Sensitivity of FAO Penman–Monteith reference evapotranspiration (ET_o) to climatic variables under different climate types in Nigeria

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ABSTRACT

Understanding the impact of changes in climatic variables on reference evapotranspiration (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 ET_o with respect to changes in climatic variables. In addition, the specific objective was to determine the sensitivity coefficients of 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 ET_o is most sensitive to changes in maximum temperature (T_{max}) in Maiduguri, Sokoto, Kaduna, and Jos. In Enugu and Ibadan, ET_o is most sensitive to changes in solar radiation (R_s), while in Port Harcourt, 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: $RH > R_s > T_{max} > U_2 > T_{min}$. Also, the results showed positive SCs of ET_o to R_s, T_{max}, U_2, T_{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

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HIGHLIGHTS

- For the first time, the influence of climatic variables on reference evapotranspiration (ET_o) was evaluated under different agro-ecological zones in Nigeria.
- For all locations in northern Nigeria, ET_o is most and least sensitive to maximum temperature (T_{max}) and minimum temperature (T_{min}), respectively, while in southern Nigeria, 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, ET_o is most sensitive to RH and R_s across all study locations.
- Across all agro-ecological zones, R_s, T_{max}, T_{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.

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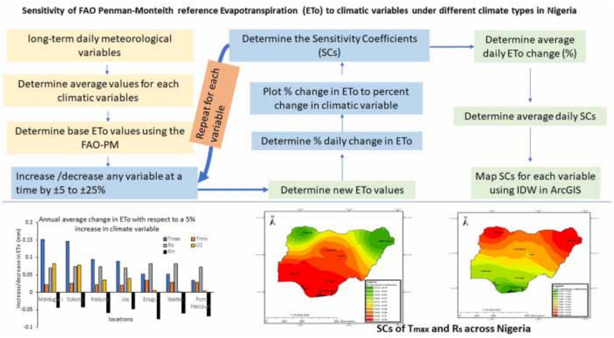
GRAPHICAL ABSTRACT



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_o). This is the first step to satisfying the water requirement of crops.

ET_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.* 2003). ET_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_o). K_c represents specific crop characteristics that differentiate a field crop from the reference grass, while ET_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_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_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_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 ET$_o$ becomes imperative, so that emphasis is placed on the measurements of those variables which could be used for developing simple empirical ET$_o$ 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 2015). 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 ET$_o$ is important to assess the possible implications of climate change on water resources, water management, and the overall hydrology of an area. ET$_o$, 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 ET$_o$ 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, ET$_o$ is most sensitive to relative humidity and solar radiation during the winter and summer seasons, respectively. Similarly, Jiang *et al.* (2019) noted that ET$_o$ is most sensitive to relative humidity under the monsoon climate in southwestern China. By studying the sensitivity of ET$_o$ in dry (arid and semi-arid) climates, Liu *et al.* (2010), Hou *et al.* (2013), and Gao *et al.* (2016) observed that ET$_o$ 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 ET$_o$. In contrast, under humid climate, Irmak *et al.* (2006), Tabari & Talaee (2014), and Koudahe *et al.* (2018) reported that ET$_o$ 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 ET$_o$ 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, ET$_o$ 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 ET$_o$. This shows that ET$_o$ 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 ET$_o$ equation (Vicente-Serrano *et al.* 2014). Previous studies have also examined the impacts of more than one variable on ET$_o$. 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, ET$_o$ 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 ET$_o$. 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 ET$_o$ with respect to changes in climatic variables under different agro-ecological types in Nigeria, (ii) determine the sensitivity coefficients of ET$_o$ to changes in climatic variables under different agro-ecological types in Nigeria, and (iii) develop spatial maps of ET$_o$ 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 km^2, 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 2017). 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

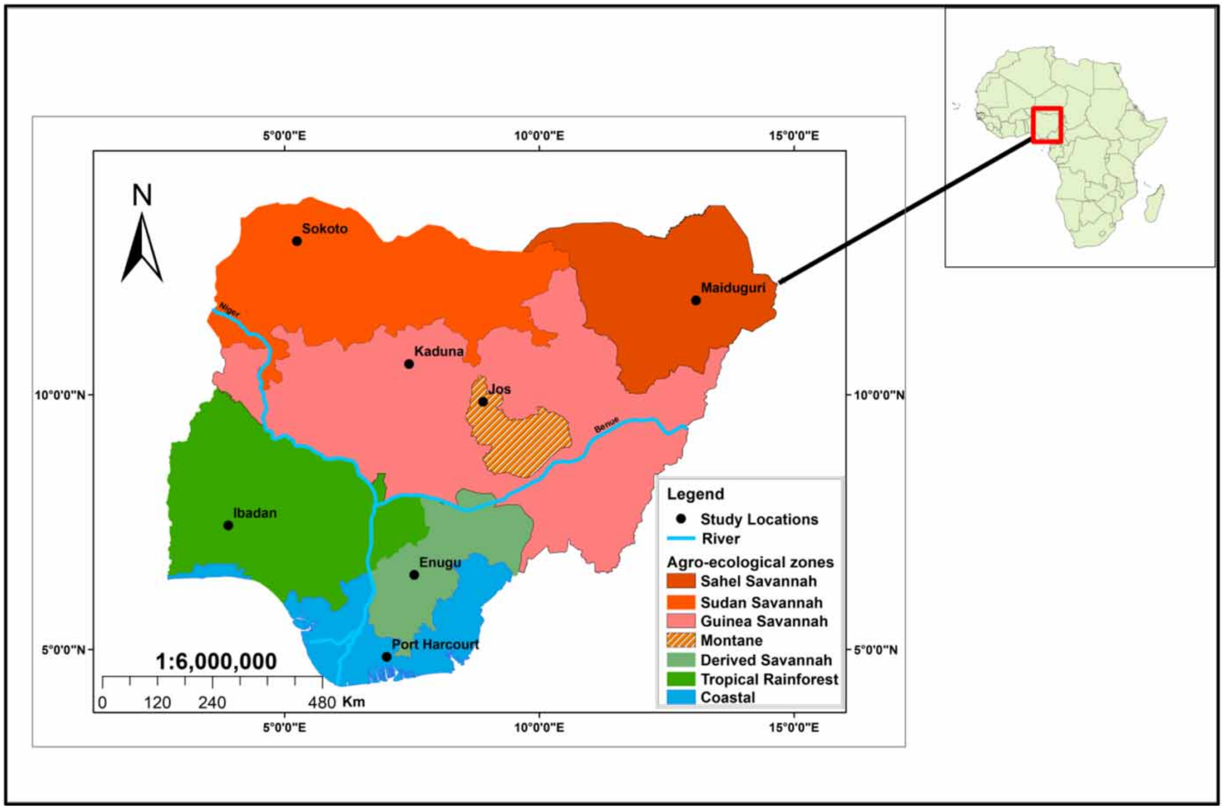


Figure 1 | Study locations showing the agro-ecological zones in Nigeria inset map of Africa.

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 season, 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 (POWER) (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 $0.5° \times 0.5°$. 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 (R_s), minimum temperature ($T_{\min}$), maximum temperature ($T_{\max}$), relative humidity (RH), and wind speed (U_2). The data were further screened and checked for inconsistency following the recommendation of Allen (1996). Data quality checks include (i) $T_{\max} > T_{\min}$, (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):

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

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

$$\text{SC}_i = \lim_{\Delta x \to 0} \left(\frac{\Delta \text{ET}_o / \text{ET}_o}{\Delta X_i / X_i} \right) = \frac{\delta \text{ET}_o}{\delta X_i} \cdot \frac{X_i}{\text{ET}_o} \tag{2}$$

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 °C in 2100 (USGCRP 2018). Numerous researchers have adopted similar ranges varying from ±5 to ±30% (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 km^2, given that agricultural land constitutes about 77.74% (718,138.02 km^2) 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 $\mathrm{ET_o}$. 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 $\mathrm{ET_o}$ (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 $\mathrm{ET_o}$ 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 $\mathrm{ET_o}$ were observed in Maiduguri, while the lowest average wind speed and $\mathrm{ET_o}$ 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).

Changes in $\mathrm{ET_o}$ with respect to changes in the climatic variable

Figure 2 shows the percent change in $\mathrm{ET_o}$ versus the percent change in each of the meteorological variables (T_{max}, T_{min}, R_s, U_2, and RH) for each location. The steeper the slope (Figure 2), the larger the impact the variable has on $\mathrm{ET_o}$ or the more sensitive the variable is on $\mathrm{ET_o}$. The response of $\mathrm{ET_o}$ to changes in each variable varied across different locations. In Maiduguri, Sokoto, Kaduna, and Jos, $\mathrm{ET_o}$ was most sensitive to changes in T_{max}. In Ibadan and Enugu,

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	1,435.35 ± 3.22	2,415.21 ± 4.31
T_{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_{max} (°C)	37.56 ± 3.19	35.20 ± 3.14	30.52 ± 2.64	29.82 ± 2.97	29.27 ± 1.13	29.38 ± 1.21	27.74 ± 1.02
R_s (MJ/m^2/day)	21.31 ± 1.89	22.29 ± 2.13	20.35 ± 0.6	19.60 ± 2.68	17.69 ± 0.3	17.64 ± 0.29	15.14 ± 2.79
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
$\mathrm{ET_o}$ (mm/yr)	6.95 ± 1.70	6.93 ± 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_{min}, minimum temperature; T_{max}, maximum temperature; R_s, solar radiation; RH, relative humidity; U_2, wind speed measured at 2 m height.

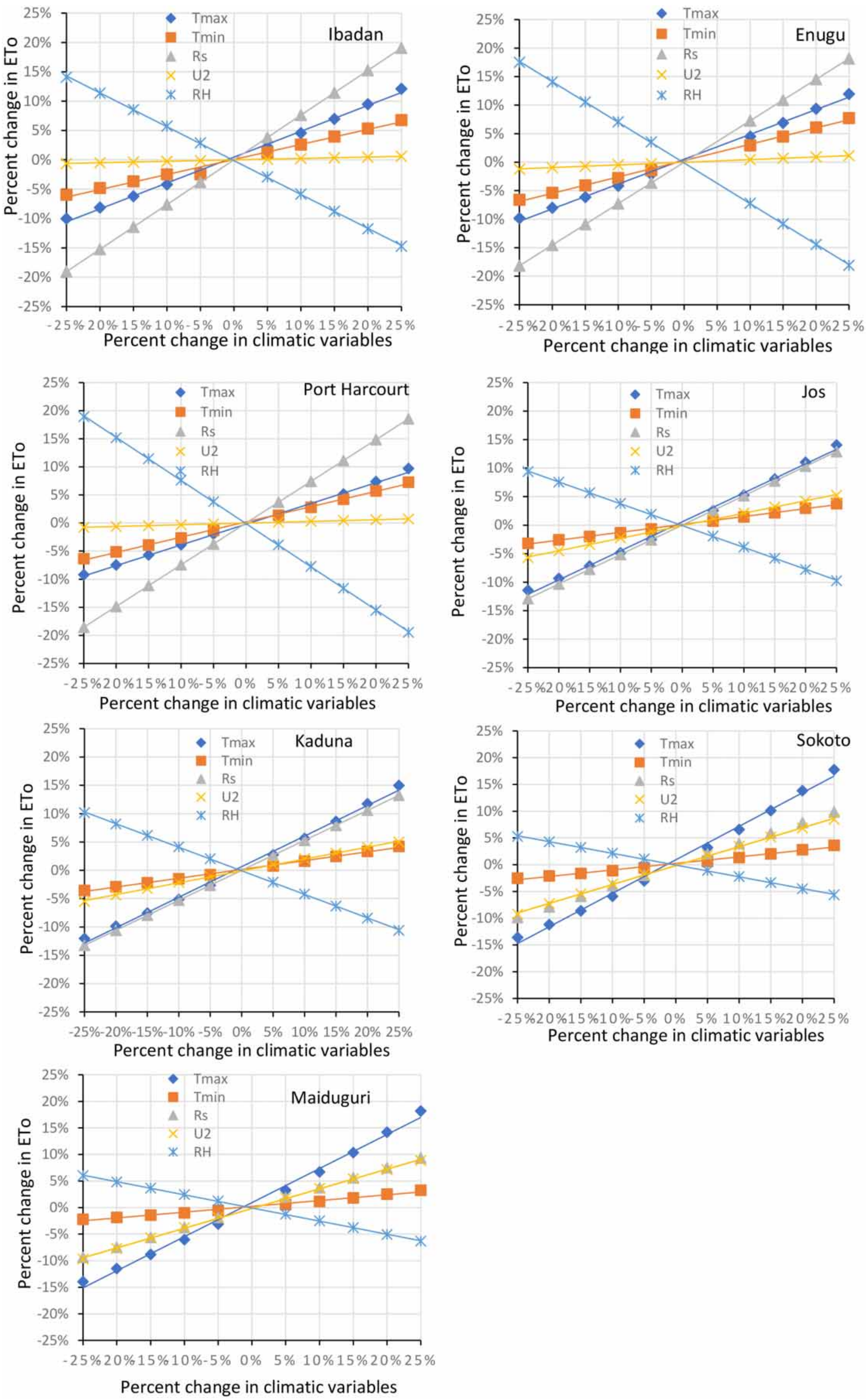


Figure 2 | Percent change in ET_o with respect to changes in percent change in the climatic variable.

ET_o was most sensitive to changes in R_s, while in Port Harcourt, ET_o was most sensitive to changes in RH.

A 25% increase in T_{max} resulted in an average annual increase in ET_o by 0.76 mm in Maiduguri and 0.17 mm in Port Harcourt, respectively. A variation in ±25% in T_{max} affected ET_o 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 T_{max} resulted in a 10–64.05% change in ET_o in various locations, while in Cote d'Ivoire, Koudahe *et al.* (2018) noted that ET_o increase by 0.49 mm in response to a 15% increase in T_{max} in Ferkessedougou station. In the US, Irmak *et al.* (2006) reported that a 5% increase in T_{max} can increase ET_o between 0.06 and 0.11 mm/day. There is a consensus in the literature that temperature is most sensitive to ET_o 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 ET_o. 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 T_{max}, ET_o varied between 6 and 17%.

The impact of the change in U_2 on ET_o was observed mainly in northern locations and had almost a zero effect in some months in the southern region. The effect of U_2 on ET_o decreased from the north to south. In Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, ET_o 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 U_2 (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 ET_o in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively (Table 2). This suggests that an increase in U_2 caused an increase in ET_o 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 U_2 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 ET_o. Tabari & Talaee (2014) found that under arid climate, ET_o varies between ±9% in response to a ±20% change in U_2. Irmak *et al.* (2006) noted that a 10% change in U_2 led to a 3.2% change in ET_o under semi-arid climate. Similarly, a 5% increase in U_2 caused a 0.77 mm/day increase in ET_o (Jerszurki *et al.* 2019).

R_s is ranked second behind T_{max}. The effect of change in R_s on ET_o was observed in almost all the locations. R_s had diverse effects on ET_o 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 R_s resulted in 0.352, 0.375, 0.374, 0.35, 0.41, 0.41, and 0.36 mm increase in ET_o in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. A ±25% change in R_s led to a ±9.4, ±9.9, ±13.2, ±12.9, ±18.6, ±19.05, and ±18.6% change in ET_o estimate in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. The highest impact of the increase in R_s was observed in Enugu and lowest in Maiduguri. In western Himalayas, Poddar *et al.* (2018) noted that in response to a ±20% change in R_s, ET_o changed by ±12%.

Changes in RH had more effect on ET_o in locations in the south than locations in the north. In response to the change in RH by ±25%, ET_o estimates varied by ±6.3, ±5.65, ±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 ET_o in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. Across all locations, increased RH resulted in decreased ET_o. 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 R_s, we observed a gradual increase in the impact of RH on ET_o,

Table 2 | Monthly and annual average variation in ET$_o$ (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
	R_s	0.19	0.23	0.29	0.39	0.47	0.46	0.43	0.41	0.46	0.43	0.28	0.19	0.35
	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
	R_s	0.17	0.22	0.30	0.43	0.51	0.52	0.49	0.47	0.51	0.44	0.26	0.17	0.37
	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
	R_s	0.25	0.29	0.37	0.47	0.48	0.43	0.38	0.36	0.42	0.43	0.35	0.26	0.37
	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	−0.23	−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	0.10	0.11	0.09	0.06	0.10
	R_s	0.23	0.28	0.37	0.44	0.43	0.39	0.34	0.32	0.36	0.39	0.34	0.25	0.35
	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
	R_s	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
	U_2	0.10	0.08	0.04	0.02	0.01	0.00	0.01	0.01	0.00	0.00	0.02	0.07	0.03
	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	0.13	0.14
	R_s	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
	U_2	0.05	0.05	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.04	0.01
	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
	R_s	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
	U_2	0.04	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.03	0.02
	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 ET_o, and a 10% change resulted in a 15% change in ET_o. In Brazil under semi-arid climate, a 0.4 kpa increase in VPD increased ET_o by 1.64 mm/day (Jerszurki *et al.* 2019).

T_{min} had the lowest impact on ET_o estimates in locations in the north than locations in the south. A variation in ±25% in T_{min} affected ET_o 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 T_{min} on ET_o also varied across the months at all locations. Based on an annual average, an increase in T_{min} resulted in a 0.11, 0.13, 0.11, 0.10, 0.17, 0.14, and 0.14 mm increase in ET_o in Maiduguri, Sokoto, Kaduna, Jos, Enugu, Ibadan, and Port Harcourt, respectively. The less effects of T_{min} on ET_o 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 T_{min} caused ET_o to vary between ±2 and ±18%.

Although the relationships between changes in ET_o 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 ET_o 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 ET_o 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 ET_o was higher than their decrease. However, for wind speed, ET_o 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 ET_o, while a 25% increase in wind speed led to an 8.5% increase in ET_o. This suggests that lowering wind speed has more impacts on ET_o than increasing wind speed. This was also observed by Tabari & Talaee (2014) who found that a decrease in U_2 and sunshine hours have more impact on ET_o than their increase. For example, a 20% decrease in sunshine hours and wind speed will decrease ET_o by 6.5 and 8.8%, respectively, while a 20% increase will decrease ET_o by 2.9 and 8.6%, respectively.

In this study, we observed that a small change in a meteorological variable has higher impact on ET_o 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 ET_o than a 25% change in RH and T_{min}. Similarly, a 15% change in T_{max} on ET_o is greater than a 25% change in R_s and U_2. In Kaduna and Jos, we observed that a 10% change in T_{max} on ET_o is greater than a 25% change in T_{min} and U_2. In Ibadan, Enugu, and Port Harcourt, a 5% change in R_s is greater than a 25% change in U_2. This confirms that U_2 has a minimal impact on ET_o in southern Nigeria. Also, in Enugu and Ibadan, a 15% change in R_s has a higher impact on ET_o than a 25% change in T_{min}. In addition, a 20% increase in R_s is greater than a 25% change in T_{max}. In Port Harcourt, RH has the greatest influence on ET_o. A 10% change in RH has a higher impact on ET_o 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 ET_o than other variables in northern Nigeria, while R_s and RH are the most sensitive variable in southern Nigeria.

Table 2 shows the monthly analysis of the variation of ET_o due to changes in the meteorological variables, which may be hidden in the annual analysis. The impact of increased T_{max} and U_2 on ET_o 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 ET_o 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 U_2 was observed in Maiduguri and Sokoto. Across all locations, the response of ET_o to change in T_{max} was maximum in March and minimum in August. In contrast, we observed that in all locations, the change in ET_o was most impacted by the change in RH in the rainy season than the dry season. This implies at reduced RH, monthly ET_o is increased (i.e. more water is lost) during the growing season than in the non-growing season across Nigeria. The impact of increased R_s and T_{min} on ET_o varied across the months in the north and south. We observed that in Maiduguri, Sokoto, Kaduna, and Jos, the change in ET_o was most impacted by the change in R_s and

$T_{\min}$ 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 $T_{\min}$ in the dry season than the rainy season. This suggests that while increased $T_{\min}$ 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 $> R_s > T_{\max} > U_2 > T_{\min}$. 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, $T_{\max}$ has the highest SC followed by R_s, U_2, RH, and $T_{\min}$, while in Kaduna and Jos, SC is ranked as $T_{\max}$, R_s, RH, U_2, and $T_{\min}$. This suggests that ET_o is more sensitive to changes in $T_{\max}$ 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, $T_{\max}$ had the highest SCs. This also agrees with Tabari & Talaee (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. $T_{\max}$ 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 $T_{\max}$ 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

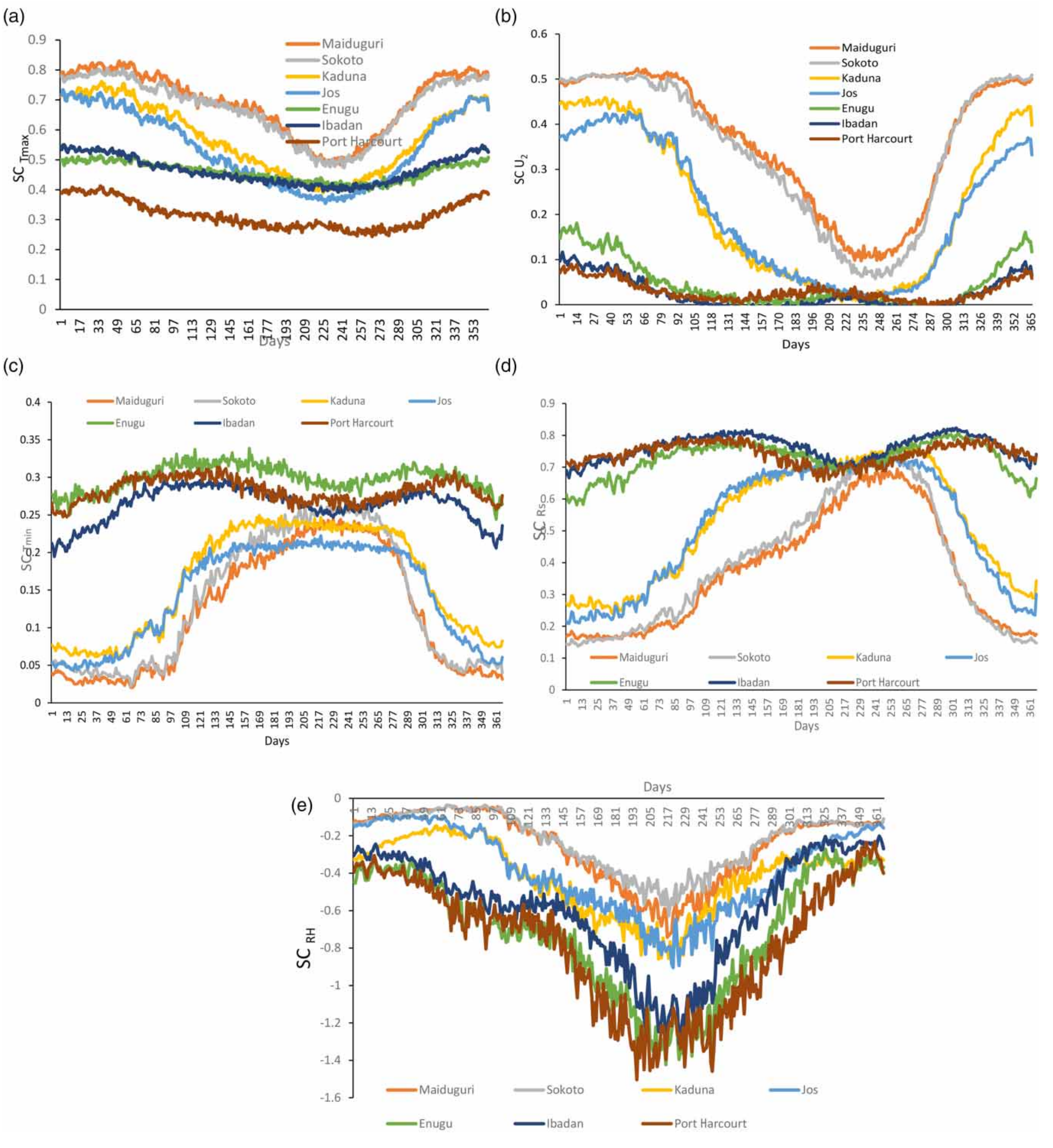


Figure 3 | Sensitivity coefficient of ET_o to (a) maximum temperature (T_{max}), (b) wind speed (U_2), (c) minimum temperature (T_{min}), (d) solar radiation (R_s), and (e) relative humidity (RH).

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

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	T_{max}	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
	T_{min}	0.03	0.03	0.04	0.08	0.15	0.19	0.22	0.24	0.23	0.16	0.05	0.04	0.12
	R_s	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
	U_2	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
	RH	−0.11	−0.07	−0.06	−0.10	−0.22	−0.38	−0.55	−0.59	−0.41	−0.22	−0.14	−0.13	−0.25
Sokoto	T_{max}	0.77	0.78	0.75	0.71	0.69	0.64	0.57	0.50	0.54	0.66	0.75	0.77	0.68
	T_{min}	0.05	0.04	0.04	0.09	0.17	0.22	0.24	0.26	0.25	0.16	0.06	0.05	0.13
	R_s	0.16	0.19	0.23	0.33	0.41	0.48	0.58	0.70	0.71	0.53	0.25	0.17	0.39
	U_2	0.49	0.49	0.49	0.43	0.36	0.29	0.19	0.09	0.09	0.25	0.46	0.50	0.34
	RH	−0.11	−0.07	−0.05	−0.09	−0.22	−0.34	−0.46	−0.49	−0.35	−0.20	−0.13	−0.14	−0.22
Kaduna	T_{max}	0.72	0.73	0.68	0.63	0.55	0.49	0.44	0.41	0.44	0.52	0.63	0.69	0.57
	T_{min}	0.07	0.07	0.09	0.15	0.22	0.24	0.24	0.24	0.24	0.21	0.12	0.09	0.16
	R_s	0.28	0.28	0.35	0.49	0.62	0.67	0.70	0.72	0.75	0.68	0.47	0.33	0.53
	U_2	0.38	0.41	0.38	0.27	0.15	0.08	0.05	0.03	0.03	0.09	0.25	0.34	0.20
	RH	−0.27	−0.19	−0.18	−0.30	−0.48	−0.63	−0.71	−0.73	−0.49	−0.36	−0.33	−0.35	−0.42
Jos	T_{max}	0.70	0.69	0.64	0.58	0.50	0.44	0.40	0.37	0.41	0.48	0.61	0.68	0.54
	T_{min}	0.05	0.06	0.09	0.15	0.20	0.21	0.21	0.21	0.21	0.20	0.11	0.06	0.15
	R_s	0.24	0.26	0.36	0.51	0.64	0.68	0.69	0.71	0.72	0.66	0.44	0.28	0.52
	U_2	0.44	0.43	0.37	0.24	0.13	0.08	0.04	0.02	0.03	0.10	0.28	0.41	0.21
	RH	−0.12	−0.11	−0.16	−0.31	−0.45	−0.55	−0.67	−0.76	−0.59	−0.45	−0.26	−0.18	−0.39
Enugu	T_{max}	0.49	0.49	0.49	0.48	0.46	0.44	0.43	0.42	0.42	0.44	0.48	0.49	0.46
	T_{min}	0.27	0.27	0.30	0.32	0.32	0.32	0.30	0.29	0.30	0.31	0.31	0.28	0.30
	R_s	0.63	0.67	0.73	0.76	0.77	0.75	0.72	0.71	0.75	0.79	0.78	0.67	0.73
	U_2	0.15	0.12	0.06	0.03	0.01	0.01	0.01	0.02	0.00	0.00	0.03	0.11	0.05
	RH	−0.39	−0.41	−0.58	−0.70	−0.72	−0.93	−1.18	−1.27	−1.01	−0.70	−0.35	−0.36	−0.72
Ibadan	T_{max}	0.52	0.51	0.48	0.47	0.45	0.43	0.42	0.41	0.41	0.45	0.50	0.52	0.46
	T_{min}	0.21	0.24	0.27	0.29	0.29	0.28	0.27	0.25	0.26	0.28	0.28	0.23	0.27
	R_s	0.71	0.74	0.77	0.79	0.80	0.78	0.74	0.72	0.77	0.80	0.80	0.74	0.76
	U_2	0.09	0.07	0.03	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.02	0.07	0.02
	RH	−0.30	−0.36	−0.49	−0.57	−0.57	−0.74	−1.02	−1.13	−0.81	−0.49	−0.26	−0.25	−0.61
Port Harcourt	T_{max}	0.39	0.39	0.34	0.32	0.30	0.28	0.27	0.28	0.26	0.27	0.31	0.37	0.32
	T_{min}	0.26	0.28	0.30	0.30	0.30	0.29	0.27	0.27	0.27	0.28	0.29	0.27	0.28
	R_s	0.72	0.74	0.77	0.78	0.78	0.73	0.69	0.70	0.72	0.76	0.78	0.75	0.74
	U_2	0.07	0.06	0.03	0.02	0.01	0.02	0.03	0.02	0.01	0.00	0.02	0.05	0.03
	RH	−0.38	−0.45	−0.60	−0.65	−0.72	−1.04	−1.29	−1.24	−1.14	−0.86	−0.55	−0.34	−0.77

the sensitivity of ET$_o$ to $T_{\max}$ and U_2 decreased from the arid to humid climate. We also observed that in the south, ET$_o$ is most sensitive to R_s, followed by RH, $T_{\max}$, $T_{\min}$, and U_2. This ranking agrees with the reports of Irmak *et al.* (2006), Tabari & Talaee (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, $T_{\max}$, sunshine hours, and U_2 as the most sensitive variable to ET$_o$. 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$_o$ 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$_o$ 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$_o$ 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$_o$ (Jerszurki *et al.* 2019).

RH had a negative effect on ET$_o$, 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$_o$ 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$_o$ in all locations. During the wet season, the SC of RH to ET$_o$ 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$_o$ 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$_o$ since the air is close to saturation. Patle & Singh (2015) also noted a high SC for RH in the winter season.

$T_{\min}$ also had different effects on ET$_o$ 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 $T_{\min}$ is maximum in Enugu and Port Harcourt and minimum in Sokoto and Maiduguri. Overall, the $T_{\min}$ is least sensitive to ET$_o$ 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 $T_{\min}$ was maximum in the monsoon season. SC for $T_{\min}$ 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 $T_{\min}$ 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, $T_{\min}$, 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_{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_{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_{max} and U_2 decreased, while the SCs of R_s, RH, and T_{min} increased. This period falls in the rainy season, which is usually the growing season. Our results agree with Ndiaye *et al.* (2017) and Koudahe *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_{min} and T_{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_{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.

Table 4 | Seasonal (wet and dry) sensitivity coefficients for all locations

	T_{max}	T_{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

Spatial distribution of sensitivity coefficient

Figure 4(a)–4(e) shows the spatial variation of the annual average SCs of ET_o to T_{max}, U_2, R_s, T_{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_{max} and U_2 have the largest SCs in the north. On the other hand, R_s, RH, and T_{min} have the largest SCs in the south. As one moves from the north to south, the variation of SCs of T_{max} and U_2 decreased, while the SCs of RH, R_s, and T_{min} increased. Specifically, T_{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

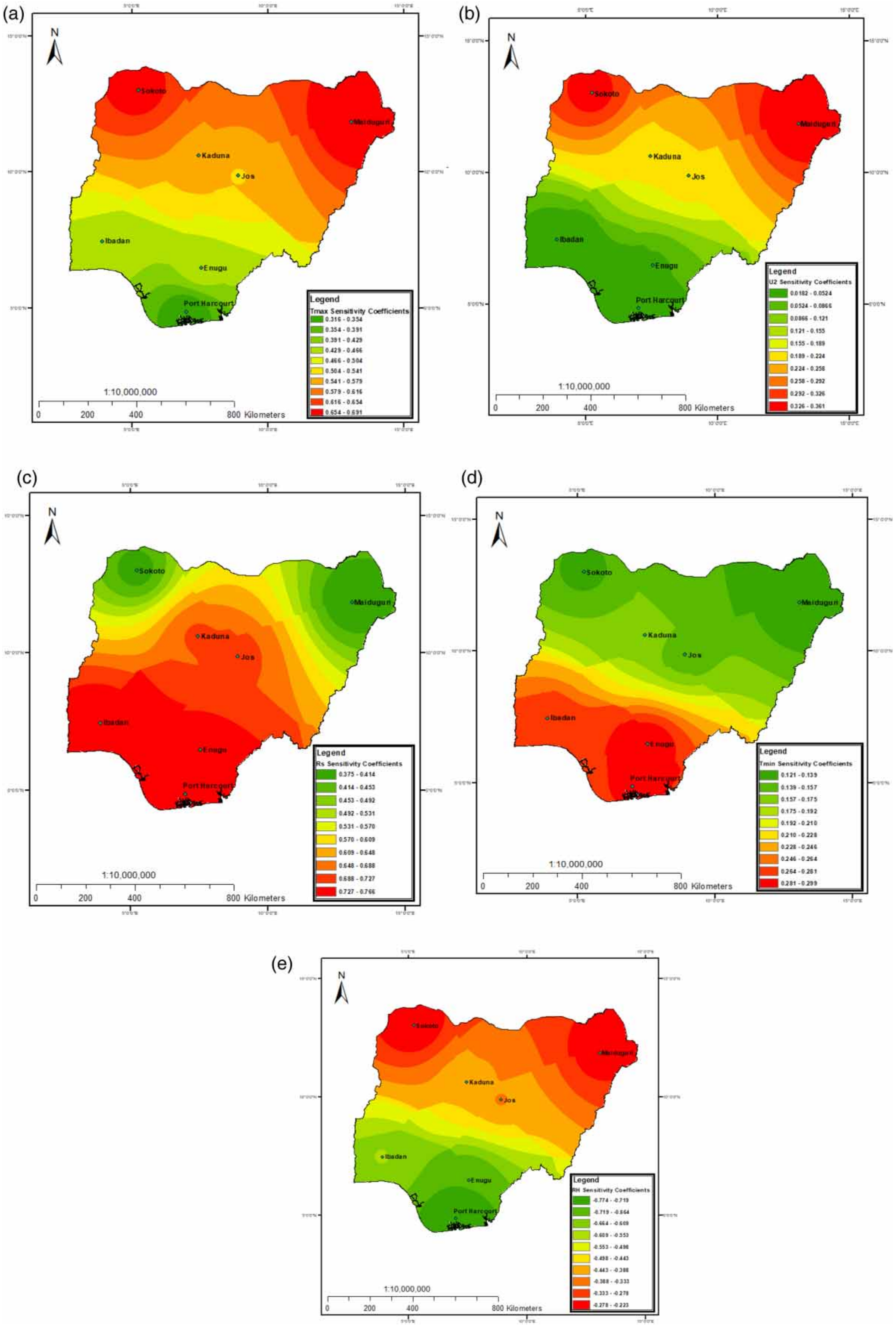


Figure 4 | Spatial distribution of the sensitivity coefficients for (a) T_{max}, (b) U_2, (c) R_s, (d) T_{min}, and (e) RH.

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_{min} 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_{max} and U_2 increased with increasing latitude. The average annual SC for T_{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_{max}, T_{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_{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.

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