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Influence of Climatic Variables on Whole-plant Water use of Cocoa under Limited Soil Moisture Condition

Femi S. Omotayo[1,2*], Philip G. Oguntunde[1] and Ayorinde A. Olufayo[1]

[1]Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure, Nigeria.
[2]Department of Agricultural and Bio-Environmental Engineering, The Federal Polytechnic, Ado- Ekiti, Nigeria.

Authors' contributions

This work was carried out in collaboration among all authors. Author PGO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AAO and FSO managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

Cocoa (*Theobroma cacao* L.) is a cash crop that is cultivated in many tropical regions of the world and is highly productive under favourable climatic conditions. Cocao, being originally an under storey tree of rainforests in tropical America, is traditionally cultivated below the canopy of shade trees. This study is carried out to establish the influence of climatic variables on whole-plant water use of cocoa under limited soil moisture conditions. An experimental plot was made in an even – aged 54 years old cocoa plantation which was demarcated while Water use measurement carried out for 20 consecutive days at the center of the cocoa plantation field at the Federal University of Technology, Akure using the temperature difference method (Sap flow meter). The results of evaporation rate and water consumed by crops led to decrease in soil water in the monitored root zone from 0.049 to 0.015 m^3 m^{-3}. Solar radiation reached a high value of 1002.37 Wm^{-2}, with day time average of 238.02 Wm^{-2}. Temperature ranges between 16.41 and 34.19ºC with a daily average of about 24.39ºC. Relative humidity varied from 98.60% to less than 32.37% with daily

**Corresponding author: E-mail: femisamuelomotayo@yahoo.com;*

mean of around 74.90%. Vapour pressure varied from 0.01 to 2.87 kpa. The day time wind speeds rarely exceed 5.2 ms^{-1} while the daily averages were generally around 1.09 ms^{-1}. The results also show that transpiration, (E_c) is mostly influenced by solar radiation with a correlation coefficient of 0.71 while other variable like temperature, Vapour pressure deficit, and Relative humidity has correlation coefficient of 0.62, 0.50 and 0.58 respectively. The total amount of rainfall during the experiment was 38.9 mm. This shows that solar radiation has greater influence on the transpiration of the cocoa plant than other variables in the study area.

Keywords: Theobroma cacao; water use; climate change; temperature difference; transpiration; limited soil moisture.

1. INTRODUCTION

One of the most useful tree crops in the world is Cocoa (*Theobroma cacao*) and this has been cultivated widely in the west Africa sub- region and was introduced in to Nigeria from 1874 [1]. Nigeria became the second largest producer in the world in the 1960's producing between 250,000 to 308,000 metric tons for export yearly and generating about 50% of Nigeria's revenue [2,3]. However, the cocoa production witnessed a decreasing trend when its export experienced a reduction about 216,000 metric tonnes which subsequently reduced the market share index to about 6% and ranking fifth world largest producer of cocoa [4]. According to [5], the yearly decline in cocoa production is normally attributed more to rainfall regimes than by any other climatic variable. Although cocoa has a trees crop thrived on annual rainfall of between 1150 and 2500 mm per annum in some cases. The ideal recommended annual rainfall ranges between 1500 and 2500 mm for optimum growth and yield of cocoa [4].

A number of factors have an interrelated impact on the growth of cocoa plant. These factors range from the climatic variable of temperature, rainfall, humidity and sunlight. Other factors include farmer's management practices, status of soil nutrient, pest and diseases, and so on. It was reported that the higher the temperature, the more the yield, while the lower the relative humidity, the better the yield [6]. Cocoa is a crop that is known to thrive well under minimal and sustained water availability all round the year [5]. Cocoa prefers calm conditions and persistent moderate wind can cause a severe damage to yield. Cocoa being a selective plant reacts badly to any incidence of extreme weather [7].

Extreme weather as defined by ICCO [8] is the one with the extreme of the historical distribution and noted that rainfall and temperature are the important factors that impacts on optimum yield. This takes place when there is a change in weather parameters which alter stages and rate of development of cocoa, cocoa pests and pathogens which modify host resistance and results in changes in the physiology of host pathogens and pest interaction, causing shift in the geographical distribution of host

The rate of plant growth and development depends basically on the climatic variables most especially temperature of the plant surrounding and each of the plant species has a specific temperature range represented by a minimum, maximum, and optimum. [9,10] presented different values of temperature for a number of different species typical of grain and fruit production. The expected changes in temperature over the next 30 - 50 years are predicted to be in the range of 2 to 3ºC [10]. Extreme temperature events are projected to become more intense, more frequent, and to last longer than what are being currently experienced in recent years [11].

The objective of this study is to: (i) determine influence of climate change on whole-plant water use of cocoa under limited soil moisture condition

2. METHODOLOGY

2.1 Description of Study Site

This study was conducted on a farmer's field near Department of Agricultural and Environmental Engineering Experimental Farm of the Federal University of Technology, Akure (lat. 7°17'N, long. 5° 7'E). It is a tropical rainforest zone of southern Nigeria, which is characterized by distinct wet (April to October) and dry (November- March) seasons. The annual rainfall varies from 2,000 mm in the southern areas to 1,150 mm in the northern areas. In the south, the mean monthly temperature is 27ºC, while the mean relative humidity is over 70%.

2.2 Soil Moisture and Weather Variable Measurement

Soil moisture was routinely measured using a 1-m profile probe type PR2 (Delta-T Devices, Cambridge, England) three times in a week between October 26 and November 18, 2015. The Delta-T soil moisture probe was used in a pre –installed fibre tube for the measurement of the soil moisture in the experimental site. Weather variables, such as incoming solar radiation (SP-LITE pyranometer, Kipp and Zonen, Delft), air temperature (50Y Temperature probe, Vaisala), relative humidity (50 Y Relative Humidity, Vaisala), wind speed and direction (A100R Anemometer, Vector Instruments), were sampled at every 30 seconds and recorded as 30 minutes averages with an automatic weather station installed about 190 m away from the field.

2.3 Sap Flow Measurement

Two cylindrical probes, 2 mm in diameter, were implanted in the cocoa trunks with previously installed aluminum tubes and separated vertically by 10 cm. The probes were then installed on the north side of each tree, to minimize the direct heating effect from sunshine, and were protected with an aluminum foil against rainfall and incident radiation. The heat was continuously applied to the downstream probe with a constant source of power while the unheated upstream probe served as a temperature reference [12,13].

The heat dissipated by the upstream heated needle increased with the increasing sap flow rate. During zero sap flow conditions, most especially at night time, the difference in temperature between the upper and the lower probes represents the steady state of temperature difference which is as a result of the heat dissipated into the non-transporting sapwood. The temperature between the heated upper needle and unheated lower reference needle were measured by a copper-constantan thermocouple.

Whole-tree sap flux density was computed using an empirical relationship validated and confirmed for many species [12,14] as:

$$f_d = 0.714\left(\frac{\Delta T_{\max} - \Delta T}{\Delta T}\right)^{1.231} \quad (1)$$

Where f_d is the average sap flow density along the length of the probe (mL cm^{-2} min^{-1}), ΔT is the temperature difference observed between the heated and reference needles and ΔT_{max} is the value of ΔT when sap flow is zero (generally taken as the peak nighttime value of ΔT)

3. RESULTS AND DISCUSSION

3.1 Observed Soil Moisture and Climatic Data

Fig. 1 shows the daily rainfall between DOY 299 to 318 in the year 2015 and the moisture content observed three times in a week for three replicates. Fig. 2a to 2e shows the diurnal course of major climatic variables. Solar radiation reached a high value of 1002.37 Wm^{-2}, with day time average of 238.02 Wm^{-2}. Temperature ranges between 16.41 and 34.19ºC with a daily average of about 24.39ºC. Relative humidity varied frotm 98.60% to less than 32.37% with daily mean of around 74.9%. Vapour pressure varied from 0.01 to 2.87 kpa. The day time wind speeds rarely exceed 5.2 ms^{-1} while the daily averages were generally around 1.09 ms^{-1}.

Diurnal patterns of sap flow (Lh^{-1}) for a period of 20 days for complete 24 –hours records are shown in Fig. 3a, while the daily water use of cocoa and the prevailing potential evaporation estimated based on [15] equation is presented in Fig. 3b. It has maximum rates (0.121 – 0.256 Lh^{-1}) of sap flow occurred shortly after its onset in the mid morning of each day which were followed by continuous decrease during the remaining time of the day irrespective of solar radiation changes. Plot- level transpiration for DOY 302 – 305 and 311 – 316 gives values greater than 1.0 mm day^{-1} while the remaining days are less than 0.9 mm day^{-1}. Estimated potential evaporation which is however an indicator of atmospheric water demand, gives a high values ranging from 2.74 and 4.42 $mmday^{-1}$.

3.2 Sap Flow and Cocoa Water Use

The Fig. 4 shows a scattered plot of canopy transpiration and climatic drivers. The highest correlation was found between solar radiation and cocoa water use compared to other climatic parameters. Transpiration was highly correlated with solar radiation with variance 71% (Fig. 4a) while the correlation between transpiration and other climatic parameters were not significant.

This agreed with Oguntunde [13] that transpiration, (E_c) is highly correlated to solar radiation (Rs) than with other climatic variables and is also in line to the findings of [16] on

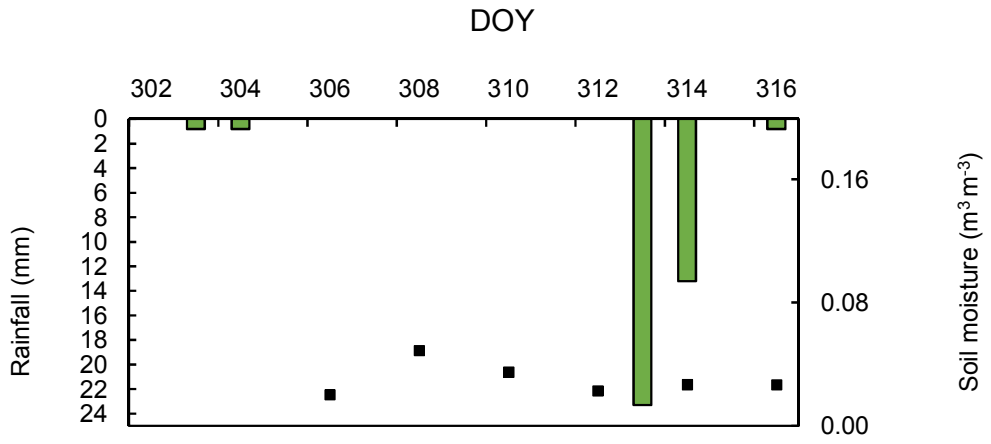
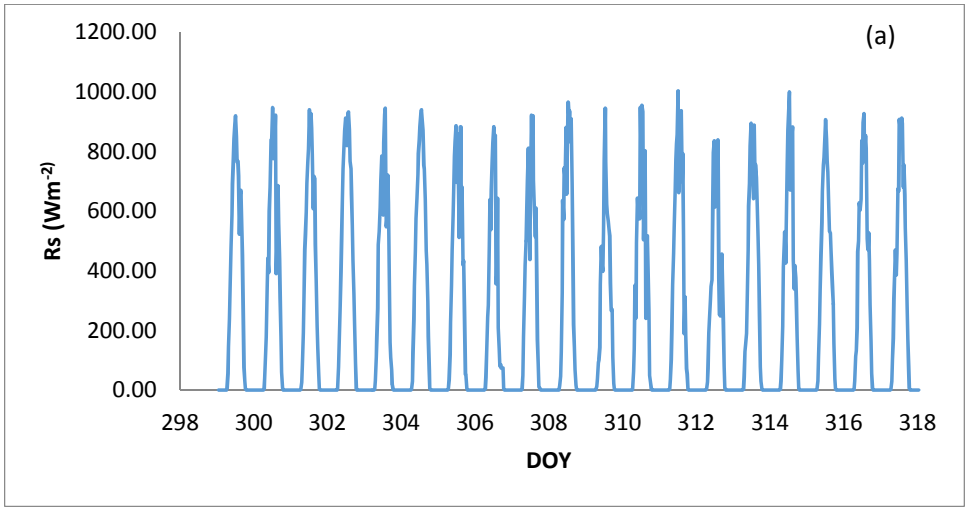


Fig. 1. Average profile soil moisture and daily precipitation distribution at Akure, Nigeria

cashew orchard. Fig. 4 (b) shows that transpiration occurred at steady rate between 16.4 and 34.2ºC in the cocoa plantation while in the case of humidity, as the humidity increases the transpiration of the cocoa plant decreases as shown in Fig. 4(c). The above meteorological factors effect on transpiration pattern agreed with Oguntunde [13] that transpiration, (E_c) is mostly influenced by solar radiation. Transpiration was correlated with solar radiation with variance 71%, the variance between transpiration and temperature was 62% and the variance of transpiration with relative humidity was 50%. The correlation coefficient of transpiration with wind speed was 38%. This shows that solar radiation has greater influence on the transpiration of the cocoa plant while temperature, wind, Relative humidity and wind speed has weak influence on transpiration of cocoa. However, increase in solar radiation (Rs) will lead to increase in evaporative demand. Also, irrigation water requirement of crop is influenced by solar radiation rate in the environment. These determine the quantity of water to be applied for irrigation. If the solar radiation in an area is high, there will increase in evapotranspiration rate which in turn will increase the irrigation water requirement of crops.



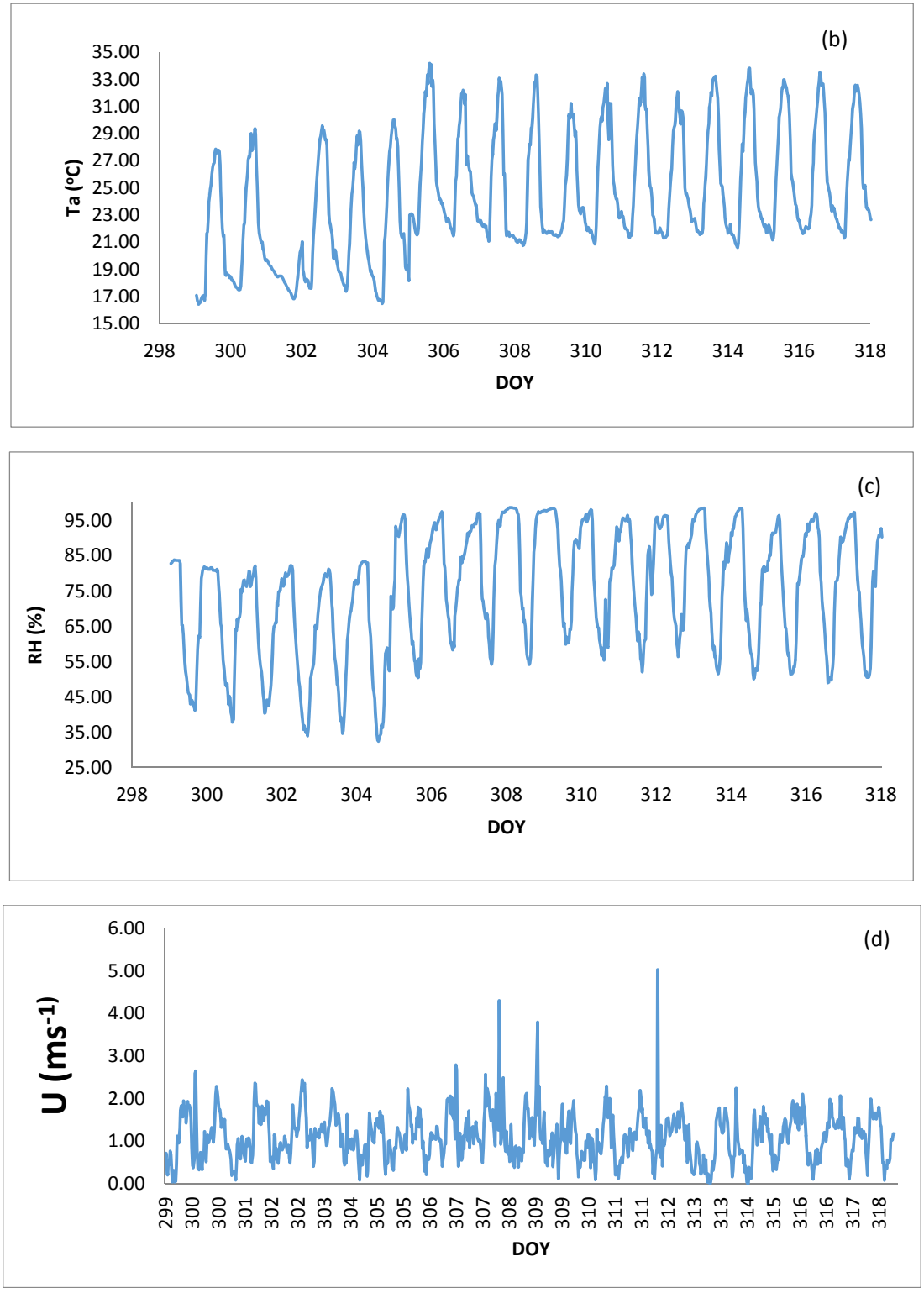


Fig. 2. Diurnal pattern of (a) solar radiation (Rs), (b) air temperature (Ta), (c) relative humidity (RH), and (d) wind Speed (U) during the sap flow measurement at Akure, Nigeria

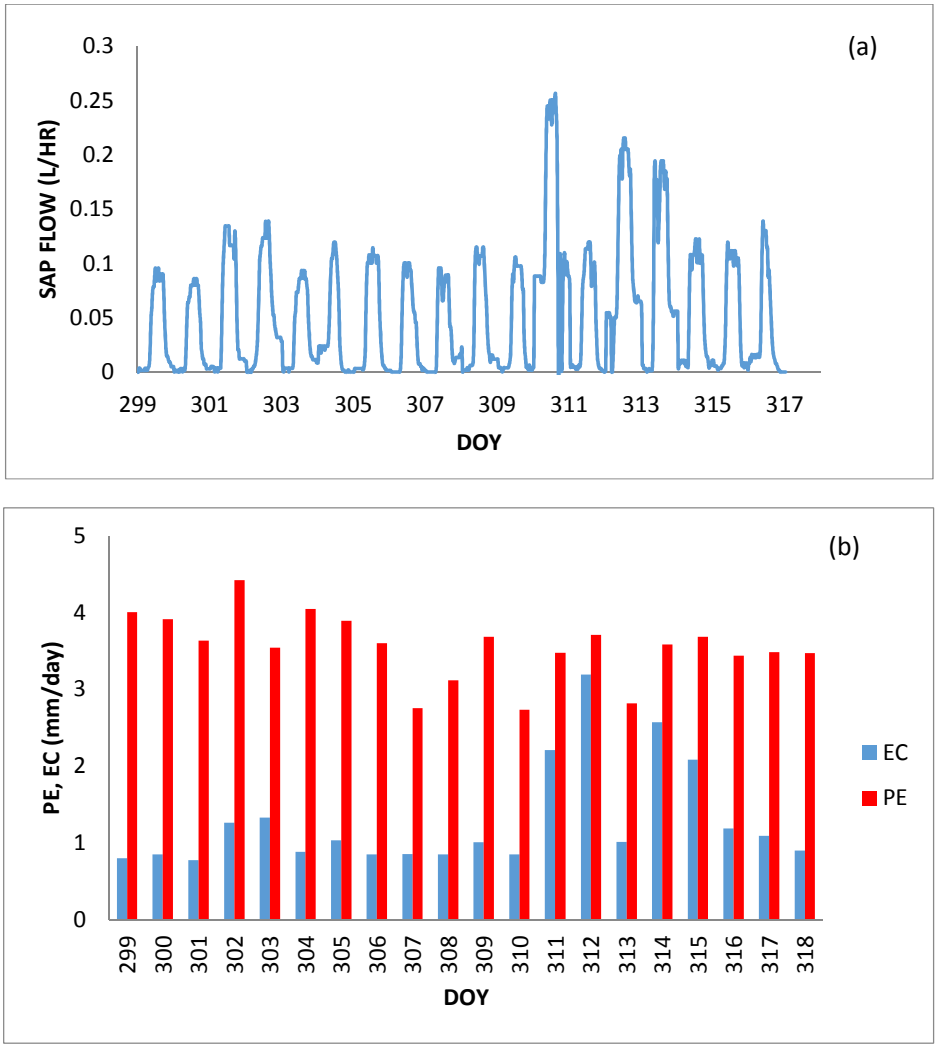
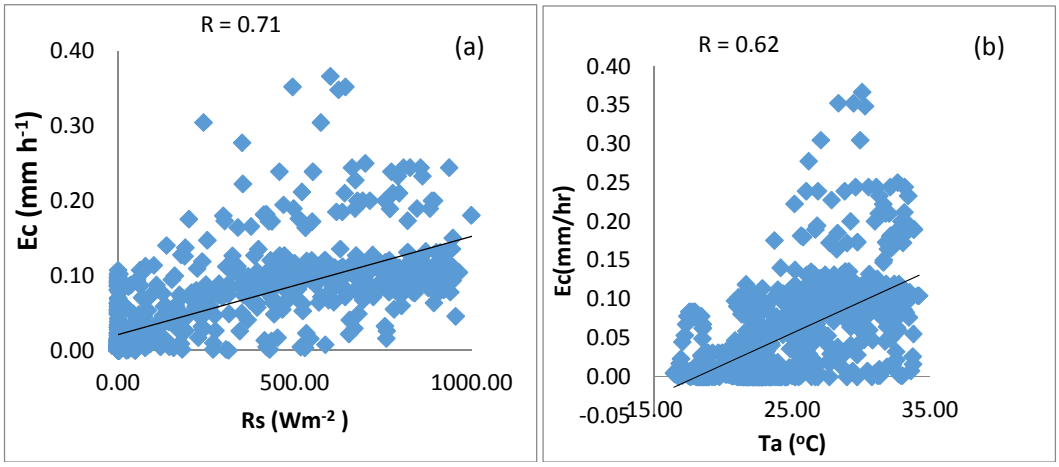


Fig. 3. Diurnal pattern of cocoa sap flow and (b) daily values of potential evaporation (PE) and Plot-level canopy transpiration



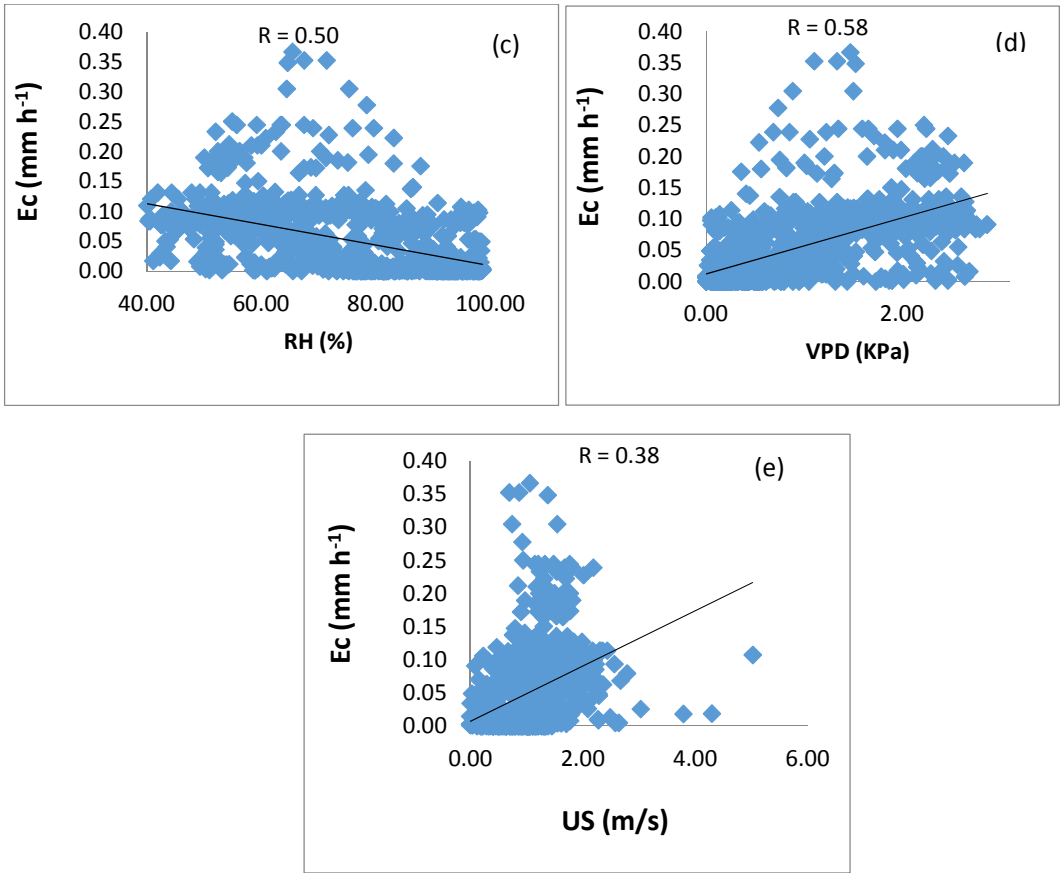


Fig. 4. The influence of cocoa transpiration on transient meteorological conditions (a) solar radiation (Rs), (b) air temperature (Ta), (c) relative humidity (RH), (d) vapour pressure deficit, and (e) wind (Us)s during DOY 299 – 318 at Akure, Nigeria

4. DISCUSSION AND CONCLUSION

The total amount of rainfall recorded during the 20 days period was 38.9 mm for the period of the research. The scanty rain and water consumed by the crop led to decrease in soil water in the monitored root zone from 0.049 to 0.015 m^3 m^{-3}. This amount of rainfall was far below the potential evaporation (atmospheric water demand) which was estimated at an average of 4.1 mm/day according to Oguntunde [13]. The very low value of transpiration observed during the cause of the study was in line with [17,18]. [19] reported increased in climatic variable most especially temperature to have impact on plant transpiration and water use. During the period of the study the cocoa plant was under water shortage. This indicates that cocoa plant water use during the period of study was limited by soil water deficit. Sap flow data from cocoa plantation was measured and the results have been analyzed under tropical climatic conditions in order to evaluate the influence of climate on the water use of cocoa. In all, solar radiation has the highest value of correlation coefficient amongst the other climatic variables having the highest influence on the water use of cocoa. Further studies are required for grown cocoa under unlimited-watered condition so as to enable us know the influential variable amongst the other climatic variables.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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