Sensitivity of FAO Penman–Monteith reference evapotranspiration ($\text{ET}_o$) to climatic variables under different climate types in Nigeria

Ndulue Emeka, Onyekwelu Ikenna, Michael Okechukwu, Anyadike Chinenye and Echiegu Emmanuel

ABSTRACT

Understanding the impact of changes in climatic variables on reference evapotranspiration ($\text{ET}_o$) is important for predicting possible implications of climate change on the overall hydrology of an area. This study aimed to determine the effects of changes in $\text{ET}_o$ with respect to changes in climatic variables. In addition, the specific objective was to determine the sensitivity coefficients of $\text{ET}_o$ in seven different locations in Nigeria with distinct agroecology, namely Maiduguri (Sahel savannah), Sokoto (Sudan savannah), Kaduna (Guinea savannah), Jos (Montane), Enugu (Derived Savannah), Ibadan (tropical rainforest), and Port Harcourt (coastal). The results showed that $\text{ET}_o$ is most sensitive to changes in maximum temperature ($T_{\text{max}}$) in Maiduguri, Sokoto, Kaduna, and Jos. In Enugu and Ibadan, $\text{ET}_o$ is most sensitive to changes in solar radiation ($R_s$), while in Port Harcourt, $\text{ET}_o$ is most sensitive to relative humidity (RH). Overall, based on the average annual sensitivity coefficients (SCs) of the study area, the SC is ranked in the order: RH > $R_s$ > $T_{\text{max}}$ > $U_2$ > $T_{\text{min}}$. Also, the results showed positive SCs of $\text{ET}_o$ to $R_s$, $T_{\text{max}}$, $U_2$, $T_{\text{min}}$, and negative SC for RH. This study can serve as a baseline for sustainable water management in the context of climate change and adapted to areas with a similar climate.

Key words | climate change, evapotranspiration, Nigeria, sensitivity analysis, sensitivity coefficient, tropics

HIGHLIGHTS

- For the first time, the influence of climatic variables on reference evapotranspiration ($\text{ET}_o$) was evaluated under different agro-ecological zones in Nigeria.
- For all locations in northern Nigeria, $\text{ET}_o$ is most and least sensitive to maximum temperature ($T_{\text{max}}$) and minimum temperature ($T_{\text{min}}$), respectively, while in southern Nigeria, $\text{ET}_o$ is sensitive to solar radiation ($R_s$) and relative humidity (RH) and least sensitive to wind speed ($U_2$).
- During the growing season, $\text{ET}_o$ is most sensitive to RH and $R_s$ across all study locations.
- Across all agro-ecological zones, $R_s$, $T_{\text{max}}$, $T_{\text{min}}$, and $U_2$ had positive sensitivity coefficients (SCs), while RH had a negative SC.
- This study can serve as a baseline for sustainable water management in the context of climate change and adapted to areas with a similar climate.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).

doi: 10.2166/wcc.2020.200
INTRODUCTION

To meet the food demand of the projected human population of 9 billion by 2050, the world is expected to produce more than 60% more food relative to its 2005 production (Lal 2016). Water is an indispensable resource for food production. However, available water is under immense pressure as about 70% of the total available freshwater is used for agricultural purposes (Pimentel et al. 2004; Hertel & Liu 2016). This is further worsened by climate change, water scarcity, and other water-related problems (Hertel & Liu 2016; Sadow et al. 2017). This has necessitated the need for efficient and effective management of water resources. Sustainable water management in agriculture requires an accurate estimate of the reference crop evapotranspiration (ET\(_\text{o}\)). This is the first step to satisfying the water requirement of crops.

ET\(_\text{o}\) is one of the most important components of the hydrologic cycle. It is a combined term of evaporation through the soil surface and transpiration, a process where water is lost through the stomatal openings in the leaves. It has been referred to as the second most important hydrologic variable after precipitation (Goyal 2004; Alexandris et al. 2008) and the least understood hydrologic variable (Silva 2015). In a dry climate, it can constitute about 95% of the water balance (Wilcox et al. 2005). ET\(_\text{o}\) is important in determining water use of crops, water balance studies, hydrologic modelling, irrigation scheduling, and irrigation management (Allen et al. 1998). The direct method of determining actual crop water use involves the use of a lysimeter, which is based on the principle of water balance. Although it is more accurate, it is time demanding, laborious, and expensive and requires skills and experience (Allen et al. 1998). The indirect method is simply by multiplying crop coefficient (\(K_c\)) and reference evapotranspiration (ET\(_\text{o}\)). \(K_c\) represents specific crop characteristics that differentiate a field crop from the reference grass, while ET\(_\text{o}\) is an indication of climatic demand (Allen et al. 1998). The FAO Penman–Monteith equation (FAO-PM) is the recommended standard equation for estimating ET\(_\text{o}\) because it has a high correlation with a lysimeter (Allen et al. 1998; Bakhtiari et al. 2011). However, the FAO-PM equation is limited in application because its inputs (solar radiation, air temperature, air humidity, and wind speed) are not readily available in most weather stations, especially in developing countries.

The FAO-PM equation combines the energy balance (radiative) and the mass transfer (aerodynamic) equations to compute ET\(_\text{o}\) using weather variables (Allen et al. 1998). The dominating component in the FAO-PM depends on the location. For example, the energy component is the controlling term in the humid climates, while the mass transfer component is dominant in semi-arid regions (Allen et al. 1998; Irmak et al. 2006; Vicente-Serrano et al. 2014).

Among the variables used for computing ET\(_\text{o}\), some are more influential than others (Debnath et al. 2015), depending on the climate, location, and local conditions of the area. Under limiting conditions, Koudahe et al. (2018) argue that...
identifying the climatic variables most sensitive to ET₀ becomes imperative, so that emphasis is placed on the measurements of those variables which could be used for developing simple empirical ET₀ models. Identifying sensitive variables is also important in adapting and mitigating climate change impacts (Nouri et al. 2017). Observations around the world have revealed that the earth’s climate has changed and is still changing (IPCC 2013; USGCRP 2018). Between 1901 and 2016, global temperature has increased by about 1 °C (USGCRP 2018), while rainfall variability and extreme rainfall events have also been on the rise (IPCC 2013; Alexander 2016). The African continent is most vulnerable to climate change because of its high dependence on rainfall for agriculture (IPCC 2013). Specifically, sub-Saharan Africa has been identified as the greatest food security risk region (Van Ittersum et al. 2016) since 96% of total crop production depends on rainfall (World Bank 2013). Nigeria has been singled out to receive a great deal of these impacts because of its burgeoning population and dominant rainfed agriculture (Ayinde et al. 2011).

Understanding the impact of changes in climatic variables on ET₀ is important to assess the possible implications of climate change on water resources, water management, and the overall hydrology of an area. ET₀, alongside other meteorological parameters, is an important variable that can be used to study climate change and examine its impacts on water use (Darshana et al. 2013; Wang et al. 2013). The sensitivity of ET₀ to changes in climate variables has been studied widely in various countries, including China (Gong et al. 2006; Gao et al. 2016), India (Darshana et al. 2013; Patle & Singh 2015; Patle et al. 2019), the US (Irmak et al. 2006), Cote d’Ivoire (Koudahe et al. 2018), Iran (Sharif & Dinpashoh 2014), Spain (Vicente-Serrano et al. 2014), and Germany (Bormann 2011). Yang et al. (2013) observed that in the temperate, sub-humid climate of northern China, ET₀ is most sensitive to relative humidity and solar radiation during the winter and summer seasons, respectively. Similarly, Jiang et al. (2013) noted that ET₀ is most sensitive to relative humidity under the monsoon climate in southwestern China. By studying the sensitivity of ET₀ in dry (arid and semi-arid) climates, Liu et al. (2010), Hou et al. (2015), and Gao et al. (2016) observed that ET₀ is most sensitive to solar radiation and temperature (Goyal 2004; Patle & Singh 2015). Irmak et al. (2006) attributed the influential role of temperature under dry climate to the exponential relationship between temperature and saturation vapour deficit and the linear relationship between vapour pressure deficit (VPD) and ET₀. In contrast, under humid climate, Irmak et al. (2006), Tabari & Talaei (2014), and Koudahe et al. (2018) reported that ET₀ is highly influenced by solar radiation and sunshine hours. The dominance of solar radiation under wet climate is attributed to the lower influence of other climatic variables (Hupet & Vanclooster 2001). Besides, under all climate types in Brazil (tropical, subtropical, and semi-arid), Jerszurki et al. (2019) found out that ET₀ is most sensitive to VPD, followed by wind speed. This agrees with Vicente-Serrano et al. (2014), although in a semi-arid climate. Moreover, Zhao et al. (2015) reported that under arid climate, ET₀ is most sensitive to relative humidity. From the literature, even under similar climates, we observed diverging results and no clear pattern of the climate variable influencing ET₀. This shows that ET₀ sensitivity is location-specific (Liu et al. 2010). This may be due to non-climate related factors (Gao et al. 2016; Jerszurki et al. 2019) and the complexity of the FAO-PM ET₀ equation (Vicente-Serrano et al. 2014). Previous studies have also examined the impacts of more than one variable on ET₀. Under arid and semi-arid climate, Sharif & Dinpashoh (2014) reported that by increasing mean temperature and wind speed at 20%, while decreasing actual vapour pressure, ET₀ increased by 36.4%.

The subject on sensitivity analysis and sensitivity coefficient has continued to be studied under different locations and climates, while there are no general conclusions regarding the most sensitive weather variable to ET₀. From the above literature review, it can be seen that the research on the sensitivity coefficient has been reported for different parts of the globe, with very little or no information available for Nigeria. This may be due to data scarcity, limited meteorological stations, and long-term quality meteorological data. Therefore, the objectives of this study are to (i) determine the magnitude of changes in ET₀ with respect to changes in climatic variables under different agro-ecological types in Nigeria, (ii) determine the sensitivity coefficients of ET₀ to changes in climatic variables under different agro-ecological types in Nigeria, and (iii) develop spatial maps of ET₀ sensitivity coefficients in Nigeria.
MATERIALS AND METHODS

Study area

Locations within Nigeria were selected for this study (Figure 1). The study area represents unique and different agro-ecological zones found in Nigeria. Nigeria is on the western coast of Africa, located on latitude 3°–15° E and longitude 4°–14° N, with a land area of 923,769 km², which is about 14% of West Africa. The country is also the most populous nation in the African continent with a current population of about 200 million (World Bank 2019). Agriculture is the highest employer of labour, where about 20–50% of her citizens earn their living from agriculture. Although agriculture is small scale, it contributed about 24.44% to GDP (NBS 2019). Major crops produced in the country are broadly classified into root crops (cassava and yams), grains (millet, corn, and sorghum), and legumes (cowpea and beans). Others are industrial crops, which include oil palm, rubber, groundnut, and cocoa. The type of crop grown in an area is dictated by the climate and soil type. In general, tree crops are cultivated in the south, while grains, legumes, and groundnut are grown in the north (Anthony et al. 2019).

The climate of Nigeria is broadly classified into the tropical rainforest, tropical savannah, and montane climate (Iloeje 2001). Based on rainfall, temperature, elevation, and vegetation, Nigeria is classified into different agro-ecological zones. The tropical rainforest is subdivided into coastal (tropical wet) and tropical wet and dry, while the savannah includes Derived savannah, Guinea savannah, Sudan savannah, and Sahel savannah. The montane climate has a cool climate with highland areas that are more than 1,520 m above sea level (Iloeje 2001). The climate of Nigeria is influenced by three atmospheric air masses: maritime tropical (mT), continental tropical (cT), and equatorial easterlies (Eludoyin et al. 2014). The mT and cT air masses originate from the Atlantic Ocean and the Sahara Desert. The point where both air masses meet is called the intertropical
discontinuity (ITD), which controls the rainfall pattern and season (Ugbah et al. 2020). Nigeria is marked by two distinct seasons: wet and dry season. Generally, the south has about 8–10 months of rainfall with an annual mean rainfall of about 1,200–3,000 mm, while rainfall in the north lasts for 2–4 months, with an annual mean rainfall amount of 400–1,100 mm. The wide difference in rainfall is due to the closeness of the Atlantic Ocean in the south and the Sahara Desert in the north. The south usually experiences bimodal peaks of rainfall in June and September, while the north has one rainfall peak in August. During the rainy and dry seasons, temperature ranges between 25–30°C and 20–30°C, respectively (Ugbah et al. 2020).

Figure 1 shows the specific study areas, namely Port Harcourt, Ibadan, Enugu, Jos, Kaduna, Sokoto, and Maiduguri. Each location represents a unique and agro-ecological zone. Port Harcourt represents the coastal zone. Ibadan, Enugu, Jos, Kaduna, Sokoto, and Maiduguri represents forest, Derived savannah, Montane, Guinea, Sudan, and Sahel agroecology, respectively. In this study, the southern region includes Port Harcourt, Ibadan, and Enugu, while Jos, Kaduna, Sokoto, and Maiduguri are broadly classified as the northern region. In general terms, the northern and southern regions can be classified as semi-arid and humid climate, respectively (FAO 2005). Also, in the southern region, the wet and dry season runs from April to October and November to March, respectively, while in the north, wet and dry season runs from May to September and October to April, respectively (Eludoyin et al. 2014). However, Maiduguri and Sokoto have very long dry season lasting from October to May and short wet season which runs from June to September (Singh 1995). Also, in Port Harcourt, the wet and dry season runs from March to October and November to February, respectively (Adejuwon 2012).

Data

The absence of meteorological stations and the accurate measuring equipment poses a serious challenge in many regions, especially in Africa (Van de Giesen et al. 2014). Nigeria, for example, has only about 54 weather stations serving the whole country (Obarein & Amanambu 2019). This is grossly inadequate based on the WMO (World Meteorological Organization) recommendations (Abdullateef 2017). Even with this limited number, most stations do not have long-term quality data (Oguntunde et al. 2012). Numerous studies have resorted to satellite data for their analysis (Bois et al. 2008; Agrawal et al. 2014; Dezfuli et al. 2017; Goroshi et al. 2017; Da silva et al. 2019; Ndulue et al. 2019). In this study, climate data were downloaded from the archives of NASA (Prediction of Worldwide Energy Resource) (NASA POWER 2019) at https://power.larc.nasa.gov/data-access-viewer/ from 1984 to 2018 (35 years). The database provides historical climatic datasets by inputting geographical coordinates of interest. NASA’s POWER global climate datasets (Stackhouse et al. 2018) are at a grid resolution of 0.5° × 0.5°. They have been found to reasonably represent different climates and, thus, have been widely applied in various studies (Lhendup & Lhundup 2007; Scorza Júnior et al. 2018; Laborde et al. 2019; Ndulue et al. 2019). For example, White et al. (2008), Lobell et al. (2011), Wart et al. (2013), Aramburu et al. (2015), Ojeda et al. (2018), and Bender & Sentelhas (2018) reported the close agreement of NASA climate data with ground-based weather stations. Therefore, for long continuous climate data, POWER Release 8.0.1 (with GIS applications) dataset was used.

Each study area was located on the GIS-enabled data viewer webpage and all the associated agroclimatology data, namely solar radiation (Rs), minimum temperature (Tmin), maximum temperature (Tmax), relative humidity (RH), and wind speed (U2). The data were further screened and checked for inconsistency following the recommendation of Allen (1996). Data quality checks include (i) Tmax > Tmin, (ii) Precipitation > 0, and (iii) Long-term (35) years of meteorological data were used. Trends and patterns of meteorological variables observed in ground-based weather stations are well accounted for and represented in the NASA POWER data. For example, bimodal rainfall peaks, rainfall seasonality, temperature ranges, etc., as observed in ground-based weather stations and gridded Climatic Research Unit time-series datasets (CRU TS 4.01; Harris et al. 2014) were represented in the NASA POWER data.

Reference crop evapotranspiration

The FAO-56 PM equation is expressed as follows (Allen et al. 1998):

\[
ET_0 = \frac{0.408 \Delta (R_s - G) + \gamma \frac{900}{T+273} [e_s - e_a] u_2}{\Delta + \gamma \times (1 + 0.34 \times u_2)}
\]

(1)
where $ET_o$ is the reference crop evapotranspiration (mm/day); $R_n$ is the net radiation (MJ/m²/day); $G$ is the soil heat flux (MJ/m²/day); $T$ is the average daily air temperature at a height of 2 m ($^\circ$C); $U_2$ is the wind speed at a height of 2 m (m/s); $e_a$ is the saturation vapour pressure (kPa); $e_v$ is the actual vapour pressure (kPa); $e_v - e_a$ is the VPD (kPa) $\Delta$ is the slope of the saturation vapour pressure–temperature curve (kPa/$^\circ$C); and $\gamma$ is the psychrometric constant (kPa/$^\circ$C).

**Sensitivity analysis and sensitivity coefficient**

Sensitivity analysis was performed to determine the most sensitive weather variable to $ET_o$ in a given location and to determine the extent to which changes in a weather variable affects $ET_o$. There are various methods of sensitivity analysis (Yin et al. 2010), and no method is superior over another as there is no single, universally accepted method (Irmak et al. 2006; Debnath et al. 2015; Ndiaye et al. 2017). However, a simple technique as used in this study and adopted by numerous hydrological studies involves plotting the relative change in dependent variables ($ET_o$) against the relative change in independent variables (solar radiation, minimum temperature, maximum temperature, wind speed, and relative humidity).

Partial derivatives have been used to compute the sensitivity coefficient (McCuen 1974; Saxton 1975). Since the FAO equation is a multivariable equation, the sensitivity coefficient transforms the partial derivatives into a dimensionless form (Gong et al. 2006; Nouri et al. 2017). The sensitivity coefficient ($SC$) is simply defined as the ratio of the changes in the $ET_o$ with respect to changes in a climatic variable (Irmak et al. 2006). $SC$ is expressed as follows (McCuen 1974; Beven 1979):

$$SC_i = \lim_{\Delta x \to 0} \left( \frac{\Delta ET_o/ET_o}{\Delta x_i/X_i} \right) = \delta ET_o \frac{X_i}{\delta X_i ET_o}$$

(2)

where $SC_i$ is the sensitivity coefficient and $X_i$ is the climate variable.

We adopted the procedure of Irmak et al. (2006) in computing the SCs for each variable and location. Numerous studies have also adopted this procedure (Gao et al. 2016; Nouri et al. 2017; Koudahe et al. 2018; Poddar et al. 2018; Jerszurki et al. 2019). First, the average daily value of each climatic variable and location for a period of 35 years (1984–2018) was calculated. This was used to calculate $ET_o$ using the FAO-PM equation. Then, a ±5 to ±25% increase and decrease were applied to each climate variable and new sets of daily $ET_o$ values were calculated. We believe that the range, ±5 to ±25%, captures plausible future climate change scenarios following current global events and global climate models (GCMs) estimates. For example, global temperature has been predicted to rise by 5 $^\circ$C in 2100 (USGCRP 2018). Numerous researchers have adopted similar ranges varying from ±5 to ±50% (Yin et al. 2010; Gao et al. 2016; Nouri et al. 2017; Koudahe et al. 2018; Poddar et al. 2018; Jerszurki et al. 2019; Patle et al. 2019).

With this, a plot showing the response of $ET_o$ to relative increase and decrease of the climate variable is developed. Monthly and annual changes in $ET_o$ were obtained by averaging daily changes. By simply dividing daily changes in $ET_o$ by daily changes in climatic variable gives the daily SC. Similarly, monthly, seasonal, and annual SCs were obtained by averaging the corresponding daily SCs.

A positive SC implies that an increase in the climate variable will result in an increase in $ET_o$, while a negative SC indicates that a decrease in the climate variable will result in a decrease in $ET_o$. The magnitude of the absolute value of the SC is an indication of the magnitude the climate variable has on $ET_o$. For example, a SC of 0.1 for a variable implies that a 5% increase in the variable would increase $ET_o$ by 0.5%, as other observed variables are held constant. Irmak et al. (2006) attributed the changes to the sensitivity of $ET_o$ to errors of the variable, with the assumption that other variables were accurately measured and held constant at their mean values during the period of analysis for each location.

**Spatial interpolation**

Although the number of weather stations in Nigeria is growing, it is still inadequate. The density of weather station to total agricultural land in Nigeria is about 1:2,188.17 km², given that agricultural land constitutes about 77.74% (718,138.02 km²) of the total land area (World Bank 2016). Spatial interpolation estimates unknown variables (e.g. climate) by using known measurements obtained from
weather stations (Kyriakidis & Goodchild 2006). Spatial interpolation methods include inverse distance weighing (IDW), spline, and Kriging. Numerous studies including Sharma & Irmak (2012), Gao et al. (2016), and Jiang et al. (2019) employed spatial interpolation to map ET$_o$. IDW assumes that the influence of a measured point diminishes with distance (Samanta et al. 2012). It has been widely used to spatially map weather variables, groundwater electrical conductivity, and ET$_o$ (Ha et al. 2011; Samanta et al. 2012; Seyedmohammadi et al. 2016). In this study, the spatial distribution of the average annual sensitivity coefficient was analysed for all locations by using the IDW interpolation tool in ArcGIS 10.7. IDW was chosen because it is a simple and accurate spatial interpolation method (Hodam et al. 2017; Jiang et al. 2019).

## RESULTS AND DISCUSSION

### Climatological analysis

Table 1 shows the summary statistics of the climatic variables for 35 years (1984–2018) for all the locations. It was observed that rainfall and relative humidity were highest in the south and lowest in the north, while maximum temperature, solar radiation, wind speed, and ET$_o$ were highest in the savannah and lowest in the rainforest zone. Specifically, the highest maximum temperature of 37.6 °C was observed in Maiduguri, while the lowest maximum temperature of 27.7 °C was recorded in Port Harcourt. Similarly, the highest average wind speed and ET$_o$ were observed in Maiduguri, while the lowest average wind speed and ET$_o$ were recorded in Port Harcourt. The average relative humidity and rainfall was highest in Port Harcourt and lowest in Maiduguri and Sokoto. The average minimum temperature was highest in Enugu and lowest in Jos. Overall, the averaged climate data from NASA in Table 1 agree reasonably with reported ground-based weather stations and CRU TS 4.01 datasets (Duru 1984; Chineke et al. 2010; Oguntunde et al. 2011; Oguntunde et al. 2012; Ogolo 2014; Obarein & Amanambu 2019).

**Table 1 | Average annual summary of climatic variables**

| Climatic variable | Maiduguri | Sokoto   | Kaduna   | Jos       | Enugu     | Ibadan   | Port Harcourt |
|-------------------|-----------|----------|----------|-----------|-----------|----------|---------------|
| Rainfall (mm/yr)  | 615.46 ± 2.22 | 676.06 ± 2.26 | 1,337.67 ± 3.97 | 1,071.76 ± 2.95 | 1,703.15 ± 3.3 | 1,453.35 ± 3.22 | 2,415.21 ± 4.31 |
| T$_{\text{min}}$ (°C) | 21.23 ± 3.83 | 21.42 ± 3.89 | 18.50 ± 2.15 | 17.78 ± 2.04 | 23.90 ± 2.31 | 22.10 ± 2.32 | 23.53 ± 0.88 |
| T$_{\text{max}}$ (°C) | 37.56 ± 3.19 | 35.20 ± 3.14 | 30.52 ± 2.64 | 29.82 ± 2.97 | 29.27 ± 1.13 | 29.58 ± 1.21 | 27.74 ± 1.02 |
| R$_{\text{s}}$ (MJ/m$^2$/day) | 20.35 ± 0.6 | 20.29 ± 2.13 | 19.60 ± 2.68 | 17.69 ± 0.3 | 17.64 ± 0.29 | 15.14 ± 0.7 | 15.14 ± 0.29 |
| RH (%) | 38.65 ± 22.00 | 39.39 ± 22.54 | 59.37 ± 20.72 | 56.17 ± 24.84 | 82.62 ± 7.94 | 84.58 ± 6.03 | 86.17 ± 4.65 |
| U$_2$ (m/s) | 2.61 ± 0.58 | 2.53 ± 0.63 | 2.21 ± 0.6 | 2.08 ± 0.54 | 1.71 ± 0.3 | 1.37 ± 0.29 | 1.41 ± 0.23 |
| ET$_o$ (mm/yr) | 6.95 ± 1.70 | 6.95 ± 1.53 | 5.10 ± 1.32 | 4.99 ± 1.53 | 3.74 ± 0.58 | 3.59 ± 0.49 | 3.18 ± 0.55 |
| Latitude (°N) | 11.85 | 13.01 | 10.6 | 9.86 | 6.46 | 7.43 | 4.85 |
| Longitude (°E) | 13.08 | 5.25 | 7.45 | 8.9 | 7.55 | 3.9 | 7.01 |
| Elevation (m) | 35 | 302 | 642 | 1,285 | 137 | 229 | 18 |
| Agroecology | Sahel savannah | Sudan savannah | Guinea savannah | Montane | Derived savannah | Tropical rainforest | Coastal |

T$_{\text{min}}$, minimum temperature; T$_{\text{max}}$, maximum temperature; R$_{\text{s}}$, solar radiation; RH, relative humidity; U$_2$, wind speed measured at 2 m height.

Changes in ET$_o$ with respect to changes in the climatic variable

Figure 2 shows the percent change in ET$_o$ versus the percent change in each of the meteorological variables (T$_{\text{max}}$, T$_{\text{min}}$, R$_{\text{s}}$, U$_2$, and RH) for each location. The steeper the slope (Figure 2), the larger the impact the variable has on ET$_o$ or the more sensitive the variable is on ET$_o$. The response of ET$_o$ to changes in each variable varied across different locations. In Maiduguri, Sokoto, Kaduna, and Jos, ET$_o$ was most sensitive to changes in T$_{\text{max}}$. In Ibadan and Enugu,
Figure 2 | Percent change in ET₀ with respect to changes in percent change in the climatic variable.
ET₀ was most sensitive to changes in Rₛ, while in Port Harcourt, ET₀ was most sensitive to changes in RH.

A 25% increase in Tₘₐₓ resulted in an average annual increase in ET₀ by 0.76 mm in Maiduguri and 0.17 mm in Port Harcourt, respectively. A variation in ±25% in Tₘₐₓ affected ET₀ estimates by ±18.2, ±17.8, ±14.9, ±14.1, ±11.9, ±12.1, and ±9.7% in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively (Figure 2). Our result agrees with other studies in West Africa and other regions but vary in magnitude. In Burkina Faso, Ndiaye et al. (2017) noted that a 25% change in Tₘₐₓ resulted in a 10–64.05% change in ET₀ in various locations, while in Côte d’Ivoire, Koudahe et al. (2018) noted that ET₀ increase by 0.49 mm in response to a 15% increase in Tₘₐₓ in Ferkessedougou station. In the US, Irmak et al. (2006) reported that a 5% increase in Tₘₐₓ can increase ET₀ between 0.06 and 0.11 mm/day. There is a consensus in the literature that temperature is most sensitive to ET₀ in arid and semi-arid climate (Goyal 2004; Tabari & Talaee 2014; Patle & Singh 2015). Irmak et al. (2006) attributed this to relationship between temperature, VPD, and ET₀. Goyal (2004) reported that ET could increase by 15 mm in response to a 1% rise in temperature in the arid region of Rajasthan. On the other hand, Biazar et al. (2019) noted that in the humid region of Iran, in response to a 20% increase in Tₘₐₓ, ET₀ varied between 6 and 17%.

The impact of the change in U₂ on ET₀ was observed mainly in northern locations and had almost a zero effect in some months in the southern region. The effect of U₂ on ET₀ decreased from the north to south. In Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, ET₀ estimates varied by ±9.7, ±9.2, ±5.5, ±5.7, ±1.2, ±0.62, and ±0.77% in response to change in ±25% in U₂ (Figure 2). Based on an annual average, an increase in wind speed resulted in 0.41, 0.39, 0.18, 0.2, 0.03, 0.01, and 0.02 mm increase in the ET₀ in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively (Table 2). This suggests that an increase in U₂ caused an increase in ET₀ in the north with a drier climate than the south with a humid tropical climate. This also demonstrates the impact of the mass transfer component in the FAO-PM equation in arid regions. This result agrees with Allen et al. (1998), Irmak et al. (2006), and Patle & Singh (2015), highlighting the significant role of wind speed in an arid environment as compared to the humid climate. This may be due to low humidity in the drier climate as compared to the humid climate. In the north, the highest impact of U₂ was observed during the harmattan period (November to March). During this period, the wind is dry and strong, the temperature is usually high, and the humidity is very low. These conditions favour a larger VPD, thus increasing ET₀. Tabari & Talaee (2014) found that under arid climate, ET₀ varies between ±9% in response to a ±20% change in U₂. Irmak et al. (2006) noted that a 10% change in U₂ led to a 3.2% change in ET₀ under semi-arid climate. Similarly, a 5% increase in U₂ caused a 0.77 mm/day increase in ET₀ (Jerszurki et al. 2019).

Rₛ is ranked second behind Tₘₐₓ. The effect of change in Rₛ on ET₀ was observed in almost all the locations. Rₛ had diverse effects on ET₀ in different agro-ecological zones and varied across the months. In Port Harcourt, Ibadan, and Enugu, the effect was more constant but varied significantly under the savannah agro-ecological zones. Based on an annual average, an increase in Rₛ resulted in 0.352, 0.375, 0.374, 0.35, 0.41, 0.41, and 0.36 mm increase in ET₀ in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. A 25% increase in Rₛ resulted in a 9.4, ±9.9, ±13.2, ±12.9, ±18.6, ±19.05, and ±18.6% change in ET₀, the estimate in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. The highest impact of the increase in Rₛ was observed in Enugu and lowest in Maiduguri. In western Himalayas, Poddar et al. (2018) noted that in response to a ±20% change in Rₛ, ET₀ changed by ±12%.

Changes in RH had more effect on ET₀ in locations in the south than locations in the north. In response to the change in RH by ±25%, ET₀ estimates varied by ±6.5, ±10.6, ±9.7, ±18.1, ±14.1, and ±19.5% in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. Based on an annual average, an increase in RH resulted in a 0.22, 0.21, 0.29, 0.24, 0.38, 0.3, and 0.34 mm decrease in ET₀ in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. Across all locations, increased RH resulted in decreased ET₀. This inverse relationship was also observed by Patle & Singh (2015), Ndiaye et al. (2017), Koudahe et al. (2018), and Poddar et al. (2018). Similar to Rₛ, we observed a gradual increase in the impact of RH on ET₀.
### Table 2

Monthly and annual average variation in $E_{To}$ (mm) with respect to change in the climate variable

| Location  | Variables | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  | Annual average |
|-----------|-----------|------|------|------|------|------|------|------|------|------|------|------|------|----------------|
| Maiduguri | $T_{max}$ | 0.90 | 1.09 | 1.16 | 1.01 | 0.85 | 0.71 | 0.48 | 0.33 | 0.38 | 0.55 | 0.79 | 0.83 | 0.76          |
|           | $T_{min}$ | 0.04 | 0.04 | 0.06 | 0.11 | 0.19 | 0.20 | 0.18 | 0.15 | 0.16 | 0.13 | 0.06 | 0.04 | 0.11          |
|           | U_2      | 0.55 | 0.67 | 0.73 | 0.62 | 0.45 | 0.33 | 0.18 | 0.08 | 0.09 | 0.22 | 0.45 | 0.51 | 0.41          |
|           | RH       | -0.12| -0.09| -0.08| -0.14| -0.27| -0.40| -0.44| -0.38| -0.29| -0.19| -0.14| -0.14| -0.22         |
| Sokoto    | $T_{max}$ | 0.89 | 1.03 | 1.03 | 0.96 | 0.87 | 0.72 | 0.50 | 0.34 | 0.38 | 0.53 | 0.74 | 0.81 | 0.73          |
|           | $T_{min}$ | 0.05 | 0.05 | 0.06 | 0.12 | 0.22 | 0.24 | 0.21 | 0.17 | 0.18 | 0.13 | 0.06 | 0.06 | 0.13          |
|           | U_2      | 0.56 | 0.64 | 0.66 | 0.57 | 0.44 | 0.31 | 0.16 | 0.06 | 0.06 | 0.20 | 0.44 | 0.52 | 0.39          |
|           | RH       | -0.13| -0.09| -0.07| -0.12| -0.27| -0.38| -0.39| -0.33| -0.26| -0.17| -0.13| -0.14| -0.21         |
| Kaduna    | $T_{max}$ | 0.67 | 0.80 | 0.75 | 0.61 | 0.43 | 0.32 | 0.24 | 0.20 | 0.24 | 0.32 | 0.46 | 0.56 | 0.47          |
|           | $T_{min}$ | 0.06 | 0.07 | 0.10 | 0.15 | 0.17 | 0.15 | 0.13 | 0.12 | 0.13 | 0.13 | 0.09 | 0.07 | 0.11          |
|           | U_2      | 0.35 | 0.44 | 0.41 | 0.26 | 0.12 | 0.05 | 0.03 | 0.01 | 0.01 | 0.06 | 0.18 | 0.27 | 0.18          |
|           | RH       | -0.25| -0.20| -0.19| -0.29| -0.37| -0.40| -0.39| -0.36| -0.27| -0.24| -0.24| -0.28| -0.29         |
| Jos       | $T_{max}$ | 0.73 | 0.77 | 0.68 | 0.51 | 0.34 | 0.26 | 0.20 | 0.17 | 0.20 | 0.28 | 0.47 | 0.64 | 0.44          |
|           | $T_{min}$ | 0.05 | 0.06 | 0.10 | 0.13 | 0.13 | 0.12 | 0.10 | 0.09 | 0.11 | 0.09 | 0.09 | 0.06 | 0.10          |
|           | U_2      | 0.45 | 0.48 | 0.39 | 0.21 | 0.08 | 0.04 | 0.02 | 0.01 | 0.02 | 0.06 | 0.21 | 0.37 | 0.20          |
|           | RH       | -0.13| -0.11| -0.16| -0.27| -0.31| -0.31| -0.33| -0.34| -0.30| -0.27| -0.20| -0.16| -0.24         |
| Enugu     | $T_{max}$ | 0.34 | 0.35 | 0.33 | 0.29 | 0.26 | 0.23 | 0.20 | 0.19 | 0.19 | 0.22 | 0.27 | 0.31 | 0.26          |
|           | $T_{min}$ | 0.18 | 0.20 | 0.20 | 0.20 | 0.18 | 0.16 | 0.14 | 0.13 | 0.14 | 0.16 | 0.17 | 0.18 | 0.17          |
|           | U_2      | 0.42 | 0.46 | 0.48 | 0.47 | 0.43 | 0.38 | 0.33 | 0.31 | 0.35 | 0.39 | 0.44 | 0.41 | 0.41          |
|           | RH       | -0.26| -0.28| -0.38| -0.43| -0.41| -0.47| -0.54| -0.56| -0.47| -0.35| -0.20| -0.22| -0.38         |
| Ibadan    | $T_{max}$ | 0.32 | 0.34 | 0.31 | 0.28 | 0.25 | 0.22 | 0.19 | 0.17 | 0.19 | 0.23 | 0.27 | 0.30 | 0.26          |
|           | $T_{min}$ | 0.13 | 0.16 | 0.18 | 0.17 | 0.16 | 0.14 | 0.12 | 0.11 | 0.12 | 0.14 | 0.15 | 0.15 | 0.14          |
|           | U_2      | 0.42 | 0.47 | 0.49 | 0.47 | 0.45 | 0.39 | 0.32 | 0.30 | 0.35 | 0.41 | 0.44 | 0.42 | 0.41          |
|           | RH       | -0.18| -0.23| -0.31| -0.34| -0.32| -0.36| -0.45| -0.47| -0.37| -0.25| -0.15| -0.14| -0.30         |
| Port Harcourt | $T_{max}$ | 0.25 | 0.26 | 0.21 | 0.18 | 0.16 | 0.13 | 0.11 | 0.12 | 0.11 | 0.13 | 0.17 | 0.22 | 0.17          |
|           | $T_{min}$ | 0.15 | 0.17 | 0.17 | 0.16 | 0.15 | 0.12 | 0.10 | 0.11 | 0.10 | 0.12 | 0.14 | 0.15 | 0.14          |
|           | U_2      | 0.42 | 0.45 | 0.43 | 0.41 | 0.37 | 0.29 | 0.25 | 0.27 | 0.28 | 0.32 | 0.37 | 0.41 | 0.36          |
|           | RH       | -0.22| -0.27| -0.33| -0.34| -0.34| -0.42| -0.47| -0.48| -0.44| -0.36| -0.26| -0.19| -0.34         |

Each value represents an average of 5 to 25% increase in each variable.
from the north to south. Gong et al. (2006) noted that RH was the most sensitive parameter to ET₀, and a 10% change resulted in a 15% change in ET₀. In Brazil under semi-arid climate, a 0.4 kpa increase in VPD increased ET₀ by 1.64 mm/day (Jerszurki et al. 2019).

T₀ had the lowest impact on ET₀ estimates in locations in the north than locations in the south. A variation in ±25% in T₀ affected ET₀ estimates by ±3.3, ±3.6, ±4.2, ±3.8, ±7.7, ±6.8, and ±7.3% in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. The impact of T₀ on ET₀ also varied across the months at all locations. Based on an annual average, an increase in T₀ resulted in a 0.11, 0.13, 0.11, 0.10, 0.17, 0.14, and 0.14 mm increase in ET₀ in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. The less effects of T₀ on ET₀ estimates using the FAO-PM equation was also reported by Irmak et al. (2006) in the US, Koudahe et al. (2018) in Cote d’Ivoire, and Ndiaye et al. (2017) in Burkina Faso. Ndiaye et al. (2017) noted that a ±5 to ±25% variation in T₀ caused ET₀ to vary between ±2 and ±18%.

Although the relationships between changes in ET₀ and changes in climatic variables were linear (Figure 2), we observed that the percent increase did not exactly match the percent decrease. Using Enugu for example, a 5, 10, 15, 20, and 25% annual increase in T_max resulted in an increase in ET₀ by 2.2, 4.4, 6.9, 9.4, and 11.9%, while a 5, 10, 15, 20, and 25% annual decrease in T_max resulted in a decrease in ET₀ by 2.1, 4.1, 6.1, 8, and 11.9%. This was also observed by numerous studies (Irmak et al. 2006; Koudahe et al. 2018; Poddar et al. 2018; Patle et al. 2019). We also observed that across all locations, the impact of an increase in T_max, RH, and T_min on ET₀ was higher than their decrease. However, for wind speed, ET₀ was more sensitive to decrease in wind speed than increase. For example, in Sokoto, a 25% decrease in wind speed resulted in a 9.2% decrease in ET₀, while a 25% increase in wind speed led to an 8.5% increase in ET₀. This suggests that lowering wind speed has more impacts on ET₀ than increasing wind speed. This was also observed by Tabari & Talaee (2014) who found that a decrease in U₂ and sunshine hours have more impact on ET₀ than their increase. For example, a 20% decrease in sunshine hours and wind speed will decrease ET₀ by 6.5 and 8.8%, respectively, while a 20% increase will decrease ET₀ by 2.9 and 8.6%, respectively.

In this study, we observed that a small change in a meteorological variable has higher impact on ET₀ than a larger change in another variable depending on the location. For example, in Maiduguri and Sokoto, we observed that a 10% change in T_max has a higher impact on ET₀ than a 25% change in RH and T_min. Similarly, a 15% change in T_max on ET₀ is greater than a 25% change in Rₛ and U₂. In Kaduna and Jos, we observed that a 10% change in T_max on ET₀ is greater than a 25% change in T_min and U₂. In Ibadan, Enugu, and Port Harcourt, a 5% change in Rₛ is greater than a 25% change in U₂. This confirms that U₂ has a minimal impact on ET₀ in southern Nigeria. Also, in Enugu and Ibadan, a 15% change in Rₛ has a higher impact on ET₀ than a 25% change in T_min. In addition, a 20% increase in Rₛ is greater than a 25% change in T_max. In Port Harcourt, RH has the greatest influence on ET₀. A 10% change in RH has a higher impact on ET₀ than a 25% change T_min, and a 15% change in RH is greater than a 25% change in T_max. Overall, this study confirms that T_max exerts a greater influence on ET₀ than other variables in northern Nigeria, while Rₛ and RH are the most sensitive variable in southern Nigeria.

Table 2 shows the monthly analysis of the variation of ET₀ due to changes in the meteorological variables, which may be hidden in the annual analysis. The impact of increased T_max and U₂ on ET₀ varied significantly across the months especially for locations in the north and was almost constant for locations in the south. For example, in Maiduguri, the change in ET₀ was most impacted by the change in T_max in the dry season than the rainy season, and the magnitude varied from 1.16 mm in March to 0.33 mm in August. The highest impact of the increase in T_max and U₂ was observed in Maiduguri and Sokoto. Across all locations, the response of ET₀ to change in T_max was maximum in March and minimum in August. In contrast, we observed that in all locations, the change in ET₀ was most impacted by the change in RH in the rainy season than the dry season. This implies at reduced RH, monthly ET₀ is increased (i.e. more water is lost) during the growing season than in the non-growing season across Nigeria. The impact of increased Rₛ and T_min on ET₀ varied across the months in the north and south. We observed that in Maiduguri, Sokoto, Kaduna, and Jos, the change in ET₀ was most impacted by the change in Rₛ and
$T_{\text{min}}$, in the rainy season than the dry season, while a reverse trend was observed in the south. In Enugu, Ibadan, and Port Harcourt, the change in ET$_{o}$ was most impacted by the change in $R_{s}$ and $T_{\text{min}}$ in the dry season than the rainy season. This suggests that while increased $T_{\text{min}}$ and $R_{s}$ in the north would increase monthly ET$_{o}$ in the rainy season, it would decrease monthly ET$_{o}$ in the south.

**Daily, monthly, seasonal, and annual sensitivity coefficients**

Figure 3(a)–3(e) shows the daily SCs of ET$_{o}$ to each meteorological variable. Across all locations with different agroecology, SC varied according to the seasons. Seasonality is a predominant phenomenon for countries in the tropics. The location of Nigeria and the influence of ITD play a significant role in the driving factors controlling the SC.

The temporal daily variations of SC are an indication of the diverse agro-ecological zones found in different parts of Nigeria. The result showed that ET$_{o}$ has a positive correlation with minimum temperature, maximum temperature, solar radiation, and wind speed, while it is negatively correlated with relative humidity as indicated in the numerical signs of their sensitivity coefficient. Table 3 shows the monthly and annual SCs of ET$_{o}$ to each meteorological variable. In terms of absolute values and on annual average, SC is ranked in the order: RH > $R_{s}$ > $T_{\text{max}}$ > $U_{2}$ > $T_{\text{min}}$. With an average annual SC of 0.77 in Port Harcourt, a 5% increase in RH, ET$_{o}$ will increase by 3.85%, as other weather variables are kept constant.

In Maiduguri and Sokoto, in terms of an annual average SC, $T_{\text{max}}$ has the highest SC followed by $R_{s}$, $U_{2}$, RH, and $T_{\text{min}}$, while in Kaduna and Jos, SC is ranked as $T_{\text{max}}$ > $R_{s}$ > RH > $U_{2}$ and $T_{\text{min}}$. This suggests that ET$_{o}$ is more sensitive to changes in $T_{\text{max}}$ in the north. An increase in temperature affects ET$_{o}$ by increasing the capacity of air to hold water vapour (Allen et al. 1998). Therefore, an increase in temperature would increase the evapotranspiration rate. This is particularly true for locations in the arid and semi-arid regions. For example, Debnath et al. (2015) reported that for locations in the semi-arid region of India, $T_{\text{max}}$ had the highest SCs. This also agrees with Tabari & Talaei (2014). From Figure 3, it was observed that the SC of all variables exhibited seasonality. That is, at some part of the season or year, they were maximum at another, minimum. $T_{\text{max}}$ had different effects on ET$_{o}$ at different times of the year. In Maiduguri, maximum and minimum SCs were observed in February and August, respectively. This corresponds to the dry and wet season, respectively. We observed the least variation of SC in Enugu, ranging between 0.42 and 0.49, with a mean average of 0.46. In general, higher SCs for $T_{\text{max}}$ were observed in the locations in the north than in the south. Jerszurki et al. (2019) noted that under tropical climate, the highest SC for air temperature occurred in spring and summer.

$U_{2}$ had diverse effects on ET$_{o}$ in different locations and agroecology. On an annual average, the highest SCs were recorded in Maiduguri and Sokoto, while other locations had SCs less than 0.1 with Enugu and Port Harcourt having the least (Table 3). We observed the least variation of SC in Port Harcourt, with SC ranging between 0.00 and 0.07, with a mean average of 0.03. As a result of the seasonality of $U_{2}$, the SC increased during the dry season for all locations but decreased during the wet season. This suggests that the effect of $U_{2}$ is felt more during the dry season than the wet season (Table 3). This also implies that small variations in wind speed during the dry season could result in larger variations in the ET$_{o}$ rate. The cool, dry, and dust-laden wind, usually referred to harmattan, from the Sahara Desert could be a contributing factor to the high SC of $U_{2}$ in the region, which increases ET$_{o}$. The dust haze from the north-easterly trade wind has also been reported to reduce radiation (Oguntunde et al. 2012). Our result agrees with Jerszurki et al. (2019) who noted that the largest and lowest SC for $U_{2}$ occurred in the semi-arid and tropical climate, respectively, in Brazil. Patle & Singh (2015) also noted a high SC for $U_{2}$ during summer in India. The role of temperature and especially wind speed in the evapotranspiration process has been noted by some researchers (Irmak et al. 2006; Jerszurki et al. 2019). Wind speed and temperature play key roles in the ET process, especially in the arid environment. The speed at which wind blows over a surface affects the ET rate. During the ET process, water vapour is moved from wet surfaces to an adjacent shallow layer until saturation. Once this is formed, wind replaces it with a drier air layer to absorb water vapour. Also, the speed at which wind moves can affect the vapour pressure. At
high wind speed, air expands, which creates room for extra water vapour and ET increases. Increasing the wind speed lowers the aerodynamic resistance, which increases ET$_o$ (Irmak et al. 2006).

In Port Harcourt, Ibadan, and Enugu, a reverse trend was observed. The SC of ET$_o$ to $T_{max}$ and $U_2$ decreased from the north to south. This signifies the greater influence of $T_{max}$ and $U_2$ on ET$_o$ in the north as compared to the south. In contrast, the SCs of ET$_o$ to $R_s$, RH, and $T_{min}$ increased from the south to north, implying the greater influence of $R_s$, RH, and $T_{min}$ in the south compared to the north. This agrees with Tabari & Talaee (2014) who reported that

Figure 3 | Sensitivity coefficient of ET$_o$ to (a) maximum temperature ($T_{max}$), (b) wind speed ($U_2$), (c) minimum temperature ($T_{min}$), (d) solar radiation ($R_s$), and (e) relative humidity (RH).
Table 3 | Monthly and annual sensitivity coefficients for all study sites

| Location   | Jan   | Feb   | Mar   | Apr   | May   | Jun   | Jul   | Aug   | Sep   | Oct   | Nov   | Dec   | Annual average |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------------|
| Maiduguri  |       |       |       |       |       |       |       |       |       |       |       |       |                 |
|            | 0.79  | 0.80  | 0.78  | 0.73  | 0.69  | 0.66  | 0.58  | 0.50  | 0.55  | 0.66  | 0.78  | 0.79  | 0.69           |
|            | 0.03  | 0.03  | 0.04  | 0.08  | 0.15  | 0.19  | 0.22  | 0.30  | 0.27  | 0.23  | 0.16  | 0.05  | 0.04           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.49  | 0.50  | 0.51  | 0.46  | 0.38  | 0.32  | 0.22  | 0.12  | 0.13  | 0.27  | 0.46  | 0.49  | 0.36           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.04  | 0.04  | 0.04  | 0.08  | 0.15  | 0.19  | 0.22  | 0.30  | 0.27  | 0.23  | 0.16  | 0.05  | 0.04           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.49  | 0.50  | 0.51  | 0.46  | 0.38  | 0.32  | 0.22  | 0.12  | 0.13  | 0.27  | 0.46  | 0.49  | 0.36           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.04  | 0.04  | 0.04  | 0.08  | 0.15  | 0.19  | 0.22  | 0.30  | 0.27  | 0.23  | 0.16  | 0.05  | 0.04           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.49  | 0.50  | 0.51  | 0.46  | 0.38  | 0.32  | 0.22  | 0.12  | 0.13  | 0.27  | 0.46  | 0.49  | 0.36           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.04  | 0.04  | 0.04  | 0.08  | 0.15  | 0.19  | 0.22  | 0.30  | 0.27  | 0.23  | 0.16  | 0.05  | 0.04           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.49  | 0.50  | 0.51  | 0.46  | 0.38  | 0.32  | 0.22  | 0.12  | 0.13  | 0.27  | 0.46  | 0.49  | 0.36           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.04  | 0.04  | 0.04  | 0.08  | 0.15  | 0.19  | 0.22  | 0.30  | 0.27  | 0.23  | 0.16  | 0.05  | 0.04           |
|            | 0.18  | 0.18  | 0.20  | 0.29  | 0.39  | 0.44  | 0.53  | 0.65  | 0.66  | 0.52  | 0.26  | 0.19  | 0.37           |
|            | 0.49  | 0.50  | 0.51  | 0.46  | 0.38  | 0.32  | 0.22  | 0.12  | 0.13  | 0.27  | 0.46  | 0.49  | 0.36           |
the sensitivity of ET\textsubscript{o} to \(T\text{\scriptscriptstyle{max}}\) and \(U_2\) decreased from the arid to humid climate. We also observed that in the south, ET\textsubscript{o} is most sensitive to \(R_s\), followed by RH, \(T\text{\scriptscriptstyle{max}}\), \(T\text{\scriptscriptstyle{min}}\), and \(U_2\). This ranking agrees with the reports of Irmak et al. (2006), Tabari & Talaei (2014), and Gao et al. (2016). This may be due to increased humidity, cloud cover, and rainfall in the tropical rainforest climate. In the West Liao River Basin, Gao et al. (2016) ranked \(R_s\), RH, \(T\text{\scriptscriptstyle{max}}\), sunshine hours, and \(U_2\) as the most sensitive variable to ET\textsubscript{o}. The amount of humidity in the air has a direct relationship with the rate of water loss from a surface. Under humid conditions, the wind replaces the saturated air and removes heat energy, which reduces the rates ET process will occur. For \(R_s\), locations in the south with rainforest agroecology have the highest SCs. Specifically, Ibadan has a SC of 0.76, while Port Harcourt and Enugu have a SC of 0.74 and 0.73, respectively. Our results agree with Irmak et al. (2006) and Koudahe et al. (2018), Gao et al. (2016) reported an average annual \(R_s\) SC of 0.89 in China. Oguntunde et al. (2012) confirmed the significant role of \(R_s\) in the ET process in Ibadan. The decrease in the SC of \(R_s\) is because of the decrease in the energy term which favours the aerodynamic term in the Penman–Monteith ET\textsubscript{o} equation. We observed a decrease in the \(R_s\) SC from the south to north and a negative relationship between the SC of \(R_s\) and \(U_2\).

The strongest and positive correlation between \(R_s\) and ET\textsubscript{o} have been observed under humid, wet, and warm conditions (Irmak et al. 2006). This is because solar radiation is the largest energy source in the ET process and water loss is influenced by the amount of energy available to evaporate water (Allen et al. 1998). The sensitivity of climatic variables in the tropical climate is strongly dependent on its seasonality throughout the year. As a result of \(R_s\) seasonality, the SC of \(R_s\) is bimodal in locations within the south, reaching its peak values in April and November and lowest in July for most locations in the south. Large \(R_s\) SC to ET\textsubscript{o} has been reported in the humid climate (Irmak et al. 2006), although it depends on the interplay between relative humidity and temperature, to decrease VPD and increase ET\textsubscript{o} (Jerszurki et al. 2019).

RH had a negative effect on ET\textsubscript{o}, as seen in the negative SC. This means that an increase in RH reduces the ET rate and vice versa. Although our result agrees with numerous studies (Patle & Singh 2015; Gao et al. 2016; Koudahe et al. 2018; Poddar et al. 2018), it disagrees with Debnath et al. (2015). We observed the diverse effect of RH on ET\textsubscript{o} in different locations. The largest and lowest annual SCs were observed in Port Harcourt and Maiduguri, respectively. RH had a pronounced seasonality effect on ET\textsubscript{o} in all locations. During the wet season, the SC of RH to ET\textsubscript{o} varied between 0.8 and 1.2 for locations in the south and ranged from 0.36 to 0.53 in the savannah agroecology. Within the wet season, the influence of RH on ET\textsubscript{o} was pronounced across all the locations. The highest SCs were observed during the wet season and lowest during the dry season. This could be because of rainfall, cloud, and low air temperature. Despite high \(R_s\) in humid conditions, high RH reduces the ET\textsubscript{o} since the air is close to saturation. Patle & Singh (2015) also noted a high SC for RH in the winter season.

\(T\text{\scriptscriptstyle{min}}\) also had different effects on ET\textsubscript{o} in different agroecology and locations. It is highest in the savannah during the wet season and lowest in the dry season. In the south, we observed very little variation in SC across the months. In Enugu, it ranges between 0.27 and 0.32, with a mean average of 0.3, and in Ibadan, it ranges between 0.21 and 0.29, with a mean average of 0.26, while in Port Harcourt, it ranges between 0.26 and 0.3, with a mean average of 0.28. Based on an annual average, SC for \(T\text{\scriptscriptstyle{min}}\) is maximum in Enugu and Port Harcourt and minimum in Sokoto and Maiduguri. Overall, the \(T\text{\scriptscriptstyle{min}}\) is least sensitive to ET\textsubscript{o} in almost all locations. This agrees with Irmak et al. (2006) and Debnath et al. (2015). On the contrary, Patle & Singh (2015) reported that the SC of \(T\text{\scriptscriptstyle{min}}\) was maximum in the monsoon season. SC for \(T\text{\scriptscriptstyle{min}}\) for all locations follows the same pattern as the SC for \(R_s\) but differ in magnitude (Figure 3). Gong et al. (2006) also observed that the daily variation of the SCs of \(R_s\) and \(T\) follows the same pattern. We observed that Port Harcourt, Ibadan, and Enugu have bimodal peaks at the start (April) and end of the growing season (October), and depression in September. However, for locations in the north, they have a uni-modal peak coinciding with the month of September. Consequently, we observed that the period where the SC was maximum for \(T\text{\scriptscriptstyle{min}}\) in the north (savannah), it was minimum in the south (Figure 3(d)). For all locations in the north, we observed that the SCs of \(R_s\), \(T\text{\scriptscriptstyle{min}}\), and RH reached peak values in July and August and were minimum at the start
and end ending of the season. In contrast, the SCs for $T_{\text{max}}$ and $U_2$ were lowest in July and August. A similar trend was also observed by Gao et al. (2016) and Jiang et al. (2019). We also observed a close resemblance between the SCs of $T_{\text{max}}$ and $U_2$ for Maiduguri and Sokoto, Kaduna and Jos, and Ibadan and Enugu. This might be because of the close distance between the locations; thus, may have similar agro-ecological characteristics. Also, we observed a seasonal variation of SCs for different variables and locations. For example, in Maiduguri, Sokoto, Kaduna, and Jos, between April and October, the SCs of $T_{\text{max}}$ and $U_2$ decreased, while the SCs of $R_s$, RH, and $T_{\text{min}}$ increased. This period falls in the rainy season, which is usually the growing season. Our results agree with Ndiaye et al. (2017) and Kou-dahe et al. (2018), whose study locations are in West Africa.

We also observed an almost constant SCs in some weather variables (Table 3). For example, in Enugu, we observed very little fluctuation in $T_{\text{min}}$ and $T_{\text{max}}$ while in Ibadan and Port Harcourt, we observed that $R_s$ and $U_2$ SC varied between 0.71–0.8 and 0.00–0.07, respectively. This agrees with the reports of Irmak et al. (2006), Nouri et al. (2017), and Jerszurki et al. (2019). Nouri et al. (2017) reported that the SC of $U_2$ varied between 0.27 and 0.31 at different seasons in Iran. Jerszurki et al. (2019) observed that the SCs of $R_s$ and $U_2$ were almost constant under the tropical climate of Brazil.

In summary and as shown in Table 4, $T_{\text{max}}$ and $U_2$ have greater SCs in the dry season than in the wet growing season for all locations. An opposite trend was observed for $R_s$ and RH, which have higher SCs in the wet season than in the dry season for all locations. $R_s$ had greater SC in the wet season than in the dry season for all locations except Port Harcourt. Numerous studies have reported that the SCs of average temperature and $R_s$ were higher in summer than in the winter (Gong et al. 2006; Yang et al. 2013; Nouri et al. 2017; Jiang et al. 2019).

The SCs of meteorological variables during the dry season are of interest because crop water demand is maximum and studies have shown a decline in rainfall due to changes in climate and landcover (Oguntunde et al. 2011; Ndulue & Mbajiorgu 2018). Crop production is important during the dry season because it could generate higher income for farmers since crops command high prices. During this period, irrigation would be the only source of water supply to crop. So, it is pertinent to identify climate variables that are most sensitive to ET and devise means to adapt and conserve water through an efficient water-saving irrigation system.

### Spatial distribution of sensitivity coefficient

Figure 4(a)–4(e) shows the spatial variation of the annual average SCs of $E_{\text{To}}$ to $T_{\text{max}}$, $U_2$, $R_s$, $T_{\text{min}}$, and RH across Nigeria. As shown in Figure 4(a)–4(e), we observed the large spatial variations in the climatic variables. For example, $T_{\text{max}}$ and $U_2$ have the largest SCs in the north. On the other hand, $R_s$, RH, and $T_{\text{min}}$ have the largest SCs in the south. As one moves from the north to south, the variation of SCs of $T_{\text{max}}$ and $U_2$ decreased, while the SCs of RH, $R_s$, and $T_{\text{min}}$ increased. Specifically, $T_{\text{max}}$ had maximum SCs in Maiduguri and Sokoto, which reduced in Jos and Kaduna, and was lowest in Port Harcourt and Ibadan. Similarly, $U_2$ had maximum SCs in Maiduguri and Sokoto; least SCs in Enugu and Port Harcourt, while other locations have SCs less than 0.1. The spatial distribution of the SC for $R_s$ had the highest values in the south, with the peak value in Ibadan, and the least value in Maiduguri. The spatial

| Seasonal (wet and dry) sensitivity coefficients for all locations | $T_{\text{max}}$ | $T_{\text{min}}$ | $R_s$ | $U_2$ | RH |
|---|---|---|---|---|---|
| Wet season | Maiduguri | 0.57 | 0.22 | 0.57 | 0.20 | –0.49 |
| | Sokoto | 0.59 | 0.21 | 0.57 | 0.21 | –0.35 |
| | Kaduna | 0.47 | 0.23 | 0.69 | 0.07 | –0.57 |
| | Jos | 0.40 | 0.21 | 0.70 | 0.04 | –0.65 |
| | Enugu | 0.44 | 0.31 | 0.74 | 0.01 | –0.97 |
| | Ibadan | 0.43 | 0.27 | 0.77 | 0.00 | –0.80 |
| | Port Harcourt | 0.28 | 0.28 | 0.74 | 0.02 | –0.99 |
| Dry season | Maiduguri | 0.75 | 0.07 | 0.28 | 0.44 | –0.13 |
| | Sokoto | 0.76 | 0.05 | 0.22 | 0.48 | –0.10 |
| | Kaduna | 0.68 | 0.10 | 0.36 | 0.34 | –0.27 |
| | Jos | 0.61 | 0.11 | 0.42 | 0.30 | –0.26 |
| | Enugu | 0.48 | 0.29 | 0.71 | 0.08 | –0.47 |
| | Ibadan | 0.49 | 0.26 | 0.77 | 0.04 | –0.42 |
| | Port Harcourt | 0.36 | 0.28 | 0.75 | 0.05 | –0.46 |
Figure 4 | Spatial distribution of the sensitivity coefficients for (a) $T_{\text{max}}$, (b) $U_2$, (c) $R_s$, (d) $T_{\text{min}}$, and (e) RH.
distribution of SC for RH had the highest values in the south, with the peak value in Port Harcourt, and the lowest values in the north, with the least SC value in Sokoto. The spatial distribution of SC for $T_{\text{max}}$ had the highest values in the south, with the peak value in Enugu, and the lowest values in the north, with the least SC value in Maiduguri.

Daily patterns and the spatial distribution of the SCs of the meteorological variables can be influenced by inherent local factors such as topography, elevation, latitude, and landcover. In this study, we observed that the SCs of $T_{\text{max}}$ and $U_2$ increased with increasing latitude. The average annual SC for $T_{\text{max}}$ was 0.68 in Sokoto (latitude 13.01) and 0.03 for Port Harcourt (latitude 4.85). Similarly, the SCs of RH increased with decreasing latitude. The SC of RH in Port Harcourt and Sokoto was 0.77 and 0.22, respectively. In Iran, Biazar et al. (2019) reported a positive and negative correlation with ET$_o$ for altitude and latitude, respectively, in Iran. In China, Gao et al. (2016) found out that elevation correlates positively with the SCs of RH, sunshine hours, and solar radiation, while it correlates negatively with $T_{\text{max}}$, $T_{\text{min}}$, and $U_2$.

**CONCLUSION**

In this study, the response of the FAO-PM ET$_o$ to changes in climate variables was analysed in seven different locations with distinct agroecology in Nigeria. Long-term (35 years) climate variables (solar radiation, minimum temperature, maximum temperature, relative humidity, and wind speed) were subjected to a ±5 to ±25% increase and decrease. The effects of the change of each variable on ET$_o$ and the sensitivity coefficients were determined. The results showed the wide variations of ET$_o$ sensitivities across different agro-ecological zones and seasons. ET$_o$ is most sensitive to changes in maximum temperature in Maiduguri, Sokoto, Kaduna, and Jos. In Enugu and Ibadan, ET$_o$ is most sensitive to changes in solar radiation, while in Port Harcourt, ET$_o$ is most sensitive to relative humidity. The sensitivity coefficients of relative humidity, solar radiation, and minimum temperature were higher in the wet season than the dry season, while the sensitivity coefficients of maximum temperature and wind speed were higher in the dry season than the wet season for all locations. In general, based on the average annual sensitivity coefficients, ET$_o$ is most sensitive to relative humidity, followed by solar radiation, maximum temperature, wind speed, and minimum temperature. Based on the results of the sensitivity analysis and sensitivity coefficients, we suggest the development of simple empirical ET$_o$ models that would require the most sensitive variables, i.e. RH, $R_s$, and $T_{\text{max}}$.

In conclusion, the results from this study showed that the climate change and climate variability could have significant impacts on the consumptive crop water use and increased crop water demand in the future in Nigeria. Therefore, there is need for adopting appropriate water management through an effective irrigation method and efficient irrigation design system that conserves water and cope with predicted impacts of climate change in Nigeria, as the country continues to seek means to attain food security.

**REFERENCES**

Abdullateef 2017 Densification of Nigerian Meteorological Agency automatic weather stations. In The WMO International Conference on Automatic Weather Stations (ICAWS-2017), 24–26 October 2017, Offenbach am Main, Germany.

Adejuwon, J. O. 2012 Rainfall seasonality in the Niger Delta Belt, Nigeria. *Journal of Geography and Regional Planning* 5 (2), 51–60.

Agrawal, A., Sharma, A. R. & Tayal, S. 2014 Assessment of regional climatic changes in the Eastern Himalayan region: a study using multi-satellite remote sensing data sets. *Environmental Monitoring and Assessment* 186, 6521–6536.

Alexander, L. V. 2016 Global observed long-term changes in temperature and precipitation extremes: a review of progress and limitations in IPCC assessments and beyond. *Weather and Climate Extremes* 11, 4–16.

Alexandris, S., Strivevic, R. & Petkovic, S. 2008 Comparative analysis of reference evapotranspiration from the surface of rainfed grass in central Serbia, calculated by six empirical methods against the Penman–Monteith formula. *European Water* 21 (22), 17–18.

Allen, R. G. 1996 Assessing integrity of weather data for reference evapotranspiration estimation. *Journal of Irrigation and Drainage Engineering* 122 (2), 97–106.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements – FAO Irrigation and Drainage Paper 56. UN-FAO, Rome, pp. 1–300.

Anthony, H. M. K.-G., Reuben, K. U., Malieze, I. & Solomon, O. 2019 Nigeria. Encyclopedia Britannica. Available from:
https://www.britannica.com/place/Nigeria (accessed 1 July 2019).

Aramburu Merlos, F., Monzon, J. P., Mercau, J. L., Taboada, M., Andrade, F. H., Hall, A. J. & Grassini, P. 2015 Potential for crop production increase in Argentina through closure of existing yield gaps. *Field Crops Research* 184, 145–154.

Ayinde, O. E., Muchie, M. & Olutunji, G. B. 2011 Effect of climate change on agricultural productivity in Nigeria: a co-integration model approach. *Journal of Human Ecology* 35 (3), 189–194.

Bakhtiari, B., Ghahreman, N., Liaghat, A. M. & Hoogenboom, G. 2011 Evaluation of reference evapotranspiration models for semiarid environment using lysimeter measurements. *Journal of Agricultural Science and Technology* 13 (2), 223–237.

Bender, F. D. & Sentelhas, P. C. 2018 Solar radiation models and gridded databases to fill gaps in weather series and to project climate change in Brazil. *Advances in Meteorology* 2018, 1–15.

Beven, K. 1979 A sensitivity analysis of the Penman–Monteith actual evapotranspiration estimates. *Journal of Hydrology* 44, 169–190.

Biazar, S. M., Dinpashoh, Y. & Singh, V. P. 2019 Sensitivity analysis of the reference crop evapotranspiration in a humid region. *Environmental Science and Pollution Research* 26, 32517–32544.

Bois, B., Pieri, P., Van Leeuwen, C., Wald, L., Huard, F., Gaudillere, J. P. & Saur, E. 2008 Using remotely sensed solar radiation data for reference evapotranspiration estimation at a daily time step. *Agricultural Forest Meteorology* 148, 619–630.

Bormann, H. 2011 Sensitivity analysis of 18 different potential evapotranspiration models to observed climatic change at German climate stations. *Climatic Change* 104 (3–4), 729–753.

Chineke, T. C., Jagtap, S. S. & Nwofor, O. 2010 West African monsoon: is the August break “breaking” in the eastern humid zone of Southern Nigeria? *Climate Change* 103 (3–4), 555–570.

Da Silva, H. J. F., Gonçalves, W. A. & Bezerra, B. G. 2019 Comparative analyses and use of evapotranspiration obtained through remote sensing to identify deforested areas in the Amazon. *International Journal of Applied Earth Observation and Geoinformation* 78, 163–174.

Darshana, D., Pandey, A. & Pandey, R. P. 2013 Analysing trends in reference evapotranspiration and weather variables in the Tons River Basin in Central India. *Stochastic Environmental Research and Risk Assessment* 27, 1407–1421.

Debnath, S., Adamala, S. & Raghuvanshi, N. S. 2015 Sensitivity analysis of FAO-56 Penman–Monteith method for different agroecological regions of India. *Environmental Process* 2, 689–704.

Dezfuli, A. K., Ichoku, C. M. & Huffman, G. J. 2017 Validation of IMERG precipitation in Africa. *Journal of Hydrometeorology* 18, 2817–2825.

Duru, J. O. 1984 Blaney–Morin–Nigeria evapotranspiration model. *Journal of Hydrology* 70, 71–83.

Eludoyn, O. M., Adelekan, I. O., Webster, R. & Eludoyn, A. O. 2014 Air temperature, relative humidity, climate regionalization and thermal comfort of Nigeria. *International Journal of Climatology* 34 (6), 2000–2018.

FAO 2009 AQUASTAT Main Database. Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/nr/water/aquastat/countries_regions/NGA/NGA-CP_eng.pdf. Accessed 5 December 2019.

Gao, Z., He, J., Dong, K., Bian, X. & Li, X. 2016 Sensitivity study of reference crop evapotranspiration during growing season in the West Liao River basin, China. *Theoretical and Applied Climatology* 124 (3–4), 865–881.

Gong, L., Xu, C. y., Chen, D., Haldín, S. & Chen, Y. D. 2006 Sensitivity of the Penman–Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin. *Journal of Hydrology* 329 (3–4), 620–629.

Goroshi, S., Pradhan, R. & Singh, R. P. 2017 Trend analysis of evapotranspiration over India: observed from long-term satellite measurements. *Journal of Earth System Science* 126, 113.

Goyal, R. K. 2004 Sensitivity of evapotranspiration to global warming: a case study of arid zone of Rajasthan (India). *Agricultural Water Management* 69, 1–11.

Ha, W., Gowda, P. H., Ommen, T., Marek, T. H., Porter, D. O. & Howell, T. A. 2011 Spatial interpolation of daily reference evapotranspiration in the Texas high plains. In: *World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability – Proceedings of the 2011 World Environmental and Water Resources Congress*, 22–26 May 2011, Palm Springs, CA, pp. 2796–2804.

Harris, I. C., Jones, P. D., Osborn, T. J. & Lister, D. H. 2014 Updated high-resolution grids of monthly climatic observations-the CRU TS4.01 dataset. *International Journal of Climatology* 34, 623–642.

Hertel, T. W. & Liu, J. 2016 *Implications of Water Scarcity for Economic Growth*. OECD Environment Working Papers No. 109. Available from: https://www.oecd-ilibrary.org/implications-of-water-scarcity-for-economic-growth_5jilsl61r132.pdf.

Hodam, S., Sarkar, S., Marak, A. G. R., Bandyopadhyay, A. & Bhadra, A. 2017 Spatial interpolation of reference evapotranspiration in India: comparison of IDW and Kriging methods. *Journal of The Institution of Engineers (India): Series A* 98 (4), 511–524.

Hou, L. G., Zou, S. B., Xiao, H. L. & Yang, Y. G. 2013 Sensitivity of the reference evapotranspiration to key climatic variables during the growing season in the Ejina oasis northwest China. *Springer Plus* 2 (1), 4–9.

Hupet, F. & Vanclooster, M. 2001 Effect of the sampling frequency of meteorological variables on the estimation of reference evapotranspiration. *Journal of Hydrology* 243, 192–204.

Ileoce, N. P. 2001 A New Geography of Nigeria, New revised edn. Longman Publishers, Ibadan, Nigeria.

IPCC 2001 *(Intergovernmental Panel on Climate Change)* *Climate Change 2001: The Physical Science Basis*. Contribution of Working Group 1 to the Fifth Assessment Report of the
Sensitivity analyses and sensitivity coefficients of standardized daily ASCE-Penman–Monteith equation. Journal of Irrigation and Drainage Engineering 132, 564–578.

Jerszurki, D., de Souza, J. L. M. & Silva, L. d. C. R. 2015 Sensitivity of ASCE-Penman–Monteith reference evapotranspiration under different climate types in Brazil. Climate Dynamics 53, 943–956.

Jiang, S., Liang, C., Cui, N., Zhao, L., Du, T., Hu, X., Feng, Y., Guan, J. & Feng, Y. 2015 Impacts of climatic variables on reference evapotranspiration during growing season in Southwest China. Agricultural Water Management 216, 365–378.

Koudahe, K., Djaman, K. & Adewumi, J. K. 2008 Evaluation of the Penman–Monteith reference evapotranspiration under limited data and its sensitivity to key climatic variables under humid and semiarid conditions. Modeling Earth Systems and Environment 4 (3), 1259–1257.

Kyrilakis, P. C. & Goodchild, M. F. 2006 On the prediction error variance of three common spatial interpolation schemes. International Journal of Geographical Information Science 20 (8), 823–855.

Laborde, J. P., Wortmann, C. S., Blanco-Canqui, H., McDonald, A. J. & Lindquist, J. L. 2019 Simulation-based maize–wheat cropping system optimization in the midhills of Nepal. Agronomy Journal 111 (5), 2569–2581.

Lal, R. 2016 Feeding 11 billion on 0.5 billion hectare of area under cereal crops. Food and Energy Security 5, 239–251.

Lhendup, T. & Lhundup, S. 2007 Comparison of methodologies for generating a typical meteorological year. Energy for Sustainable Development 11 (3), 5–10.

Liu, Q., Yang, Z., Cui, B. & Sun, T. 2010 The temporal trends of reference evapotranspiration and its sensitivity to key meteorological variables in the Yellow River Basin, China. Hydrological Process 24 (15), 2171–2181.

Lobell, D. B., Schlenker, W. & Costa-Roberts, J. 2011 Climate trends and global crop production since 1980. Science 333, 616–620.

McCuen, R. H. 1974 A sensitivity and error analysis of procedures used for estimating evaporation. Journal of the American Water Resources Association 10, 486–497.

NASA POWER 2019. https://power.larc.nasa.gov/data-access-viewer (accessed 13 June 2019).

NBS-National Bureau of Statistics 2017 Nigerian Gross Domestic Product Report Q3 2017.

Ndiaye, P., Bodian, A., Diop, L. & Djaman, K. 2017 Sensitivity analysis of the Penman–Monteith reference evapotranspiration to climatic variables: case of Burkina Faso. Journal of Water Resource and Protection 9, 1364–1376.

Ndulue, E. L. & Mbayiorgu, C. C. 2018 Modeling climate and land-use change impacts on streamflow and sediment yield of an agricultural watershed using SWAT. Agricultural Engineering International: CIGR Journal 20 (4), 15–25.

Ndulue, E., Onyekwelu, I., Ogbi, K. N. & Ogwo, V. 2019 Performance evaluation of solar radiation equations for estimating reference evapotranspiration (ET0) in a humid tropical environment. Journal of Water and Land Development 42 (7–9), 124–135.

Nouri, M., Homaei, M. & Bannayan, M. 2017 Quantitative trend, sensitivity and contribution analyses of reference evapotranspiration in some arid environments under climate change. Water Resources Management 31, 2207–2224.

Obarei, O. A. & Amanambu, A. C. 2019 Rainfall timing: variation, characteristics, coherence, and interrelationships in Nigeria. Theoretical and Applied Climatology 157, 2607.

Ogolo, E. O. 2014 The comparative analysis of performance evaluation of recalibrated reference evapotranspiration models for different regional climatic conditions in Nigeria. IIE Journal of Science 16 (2), 1–20.

Oguntunde, P. O., Abiodun, B. J. & Lischeid, G. 2011 Rainfall trends in Nigeria, 1901–2000. Journal of Hydrology 411 (3–4), 207–218.

Oguntunde, P. G., Abiodun, B. J., Olukunle, O. J. & Olufayo, A. A. 2012 Trends and variability in pan evaporation and other climatic variables at Ibadan, Nigeria, 1973–2008. Meteorological Applications 19 (4), 464–472.

Ojeda, J. J., Pembleton, K. G., Caviglia, O. P., Islam, M. R., Agnusdei, M. G. & Garcia, S. C. 2008 Modelling forage yield and water productivity of continuous crop sequences in the Argentinian Pampas. European Journal of Agronomy 92, 84–96. doi.org/10.1016/j.eja.2017.10.004.

Patle, G. T. & Singh, D. K. 2015 Sensitivity of annual and seasonal reference crop evapotranspiration to principal climatic variables. Journal of Earth System Science 124, 819–828.

Patle, G. T., Sengdo, D. & Tapak, M. 2019 Trends in major climatic parameters and sensitivity of evapotranspiration to climatic parameters in the eastern Himalayan region of Sikkim, India. Journal of Water and Climate Change. doi:10.2166/wcc.2019.121/65495/.

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E. & Vandagopal, S. 2004 Water resources: agricultural and environmental issues. Bioscience 54 (10), 909–918.

Poddar, A., Gupta, P., Kumar, N., Shankar, V. & Ohja, C. S. P. 2018 Evaluation of reference evapotranspiration methods and sensitivity analysis of climatic parameters for sub-humid sub-tropical locations in western Himalayas (India). ISH Journal of Hydraulic Engineering 1–11. doi:10.1080/09715010.2018.1551731.

Sadow, Z., Ford, D. F., Lewis, M. & Armstrong, R. L. 2017 The Water Challenge: Preserving A Global Resource. Available from: https://www.investmentbank.barclays.com/content/dam/barclaysmicrosites/ibpubpublic/documents/our-insights/water-report/ImpactSeries_WaterReport_Final.pdf.

Samanta, S., Pal, D. K., Lohar, D. & Pal, B. 2012 Interpolation of climatic variables and temperature modeling. Theoretical and Applied Climatology 107 (1–2), 35–45.
Saxton, K. E. 1975 Sensitivity analyses of the combination evapotranspiration equation. Agricultural Meteorology 15, 343–353.

Schorza Júnior, R. P., Canesin, F. H., Seabra, F. A. S. & Comunello, E. 2018 Statistically based approach to select worst-case groundwater scenarios for environmental risk assessment of pesticides in Brazil. Ecotoxicology and Environmental Contamination 151 (1), 63–71.

Seyedmohammadi, J., Esmaeelnejad, L. & Shabanpour, M. 2016 Spatial variation modelling of groundwater electrical conductivity using geostatistics and GIS. Modeling Earth Systems and Environment 2 (4), 1–10.

Sharif, A. & Dinapashoh, Y. 2014 Sensitivity analysis of the Penman–Monteith reference crop evapotranspiration to climatic variables in Iran. Water Resources Management 28, 5465–5476.

Sharma, V. & Irmak, S. 2012 Mapping spatially interpolated precipitation, reference evapotranspiration, actual crop evapotranspiration, and net irrigation requirements in Nebraska: part II. Actual crop evapotranspiration and net irrigation requirements. Transactions of the ASABE 55 (3), 923–936.

Silva, L. C. R. 2015 From air to land: understanding water resources through plant-based multidisciplinary research. Trends Plant Science 20, 399–401.

Singh, R. B. 1995 Soil management system for semi-arid ecosystem: the case of northern Nigeria. In: Sustainable Reconstruction of Highland and Headwater Regions: Proceedings of the Third International Symposium (R.B. Singh & Martin J. Haigh, eds), 6–8 October 1995, New Delhi.

Stackhouse Jr., P. W., Zhang, T., Westberg, D., Barnett, A. J., Bristow, T., Macpherson, B. & Hoell, J. M. 2018 POWER Release 8 (with GIS Applications) Methodology (Data Parameters, Sources, & Validation) Documentation Date December 12, 2018 (Data Version 8.0.1; Web Site Version 1.1.0). Available from: https://power.larc.nasa.gov/documents/POWER_Data_v9_methodology.pdf.

Tabari, H. & Talaee, P. H. 2014 Sensitivity of evapotranspiration to climatic change in different climates. Global and Planetary Change 115, 16–23.

Ugbah, P. A., Olaniyan, O., Francis, S. D. & James, A. 2020 Impact of climate change on growing season in Nigeria: Seasonal Rainfall Prediction (SRP) as assessment and adaptation tool. Handbook of Climate Change Resilience (W. Leal Filho, ed.). Springer International, Cham, pp. 2743–2769. https://doi.org/10.1007/978-3-319-93336-8_183.

USGCRP 2018 Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Vol. II (D. R. Reifmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, B. C. Stewart, eds). U.S. Global Change Research Program, Washington, DC, pp. 1515. doi:10.7930/NCA4.2018.

Van de Giesen, N., Hut, R. & Selker, J. 2014 The Trans-African Hydro Meteorological Observatory (TAHMO). Wiley Interdisciplinary Reviews: Water 1, 341–348.

Van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., Groot, D. E., Wiebe, H., MASON-D’croz, K., Yang, D., Boogaard, H., Van Oort, H., VanLoon, P. A. J., Saito, M. P., Adimo, K., AdjiNsiah, O., Agali, S., Bala, A., Chikowo, A., Kaizzi, R., Kouressy, K., Makoi, M., Ouattara, J. H. J., Tesfaye, K. & Cassman, K. G. 2016 Can sub-Saharan Africa feed itself? Proceedings of the National Academy of Sciences 113 (52), 14964–14969.

Vicente-Serrano, S. M., Azorin-Molina, C., Sanchez-Lorenzo, A., Revuelto, J., Morán-Tejeda, E., López-Moreno, J. I. & Espejo, F. 2014 Sensitivity of reference evapotranspiration to changes in meteorological parameters in Spain (1961–2011). Water Resources Research 50, 8458–8480.

Wang, W., Xing, W., Shao, Q., Yu, Z., Peng, S., Yang, T., Yong, B., Taylor, J. & Singh, V. P. 2015 Changes in reference evapotranspiration across the Tibetan Plateau: observations and future projections based on statistical downscaling. Journal of Geophysical Research Atmospheres 118 (10), 4049–4068.

Wart, J., Grassini, P. & Cassman, K. G. 2015 Impact of derived global weather data on simulated crop yields. Global Change Biology 19, 3822–3834.

White, J. W., Hoogenboom, G., Stackhouse, P. W. & Hoell, J. M. 2008 Evaluation of NASA satellite-and assimilation model-derived long-term daily temperature data over the continental US. Agricultural and Forest Meteorology 148, 1574–1584.

Wilcox, B. P., Breshears, D. D. & Seyfried, M. S. 2003 Water balance on rangelands. In: Encyclopedia of Water Science (B. A. Steawr & T. A. Howell, eds). Marcel Dekker, Inc., New York, pp. 791–794.

World Bank 2015 Rainfed Agriculture. Available from: http://water.worldbank.org/topics/agricultural-water-management/rainfed-agriculture (accessed 13 June 2019).

World Bank 2016 Agricultural Land (% of Land Area) – Nigeria. Available from: https://data.worldbank.org/indicator/AG.LND.AGRI.ZS?locations=NG (accessed 5 December 2019).

World Bank 2019 Total Population. Available from: https://data.worldbank.org/indicator/SP.POP.TOTL?locations=NG (accessed 13 June 2019).

Yang, J. Y., Liu, Q., Mei, X. R., Yan, C. R., Ju, H. & Xu, J. W. 2015 Spatiotemporal characteristics of reference evapotranspiration and its sensitivity coefficients to climate factors in Huang-Huai-Hai Plain, China. Journal of Integrative Agriculture 12 (12), 2280–2291.

Yin, Y., Wu, S., Chen, G. & Dai, E. 2010 Attribution analyses of potential evapotranspiration changes in China since the 1960s. Theoretical and Applied Climatology 101, 19–28.

Zhao, J., Xu, Z. X., Zuo, D. P. & Wang, X. M. 2015 Temporal variations of reference evapotranspiration and its sensitivity to meteorological factors in Heihe River Basin, China. Water Science and Engineering 8 (1), 1–8.