θ_e), a thermodynamic parameter that characterizes the combined effects of temperature and moisture on atmospheric instability. In addition, convective rainfall records are incorporated to establish a robust climatological dataset of convective events. Statistical analyses are subsequently performed to quantify the relationships between θ_e variability and the frequency, occurrence, and intensity of convective systems.

Under the simplifying assumption that the latent heat of vaporization (L_v), the specific heat capacity at constant pressure (c_p), and the gas constant for dry air (Rd) remain constant within the atmospheric layer considered, the equivalent potential temperature is derived by incorporating the dry potential temperature (θ). The potential temperature represents the temperature an air parcel would attain if adiabatically brought to a standard reference pressure, and it forms the thermodynamic foundation for estimating θ_e.

Several formulations exist for computing equivalent potential temperature. One common approach incorporates thermodynamic relationships derived from the Clausius–Clapeyron equation, which describes the dependence of saturation vapor pressure on temperature. Accordingly, saturation vapor pressure is first calculated as a function of temperature, after which moisture variables (e.g., mixing ratio or specific humidity) are incorporated to obtain θ_e. This method enables a physically consistent representation of moist static energy and provides a reliable metric for assessing convective potential within tropical atmospheric environments. The saturation vapor pressure is computed using the formula below;

$$e_s = e_o \exp\left[\frac{L_v}{R_v}\left(\frac{1}{T_o} - \frac{1}{T}\right)\right] \quad (1)$$

where e_o= 6.11 hPa,

T_o= 273.15 K,

$R_v = 461.J.K^{-1}.Kg^{-1}$ gas constant of water vapour

$L_v = 2.5 \times 10^6$ *J/kg is* the latent heat of vaporization.

The saturation-specific humidity (q_s) was then evaluated from the relation:

$$q_s = \frac{\varepsilon e_s}{(P + \varepsilon e_s)} \quad (2)$$

where ε=0.622g/g

P = atmospheric pressure

e_s = saturation vapour pressure

Next, the potential temperature(θ), is evaluated from the Poisson equation as:

$$\theta = T\left(\frac{100}{P}\right)^k \quad (3)$$

Where; T = atmospheric temperature (K)

P = atmospheric pressure (kPa)

k = R/Cp, R = 286.85 and Cp = 1004, are the gas constant and specific heat for dry air at constant pressure respectively.

Finally, the equivalent potential temperature, θ_e, was estimated from the expression as:

$$\theta_e = \theta \exp\left(\frac{L_C q_s}{C_p T}\right) \quad (4)$$

where $L_c = 2.5 \times 10^6$ *J/kg* is the latent heat of condensation.

Adapted from Meteorology for Scientist and Engineer, 3rd Edition.

Linear Regression Analysis

Linear regression analysis is a parametric statistical technique widely used to identify and quantify linear relationships within observational datasets. By fitting a linear equation to empirical data, the model establishes a functional relationship between an independent variable (predictor) and a dependent variable (response). The primary objective is to determine whether statistically significant dependence exists between the variables of interest and to quantify the strength and direction of this association.

Following model fitting, hypothesis testing is conducted—typically through significance tests of the regression coefficients—to evaluate whether the observed relationship differs significantly from zero. If no statistically significant relationship is detected, the linear regression model provides limited explanatory or predictive utility for the dataset under consideration.

The strength and direction of the linear association are commonly summarized using the correlation coefficient (r), which ranges from −1 to +1. A value of ±1 indicates a perfect linear relationship (positive or negative), whereas a value close to zero suggests little to no linear association, though nonlinear relationships may still exist.

The simple linear regression model is generally expressed as:

$$y = mx + c \quad (5)$$

where (Y) is the dependent variable, (X) is the independent variable, (\beta_0) is the intercept, (\beta_1) is the slope parameter representing the rate of change of (Y) with respect to (X), and (\varepsilon) is the random error term accounting for unexplained variability.

Where, Y and X are the dependent variable and the independent variable respectively,
m is the line slope and c are the intercept constant coefficient.

The coefficients (m and c) of the model are determined using the Least-Squares method, which is the most commonly used method. Slope sign defines trend variable direction; increases if the sign is positive and decreases if the sign is negative.

Pearson's Correlation Coefficient

Pearson's correlation coefficient is the test statistics that measures the statistical relationship, or association, between two continuous variables. It is known as the best method of measuring the association between variables of interest because it is based on the method of covariance. It gives information about the magnitude of the association, or correlation, as well as the direction of the relationship. It is a number between –1 and 1 that measures the strength and direction of the relationship between two variables. The formula for calculating correlation coefficient (r) is given as;

$$r = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\sqrt{[\Sigma(x-\bar{x})^2(y-\bar{y})^2]}} \quad (6)$$

Where r= correlation coefficient

x = values of the x-variable in the sample

$\bar{x}$ = mean of the values of the x variable

y = values of the y variables in the sample

$\bar{y}$ = mean of the values of the y variable

Also, the table shows the correlation values between two variables (convective rainfall and theta-a), with its description.

RESULTS AND DISCUSSION

Trend Analyses

Annual Trend of Convective Rain

Figure 2(a–d) illustrates the inter-annual variability and regime shifts in convective rainfall and equivalent potential temperature (θ_e) across the four study locations for the period 2003–2017. The time-series analyses reveal distinct spatial contrasts in annual trends between coastal and inland stations within each country.

In Togo, Lomé (coastal) exhibits a negative linear trend in convective rainfall, described by the regression equation (y = -18.671x + 38432), indicating a progressive decline over the study period. In contrast, Dapaong (northern inland) shows a slight positive trend ((y = 3.8814x - 6713)), suggesting a gradual increase in convective rainfall. These findings are consistent with Pouwèréou et al. (2020) [17], who reported a statistically significant positive rainfall trend in northern Togo, whereas southern Togo experienced a decreasing but statistically insignificant trend.

Conversely, an opposite spatial pattern is observed in Nigeria. Lagos (coastal) demonstrates an increasing rainfall trend ((y = 11.799x - 22119)), while Abuja (northern inland) shows a declining trend ((y = -12.304x + 26152)). The downward trend over Abuja aligns with the findings of Itiowe et al. (2019), who documented a reduction in rainfall over the Federal Capital Territory. These contrasting spatial patterns suggest regional differences in moisture advection, land–atmosphere feedbacks, and the meridional displacement of the Inter-Tropical Discontinuity (ITD), which collectively modulate convective activity.

Regarding climatological means, Lomé records an average annual convective rainfall of approximately 900 mm, with the wettest year occurring in 2010 (>1500 mm) and the driest year in 2016 (<750 mm). Dapaong exhibits a slightly higher annual mean of about 1000 mm, peaking in 2013 (~1300 mm) and reaching a minimum in 2003 (<850 mm). Lagos shows the highest average annual convective rainfall among the study sites, approximately 1600 mm, with a maximum in 2014 (>2000 mm) and a minimum in 2006 (<1300 mm). Abuja records an average of about 1400 mm annually, with the wettest year in 2003 (>1750 mm) and the driest in 2013 (<1200 mm).

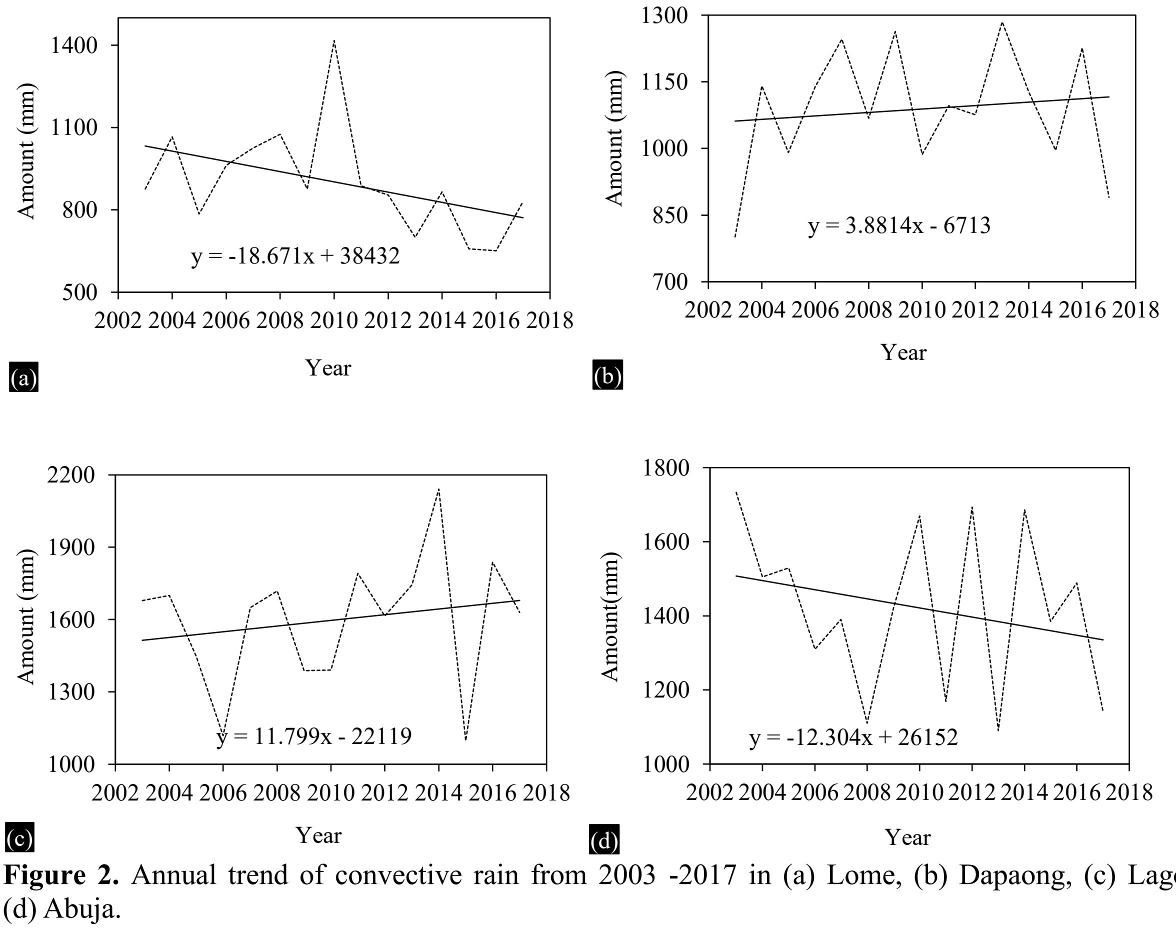


Figure 2. Annual trend of convective rain from 2003 -2017 in (a) Lome, (b) Dapaong, (c) Lagos, (d) Abuja.

Overall, the observed inter-annual variability and opposing regional trends highlight the heterogeneous response of convective systems across coastal and continental West Africa. These variations likely reflect complex interactions among thermodynamic instability (θ_e), large-scale monsoon dynamics, and localized surface–atmosphere processes.

Mean Annual Trend of Theta-e

Figure 3(a–d) presents the mean annual evolution of equivalent potential temperature (θ_e) over the period 2003–2017 for the four study locations. The analysis indicates a positive linear trend in θ_e at most stations, with the exception of Abuja, where a weak negative trend was observed. This spatial contrast suggests differential thermodynamic responses between coastal and inland environments across the study domain.

At Lomé (Figure 3a), the highest mean annual θ_e was recorded in 2010 (363.3 K), while the lowest value occurred in 2004 (360.0 K). Similarly, Dapaong (Figure 3b) exhibited its maximum θ_e in 2010 (374.6 K) and minimum in 2004 (370.1 K). The increasing tendency in Dapaong is consistent with the findings of Komlagan et al. (2023), who reported upward trends in both minimum and maximum air temperatures in northern Togo. Because θ_e integrates both thermal and moisture contributions to atmospheric energy, increases in surface temperature and atmospheric humidity naturally lead to higher θ_e values.

In Lagos (Figure 3c), the highest θ_e was also observed in 2010 (361.1 K), with the lowest value occurring in 2004 (356.9 K). Over Abuja (Figure 3d), the maximum mean annual θ_e occurred in 2010 (374.5 K), whereas the minimum was recorded in 2014 (370.4 K), despite the overall slight downward trend across the study period.

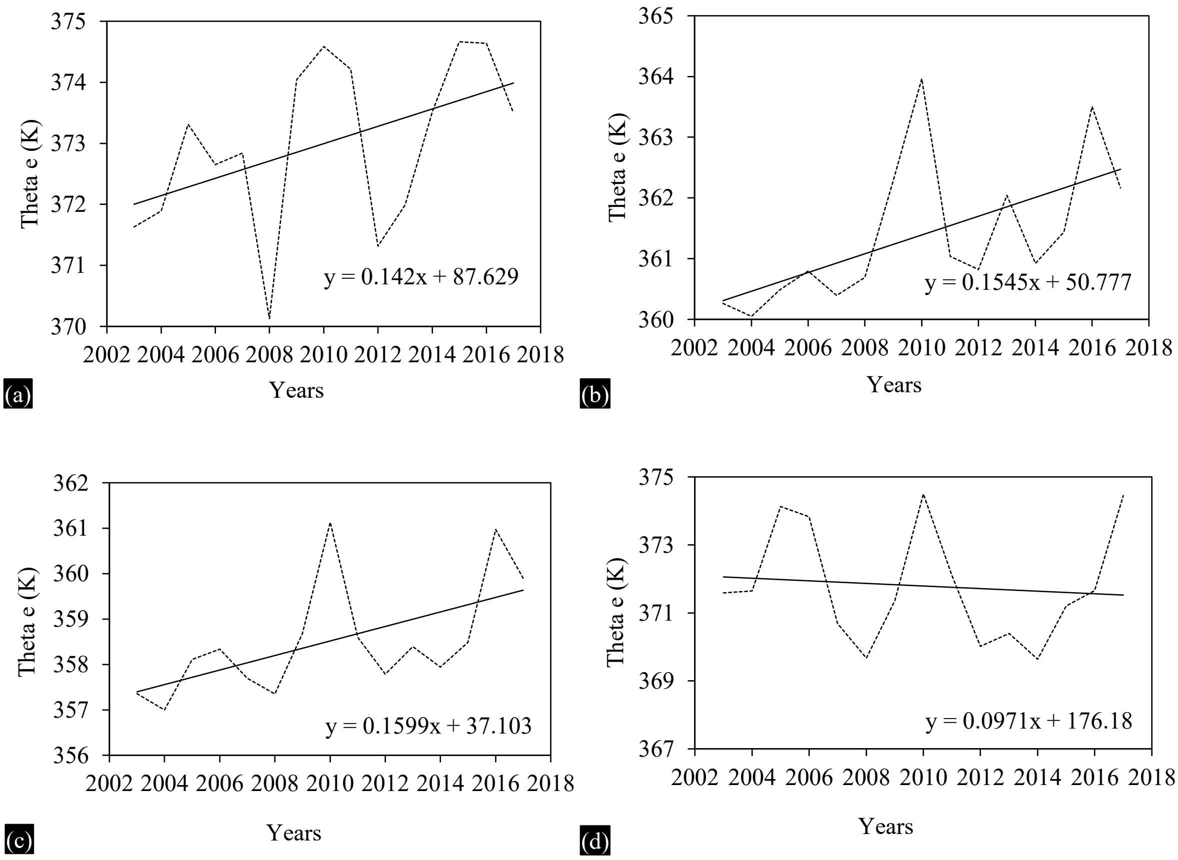


Figure 3. Mean annual trend of Theta-e from 2003-2017 in (a) Lome, (b) Dapaong, (c) Lagos, (d) Abuja.

Notably, 2010 emerges as the year with the highest θ_e across all stations, indicating enhanced thermodynamic instability and atmospheric moist static energy over West Africa during that year. This observation aligns with Cedric et al. (2022) [18] and Tanimoune et al. (2023) [19], who identified 2010 as one of the warmest years in recent decades, characterized by anomalously high sea surface temperatures (SSTs) across the tropical Atlantic.

Elevated SSTs enhance evaporation and moisture flux into the lower troposphere, thereby increasing atmospheric humidity and contributing to higher θ_e values. Since equivalent potential temperature increases with both temperature and moisture content, such large-scale oceanic warming provides a physically consistent explanation for the observed regional θ_e maxima.

Furthermore, the results indicate that inland northern stations (Dapaong and Abuja) consistently record higher θ_e values than coastal stations (Lomé and Lagos). This latitudinal gradient suggests a northward increase in thermal contribution to θ_e, likely associated with stronger continental heating and higher near-surface temperatures. This finding is consistent with Najib et al. (2017) [20], who reported a northward increase in air temperature across Nigeria. Overall, the spatial distribution of θ_e reflects the combined influence of meridional temperature gradients, moisture advection from the Gulf of Guinea, and continental heating processes that modulate convective potential across West Africa.

Monthly Distribution of Equivalent Potential Temperature and Convective Rain.

Figure 4(a–d) presents the climatological (2003–2017) mean monthly distributions of convective rainfall and equivalent potential temperature (θ_e) across the four study locations. A comparative assessment reveals seasonal phase differences between thermodynamic instability (θ_e) and rainfall, as well as marked spatial contrasts between coastal and inland regimes.

Over Nigeria, rainfall–θ_e intersections occur in May and October at Lagos and Abuja, indicating transitional periods when thermodynamic conditions and convective precipitation are closely aligned. In Togo, however, the timing differs: intersections occur in June and October at Dapaong, and in May and July at Lomé. These variations reflect local differences in moisture advection, surface heating, and the seasonal migration of the Inter-Tropical Discontinuity (ITD).

Coastal Regime (Lomé and Lagos)

Figures 4(a) and 4(c) show a pronounced bimodal rainfall distribution characteristic of the Guinea Coast. Rainfall is minimal during the dry season (December–February), increases progressively in March–April with monsoon onset, and reaches a primary maximum in May/June (approximately 200–250 mm on average).

A relative decline in July–August corresponds to the well-documented "Little Dry Season" (Ireland, 1962; Adefolalu, 1972; Ochei et al., 2015; Ochei and Oluleye, 2017) [21, 8, 22, 23], after which a secondary rainfall peak occurs in September–October (approximately 85–110 mm). November marks the transition to the dry season, with rainfall decreasing sharply into December. This bimodal structure is consistent with findings by Ogungbenro and Morakinyo (2014) [24].

In contrast, θ_e follows a distinct seasonal cycle. Maximum θ_e values occur in March–April (≈370 K), coinciding with peak pre-monsoon surface heating and elevated low-level moisture. During the core rainy season, θ_e decreases gradually, reaching a minimum in August (≈350 K), before increasing again in September–October as rainfall declines. The apparent inverse relationship between rainfall and θ_e reflects the cooling effects of persistent cloud cover, rainfall, and reduced solar insolation during peak monsoon months.

Nevertheless, θ_e remains relatively high (e.g., ~357 K in June), indicating sustained moist static energy despite enhanced precipitation. Thus, rainfall variability exerts stronger control on the seasonal cycle than temperature alone.

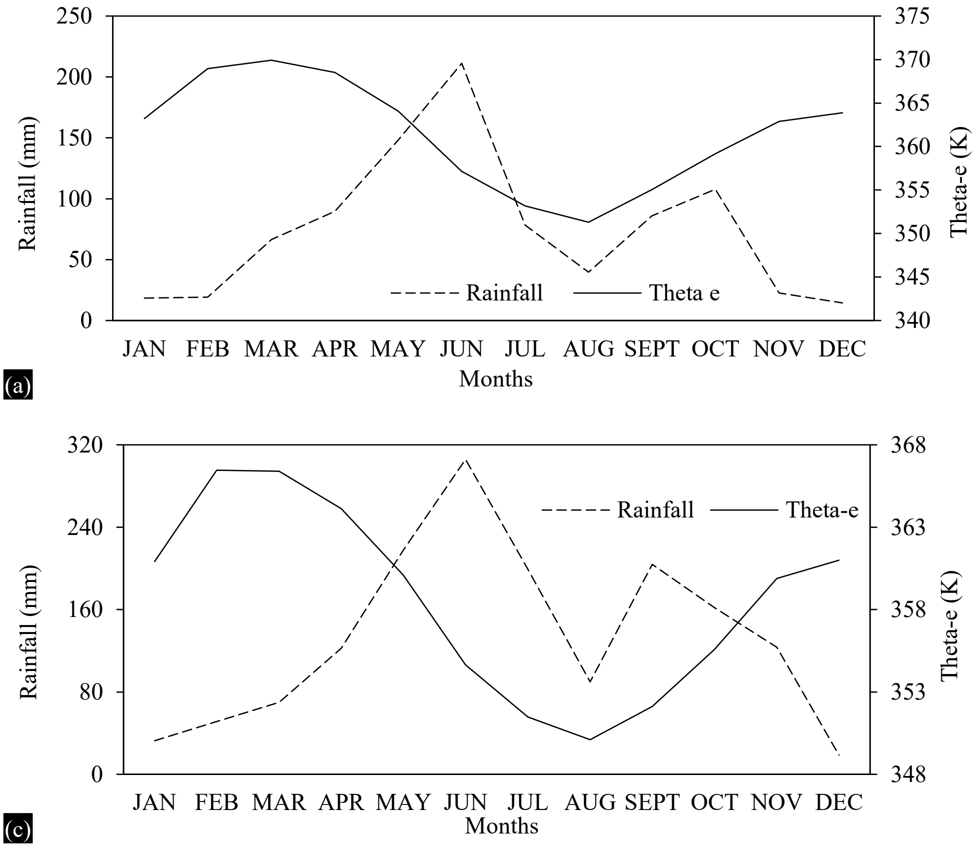


Figure 4. (a, c**).** Average monthly distribution of convective rainfall and theta-e from 2003-2017 in (a) Lome and (c) Lagos

Inland (Savannah) Regime (Dapaong and Abuja)

Figures 4(b) and 4(d) show a unimodal rainfall distribution typical of the Sudanian–Savannah zone. Rainfall is very low from December to February, increases steadily in March–April, and peaks in July/August (approximately 250–320 mm), coinciding with the monsoon maximum over northern West Africa. This period corresponds to the "Little Dry Season" observed along the coast, highlighting the latitudinal displacement of peak convection. November represents the cessation phase of the rainy season, followed by rapid decline into December, consistent with Ogunbenro and Morakinyo (2014) and Komlagan et al. (2023) [24, 25].

As observed in the coastal stations, θ_e exhibits a different seasonal evolution. Maximum values occur in March–April during peak dry-season heating. Thereafter, θ_e decreases progressively through the rainy season, reaching minima in August (below 300 K in some cases), before rising again in September–October. This pattern reflects the combined influence of reduced surface temperature during peak rainfall and seasonal modulation of moisture availability.

In general across all four locations, θ_e demonstrates a broadly similar seasonal cycle, characterized by pre-monsoon maxima and monsoon minima. In contrast, convective rainfall displays strong spatial variability: bimodal in coastal environments (Lomé and Lagos) and unimodal in inland Savannah regions (Dapaong and Abuja).

The inverse seasonal phase between rainfall and θ_e suggests that while θ_e provides a measure of atmospheric moist static energy, actual rainfall distribution is more strongly governed by large-scale monsoon dynamics, cloud–radiative feedbacks, and regional circulation patterns. Consequently, although thermodynamic instability (θ_e) establishes the potential for convection, the spatial and temporal distribution of rainfall is primarily modulated by dynamic and synoptic-scale controls.

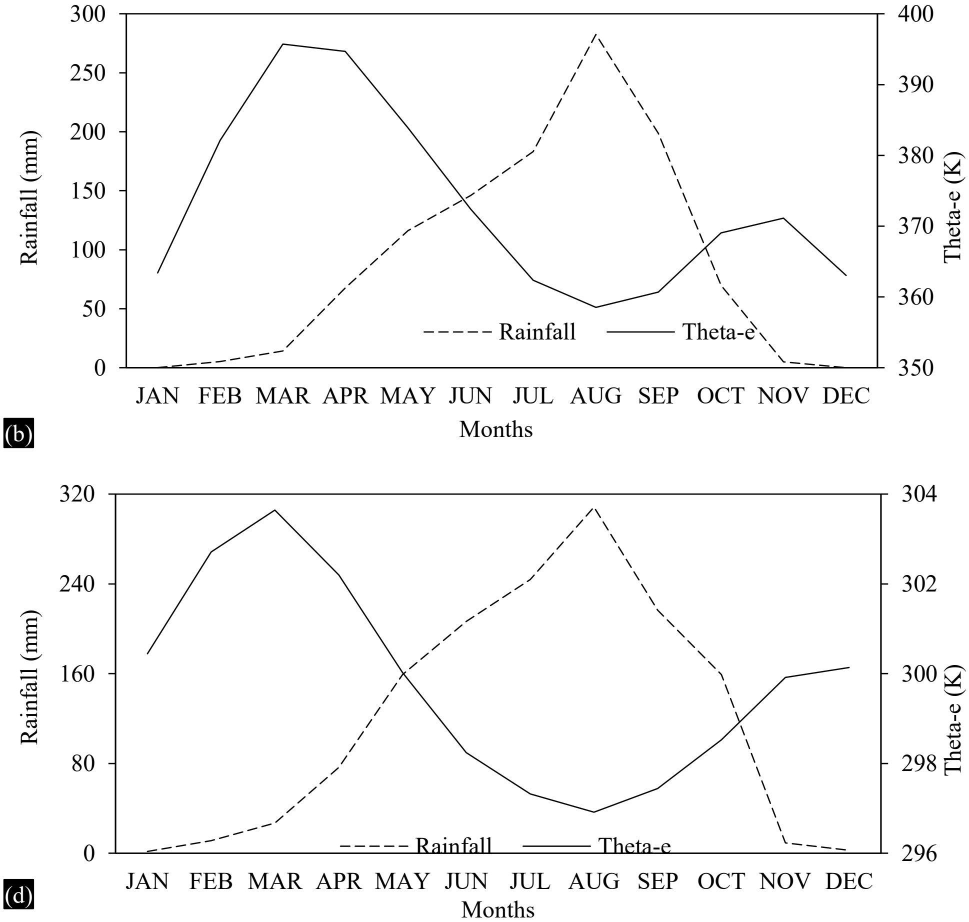


Figure 4. (b, d) Average monthly distribution of convective rainfall and theta-e from 2003-2017 in (b) Dapaong, and (d) Abuja

Correlation Between Convective Rainfall and Equivalent Potential Temperature (Theta-e)

Lagos

Figure 5 illustrates the statistical relationship between convective rainfall and equivalent potential temperature (θ_e) over Lagos. The analysis reveals a negative correlation, indicating an inverse association between the two variables. This suggests that periods of enhanced convective rainfall are generally accompanied by reduced θ_e values. Physically, this may reflect the cooling effects of cloud cover, precipitation, and reduced solar insolation during active convective phases.

However, the coefficient of determination ($r^2 = 0.17$) indicates that only 17% of the variability in convective rainfall is explained by θ_e. This falls within the threshold of a weak linear relationship, implying that additional dynamical and mesoscale factors contribute substantially to rainfall variability.

Lomé

The relationship between convective rainfall and θ_e over Lomé (Figure 6) is similarly weak, with $r^2 = 0.0355$. This indicates that approximately 3.55% of the variance in rainfall is attributable to variations in θ_e. The negative slope of the regression line confirms an inverse relationship; however, the wide dispersion of data points demonstrates considerable variability and limited predictive strength.

The occurrence of convective rainfall across a broad range of θ_e values—including moderate and relatively low θ_e—further underscores the weak thermodynamic control on rainfall at this coastal station. Local sea-breeze circulations and synoptic-scale moisture convergence may play a more dominant role.

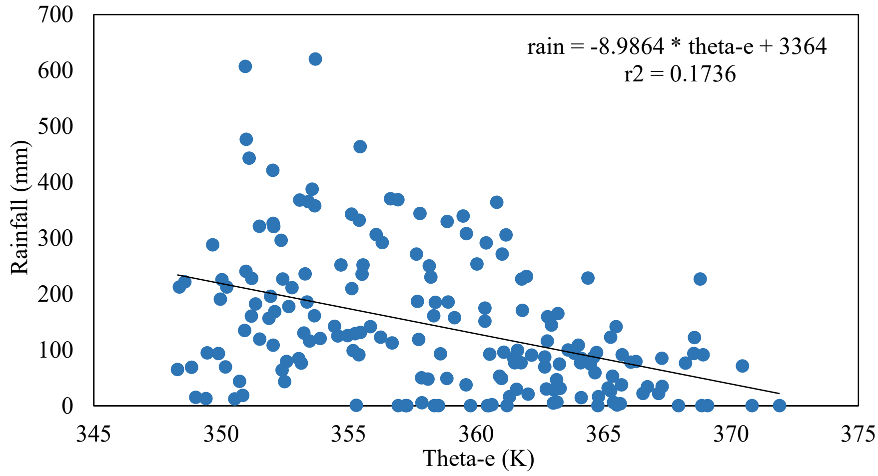


Figure 5. Correlation graph of convective rainfall and theta-e over Lagos

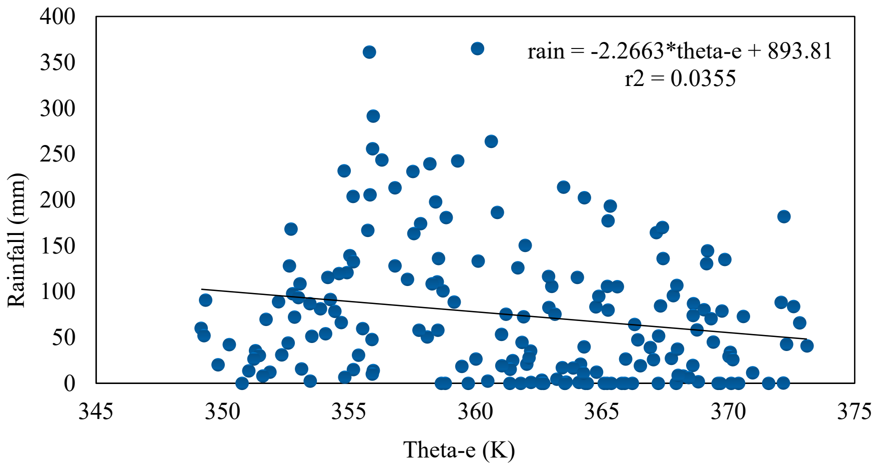


Figure 6. Correlation graph of convective rain and theta-e over Lome

Abuja

Figure 7 shows that Abuja exhibits a weak-to-moderate correlation ($r^2 = 0.3405$), indicating that approximately 34.05% of rainfall variability can be explained by θ_e. Although this represents the strongest association among the four stations, nearly two-thirds (~66%) of rainfall variability remains unaccounted for by θ_e alone.

The presence of numerous low-rainfall events at relatively high θ_e values suggests that elevated thermodynamic instability does not automatically translate into convective precipitation. This highlights the importance of additional meteorological controls such as vertical wind shear, low-level moisture convergence, synoptic forcing, and topographic influences in triggering and sustaining convection.

Dapaong

Figure 8 indicates a negative correlation between convective rainfall and θ_e in Dapaong, with $r^2 = 0.1422$. Thus, approximately 14.2% of rainfall variability is explained by θ_e, confirming a weak linear relationship. The pronounced scatter of observations around the regression line reflects substantial inter-event variability and suggests that rainfall generation is influenced by factors beyond thermodynamic energy alone. Notably, higher rainfall amounts are frequently observed at comparatively lower θ_e values, reinforcing the inverse tendency.

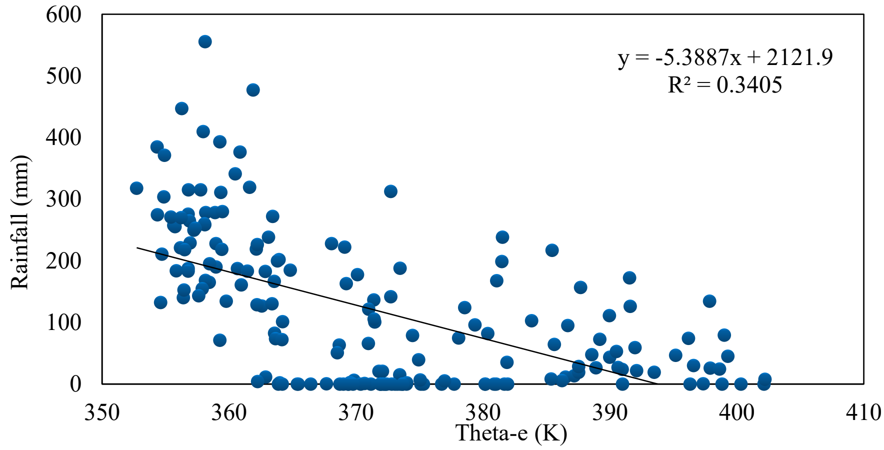


Figure 7. Correlation graph of convective rain and theta-e over Abuja

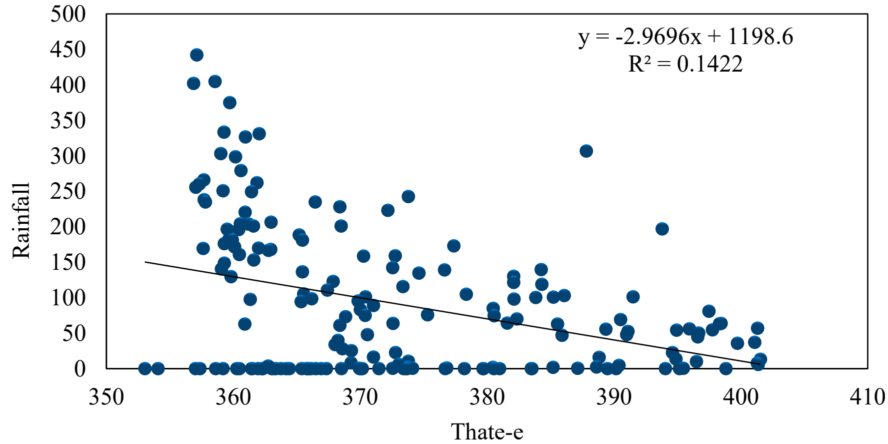


Figure 8. Correlation graph of convective rain and theta-e over Dapaong

Conclusively, all four locations—Lagos, Lomé, Abuja, and Dapaong—the correlation analysis demonstrates a generally inverse relationship between convective rainfall and θ_e, with coefficients of determination ranging from 0.04 to 0.34 (weak to weak–moderate). This pattern is consistent with Loua et al. (2019), who reported that increasing temperature trends may correspond with declining rainfall in certain West African contexts.

The inverse association likely reflects the thermodynamic response of θ_e to rainfall-induced cooling and latent heat redistribution. However, the weak explanatory power across most stations indicates that θ_e alone is insufficient to predict convective rainfall. Convective development in West Africa is governed by a complex interaction of thermodynamic instability, large-scale monsoon dynamics, vertical wind shear, moisture transport, and local forcing mechanisms. Thus, while θ_e provides a useful measure of atmospheric moist static energy, rainfall occurrence and intensity are strongly modulated by dynamic processes beyond thermodynamic potential alone.

Daily Variation of the Effect of Theta-E on Convective Rainfall

To assess the relative influence of equivalent potential temperature (θ_e) on convective rainfall variability in West Africa, Figures 9–12 present comparative daily time series of convective rainfall and θ_e during the core rainy season (June–September; 122 days). For each station, the wettest and driest years within the 2003–2017 study period were selected to evaluate thermodynamic–precipitation interactions under contrasting hydroclimatic conditions.

Lomé

Figures 9 (a) and 9 (b) illustrate the daily evolution of convective rainfall and θ_e during June–September for 2010 (wettest year) and 2016 (driest year), respectively. Convective rainfall exhibits pronounced day-to-day variability, characterized by intermittent heavy rainfall events separated by extended dry spells. In contrast, θ_e shows a gradual seasonal decline over the four-month period, generally ranging between 350 K and 370 K.

In the wet year (2010), a marked rainfall peak around day 9 is associated with a reduction in θ_e to approximately 355 K, reflecting the thermodynamic adjustment following convective activity. This inverse behavior is consistent throughout the season, suggesting that intense rainfall episodes are accompanied by cooling effects and latent heat redistribution that reduce θ_e.

During the dry year (2016), rainfall events are less frequent, and θ_e values are generally lower and less variable. Nevertheless, convective rainfall in both years tends to occur when θ_e lies within the range of approximately 350–370 K, indicating a threshold conducive to atmospheric instability.

Dapaong

Figures 10 (a) and 10 (b) depict the corresponding daily variations for 2013 (wettest year) and 2003 (driest year). As observed in Lomé, convective rainfall is highly episodic, while θ_e decreases gradually through the season, ranging approximately from 390 K to 350 K.

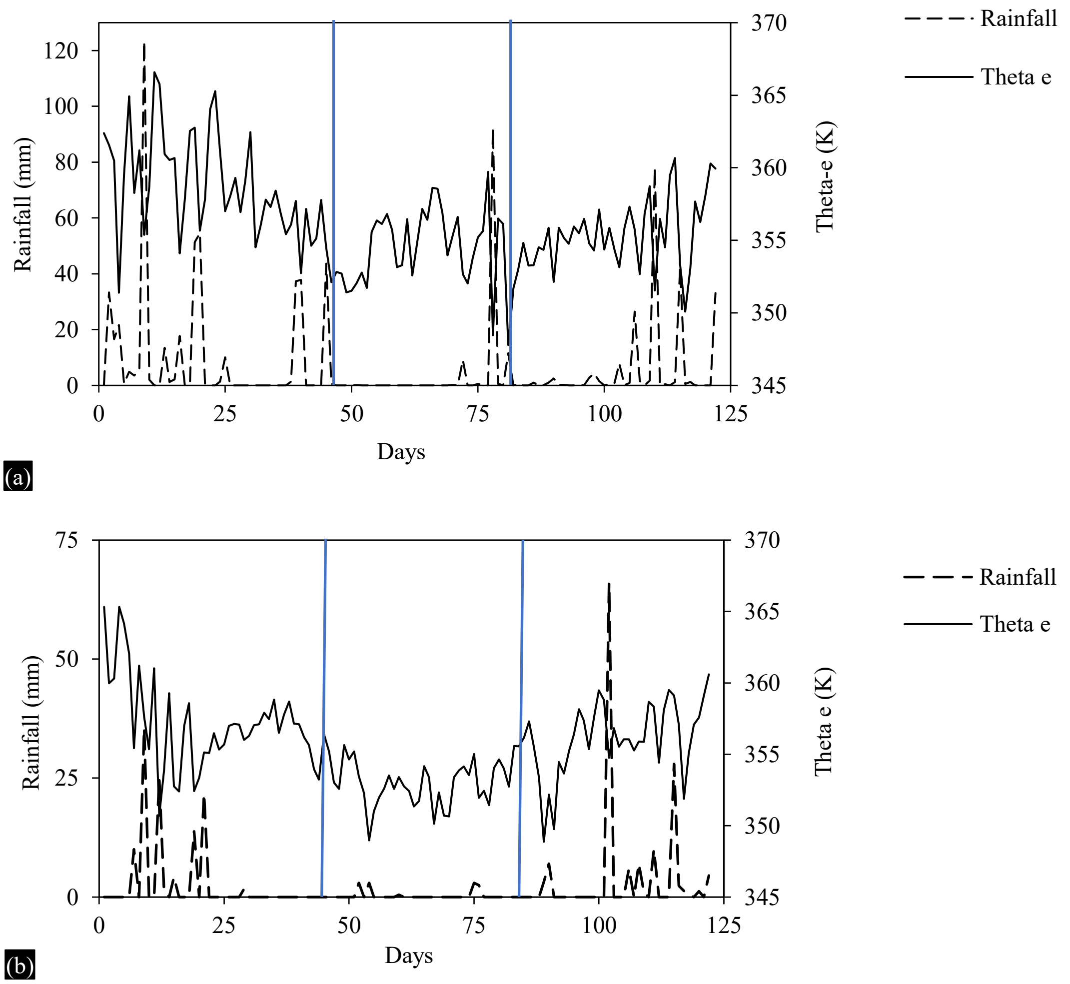
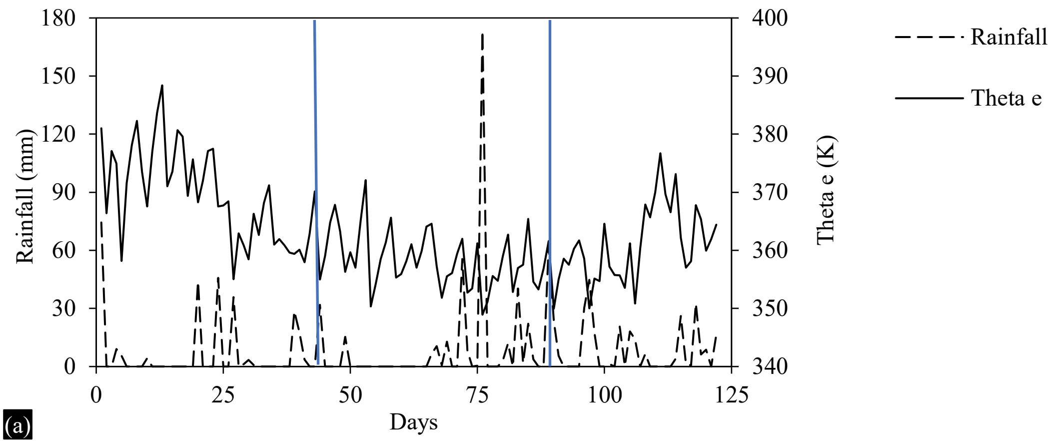


Figure 9. Daily variation of theta-e and convective rainfall in Lome during the wet (2010) and dry (2016) years



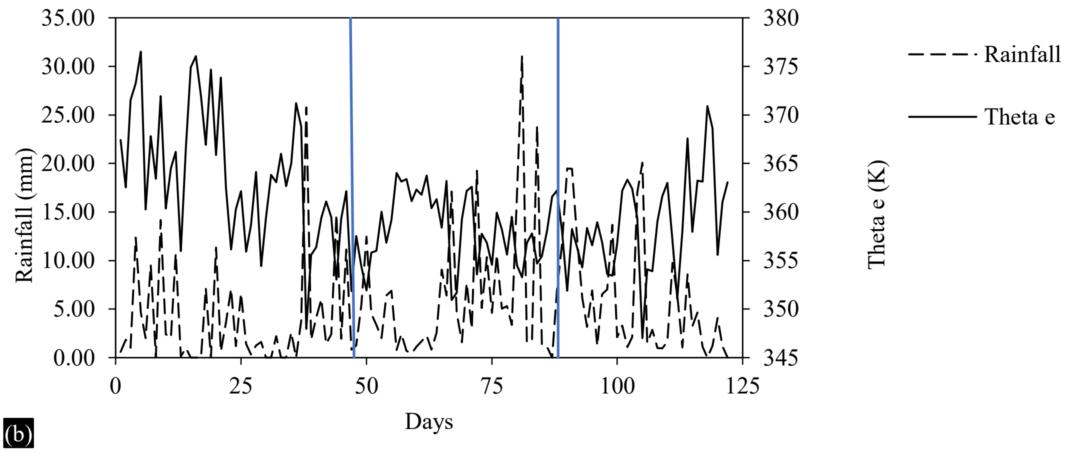


Figure 10. Daily variation of theta-e and convective rainfall in Dapaong the (a) wet (2013) and (b) dry (2003) years

In the wet year, an exceptional rainfall event (~150 mm) around day 76 (mid-August) coincides with a noticeable decline in θ_e (~350 K). This pattern suggests that although high θ_e values indicate favorable thermodynamic conditions for instability, the occurrence of intense convective rainfall can subsequently reduce θ_e through atmospheric cooling and stabilization.

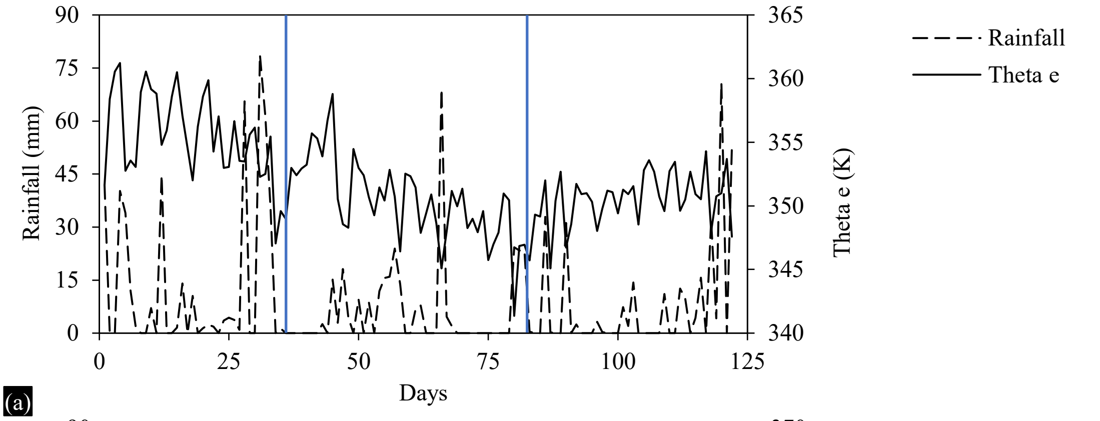
The dry year shows fewer rainfall events and generally lower θ_e values. Convective rainfall in Dapaong predominantly occurs within a θ_e range of approximately 345–375 K, reinforcing the role of moist static energy in supporting deep convection.

Lagos

Figures 11 (a) and 11 (b) present the daily variability for 2014 (wettest year) and 2006 (driest year). Rainfall variability is again pronounced, with more frequent rainfall days during the wet year. θ_e exhibits a seasonal decline from approximately 365 K to 345 K.

A notable rainfall maximum (~80 mm) around day 31 (1 July) in 2014 coincides with a reduction in θ_e (~357 K), illustrating the inverse relationship between rainfall intensity and θ_e. The dry year shows fewer convective rainfall events and relatively lower θ_e values.

The reduced frequency of convective rainfall in some years may be linked to the northward displacement of the Inter-Tropical Discontinuity (ITD) toward approximately 22°N, favoring stratiform monsoon precipitation south of 10°N (Ilesanmi, 1971; Omotosho, 1985) [26, 27]. Convective rainfall in Lagos generally occurs when θ_e ranges between approximately 345–360 K.



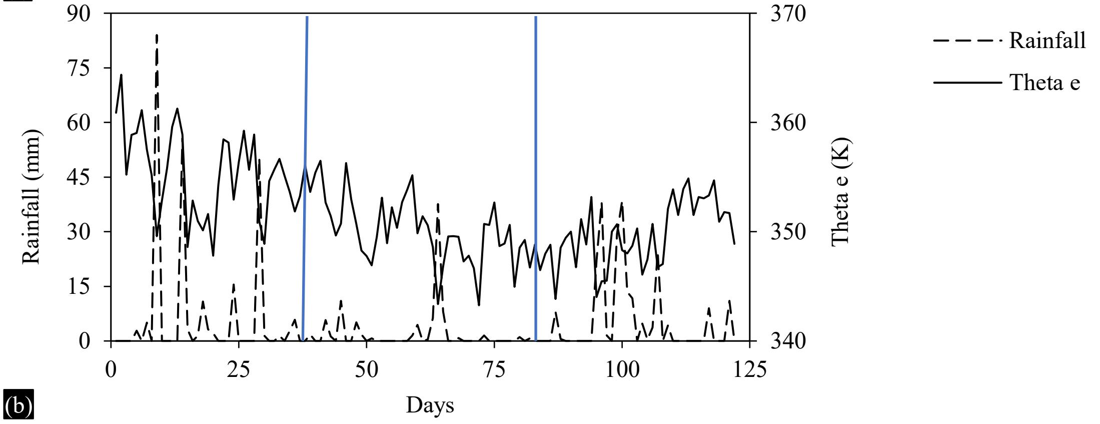


Figure 11. Daily variation of theta-e and convective rainfall in Lagos the (a) wet (2014) and (b) dry (2006) years

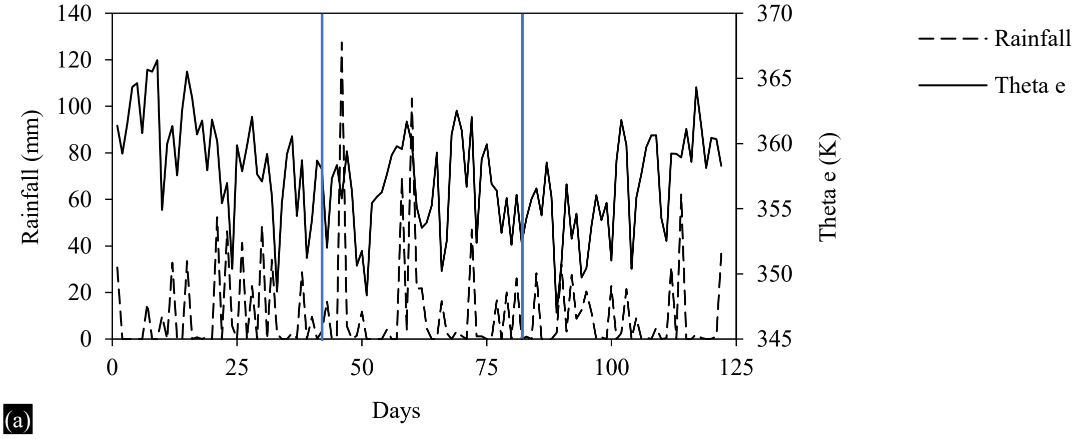
Abuja

Figures 12 (a) and 12 (b) show the daily evolution for 2003 (wettest year) and 2013 (driest year). Rainfall variability is high, with more frequent events during the wet year. θ_e declines seasonally from approximately 365 K to 345 K.

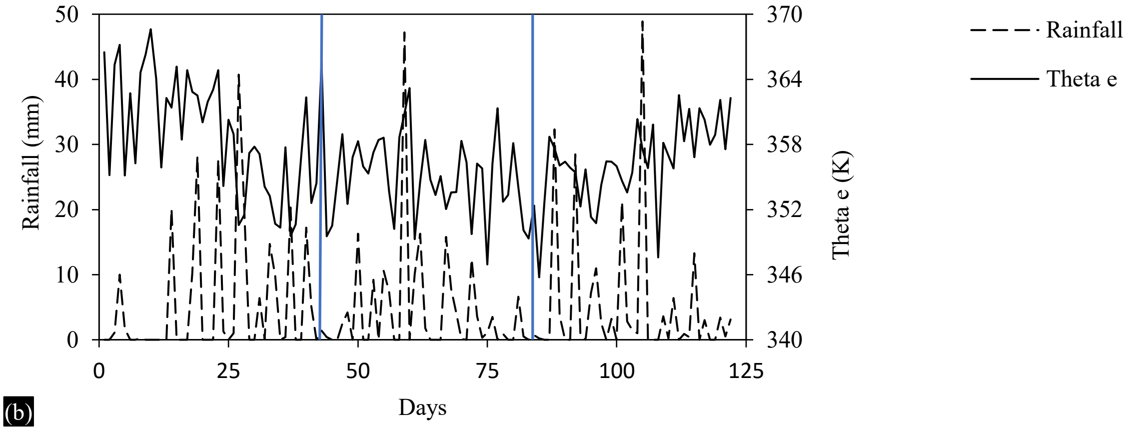
In the wet year, a major rainfall peak (~130 mm) around day 46 (16 July) is accompanied by a decrease in θ_e (~357 K), followed by another peak near day 60. These fluctuations suggest that convective outbreaks are associated with high pre-event θ_e values, followed by thermodynamic stabilization after rainfall. During the dry year, rainfall events are fewer, and θ_e values are generally lower. Convective rainfall in Abuja typically occurs when θ_e lies between 345–370 K, reflecting the combined influence of moist southwesterly flow and continental heating.

It generally implies that across all four stations, θ_e exhibits a broadly similar seasonal evolution characterized by gradual decline during the rainy season, while convective rainfall displays strong day-to-day variability. Peak rainfall events are generally preceded by elevated θ_e values (often exceeding ~355 K for several days), suggesting that the buildup of moist static energy contributes to convective initiation. Conversely, θ_e values below approximately 340 K are rarely associated with significant convective rainfall, indicating insufficient thermodynamic support for deep convection. Spatial contrasts are also evident. Northern stations (Dapaong and Abuja) record higher peak convective rainfall amounts than southern coastal stations (Lomé and Lagos).

This difference may be attributed to the latitudinal position of the ITD and the greater dominance of convective systems in the Sudanian zone, where convective rainfall contributes a substantial proportion of annual precipitation (Omotosho, 1987) [27]. In contrast, coastal stations experience a greater contribution from stratiform monsoon precipitation.



(a)



(b)

Figure 12. Daily variation of theta-e and convective rainfall in Abuja the (a) wet (2003) and (b) dry (2013) years

Overall, the daily time-series analysis confirms that while elevated θ_e provides a necessary thermodynamic condition for convection, the magnitude and frequency of convective rainfall are modulated by large-scale monsoon dynamics, ITD migration, and regional moisture availability.

CONCLUSION

This study evaluated the applicability of equivalent potential temperature (θ_e) as a thermodynamic predictor of convective rainfall over selected locations in West Africa. Using standard meteorological observations, θ_e was derived and examined across inter-annual, seasonal, and daily timescales to determine its relationship with the occurrence and intensity of convective systems.

Inter-annual analyses revealed a generally increasing trend in θ_e over the 15-year study period, despite contrasting north–south rainfall tendencies. This divergence suggests that while thermodynamic energy (as represented by θ_e) has increased, rainfall responses remain spatially heterogeneous, reflecting the influence of large-scale monsoon dynamics, moisture transport, and regional circulation patterns. Seasonal assessments demonstrated an inverse phase relationship between rainfall and θ_e during peak monsoon months, with maximum precipitation coinciding with relatively reduced θ_e values. This behavior highlights the complex feedback between latent heat release, cloud cover, atmospheric cooling, and instability during active convective periods.

Daily time-series analyses further indicated that convective rainfall events are typically preceded by elevated θ_e values, suggesting that θ_e functions as a preconditioning or energy-accumulation parameter for deep convection. However, θ_e often decreases during or immediately after rainfall events due to thermodynamic stabilization. Thus, θ_e is more appropriately interpreted as a precursor indicator of atmospheric instability rather than a concurrent signal of active convection.

Overall, the findings confirm that θ_e effectively captures the combined influence of temperature and moisture—two critical determinants of buoyancy and convective potential. While θ_e alone does not fully explain rainfall variability, it provides meaningful diagnostic insight into the thermodynamic environment favorable for storm development. Convective systems were observed to occur more frequently and contribute a greater proportion of annual rainfall in northern inland stations compared to coastal stations, consistent with the stronger dominance of deep convective processes in the Sudanian zone.

Incorporating θ_e thresholds and anomaly monitoring into operational forecasting frameworks may enhance early warning capabilities for convective hazards, including flooding, lightning, strong winds, and hail. When combined with additional dynamical parameters such as vertical wind shear, moisture convergence, and lapse rates, θ_e can contribute to improved storm prediction and risk management across West Africa. Overall, this study demonstrates that equivalent potential temperature provides added thermodynamic value for diagnosing and forecasting convective storm development and associated societal impacts in the region.

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