Modelling curves of mean monthly minute-by-minute and hourly relative humidity, air temperature and solar radiation of Ota, Nigeria

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Abstract. Agricultural, biological, environmental and physical processes require one or a combination of temperature, relative humidity and solar radiation. One-minute-data of these parameters for Ota, Nigeria, for September - December 2012 were obtained from meteorological centre of the Department of Physics Covenant University. Using MATLAB, diurnal patterns of mean monthly minute-by-minute and mean monthly hourly were fitted. Fournier, Gaussian, Sum of Sine Functions and Exponential models were also fitted, with the accuracy of the models determined from the Coefficient of Determination ($R^2$), Sum of Square Error (SSE) and Root Mean Square Error (RMSE). Best-fit-model was Fourier, the worst being Exponential. Best models obtained in case of minute-by-minute basis occurred when $R^2 = 0.9998$, RMSE $= 0.02948$ and SSE $= 1.237$ for air temperature; for relative humidity, $R^2 = 0.9998$, RMSE $= 0.1007$ and SSE $= 14.43$ while for solar radiation, $R^2 = 0.9997$, RMSE $= 9.301$ and SSE $= 1.23e+005$. In case of hourly basis $R^2 = 0.9991$, RMSE $= 0.09226$ and SSE $= 0.8512$ for air temperature; for relative humidity, $R^2 = 0.9984$, RMSE $= 0.4976$ and SSE $= 1.981$ while for solar radiation, $R^2 = 0.9995$, RMSE $= 6.631$ and SSE $= 351.7$. The results can produce input for weather pattern information planning in Ota, Nigeria.

Keywords: Relative humidity, air temperature, solar radiation, Fourier, Gaussian, exponential models

1. Introduction

The knowledge of diurnal temperature on hourly, as well as minute-by-minute basis is very important in some agricultural, biological, environmental and physical processes. Take for instance, the knowledge of both atmospheric relative humidity and temperature are required to design thermal comfort of human beings that would occupy a building. Also crop growth models require the knowledge of air temperature and relative humidity. The value of air temperature is required to track the ecosystem on a large scale. Differences in temperature from day to night on one hand, and from one season to another on the other hand are the repercussions of the solar radiation falling to the earth’s surface and atmosphere. The most readily available meteorological parameters data at ground meteorological stations are mainly daily minimum and maximum values. The widely used traditional method of finding the average of the minimum and maximum solar radiation, relative humidity and temperature results in poor estimation of the actual mean solar radiation, relative humidity and daily temperature. Estimation with better accuracy of each of the parameters is obtained if average is calculated from more readings per day, taken at regular time intervals. Direct measurements of surface solar radiation are not common phenomenon in many countries [1-3]. Only few stations have been measuring the daily solar radiation consistently in Nigeria.

Photosynthesis and evapotranspiration processes derive their from solar radiation. Thus, solar radiation is a very important parameter for many agricultural and hydrological studies [1, 4-6]. The World Meteorological Organization (WMO) defines the average daily temperature as the “average of the temperature observed at 24 equidistant times in the course of a continuous interval of
24 hours, or a combination of temperatures observed at less numerous times, so arranged as to depart as little as possible from the average defined above" [7]. Some meteorological stations capture and record hourly parameters, but most stations do not register minute-by-minute data. Based on the submission of WMO, a more reliable and accurate mean daily temperature could be considered as that in which the air temperature is taken on minute-by-minute basis. The same apply to other meteorological parameters.

The development of the land surface temperature atmospheric correction algorithms considered air temperature among other parameters [8]. Air temperature was also taken into consideration in the generation of several crop stress indexes such as Stress Degree Day or Crop Water Stress Index [9, 10]. Air temperature is used as an important parameter in modelling vector-borne diseases or to measure the effect of extreme temperatures on mortality in the field of health sciences [11]. Accurate air temperature measurements are needed to diminish error propagation in numerical models when air temperature is an important input parameter [12]. It has been reported that diurnal temperature range in most region of the world has been on the decrease [13]. Attempts have been made in the past to model daily air temperature using Sine curves [6, 14-19]. Model based on Fourier analysis was suggested by [20]. Fourier series analysis models were developed for relative humidity and dry bulb temperature for Ilorin and Ikeja using 1978 to 1992 meteorological data of the two locations [21]. Evidences of global warming were observed from the analysis of the sets of data for the two periods (1978 to 1992 and 1995 to 2008) for the same stations Ilorin and Ikeja. And same model developed by [21] for 1978-1992 period was still applicable for 1995-2008 period [22]. Analysing hourly data of dry bulb temperature and relative humidity of 18 meteorological stations in Nigeria from year 1995 to year 2009, Excellent Fourier series models were developed for mean monthly average and monthly hourly average for the two meteorological parameters for each month of each location [23]. This study focused on working with minute-by-minute data of solar radiation, relative humidity and air temperature, of Ota in order to: (i) determine the mean monthly minute-by-minute and mean monthly hourly patterns of solar radiation, relative humidity and air temperature; (ii) model the mean monthly minute-by-minute and mean monthly hourly curves of solar radiation, relative humidity and air temperature. Ota, a town located in Ogun state of Nigeria, is noted for her industrial activities. Situated in the tropical climate, having a good knowledge of the pattern of her relative humidity, temperature and the solar radiation would be of help in the having a control over the environment, as well as providing information to those in agricultural industry in the area.

2. Methodology

In this research, Department of Physics weather data of Covenant University, Ota, Nigeria was used. The considered parameters were Solar Radiation (SR), Relative Humidity (RH) and Air Temperature (AT). In the data set, there were 28 days missing data for the considered parameters in November, while other months had complete data set. The minute-interval-data were collected from Davis weather station connected to a Very Small Aperture Terminal (VSAT) satellite dish antenna installed on the top of the roof of College of Science and Technology of Covenant University, Ota, Nigeria as described by [24, 25]. The measurements were taken on the latitude 6.7° N and longitude 3.23° E while the elevation angle of the receiver antenna is 59.9°. The November data were not included in processing the data because the bulk of the data were missing. The data were processed in such a manner as to bring out the mean monthly minute by minute and the mean monthly hourly patterns of solar radiation, relative humidity and the air temperature for each month. A curve for each month was obtained for each parameter. The total mean over the three months of the parameters were also analysed both on minute-by-minute and hourly basis. For each of the three parameters considered, Fournier, Gaussian, Sum of Sine Functions and Exponential models were fitted using MATLAB with the accuracy of the models determined from the Coefficient of Determination ($R^2$), Sum of Square Error (SSE) and Root Mean Square Error (RMSE).

2.1 General equations of the models

Equations (1) to (5) represent the general equations of the models:
Gaussian: \[ f(x) = \sum_{i=1}^{n} a_i \exp \left[ -\left( \frac{x - b_i}{c_i} \right)^2 \right] \] (1)

Fourier: \[ f(x) = a_0 + \sum_{i=1}^{n} \left[ a_i \cos (x \cdot w) + b_i \sin (x \cdot w) \right] \] (2)

Sum of Sin Functions: \[ f(x) = \sum_{i=1}^{n} a_i \sin (b_i \cdot x + c_i) \] (3)

Exponential: (i) \[ f(x) = x_{\text{min}} + a \cdot (x^b) \cdot \exp(c \cdot x) \cdot (x_{\text{max}} - x_{\text{min}}) \] (4)

(ii) \[ f(x) = x_{\text{max}} - a \cdot (x^b) \cdot \exp(c \cdot x) \cdot (x_{\text{max}} - x_{\text{min}}) \] (5)

N.B.: Exponential (i) is for air temperature and solar radiation; while (ii) is for relative humidity

2.2 Accuracy of models:
Equations (6) to (8) were considered in determining the accuracy of the models.

(i) Sum of squares error is determined thus:
\[ \text{SSE} = \sum_{i=1}^{n} (\hat{y}_{oi} - y_{bi})^2 \] (6)

where \( \hat{y}_{oi} \) and \( y_{bi} \) are predicted and observed values respectively

(ii) The root mean square error (RMSE) is determined thus:
\[ \text{RMSE} = \left[ \frac{\sum_{i=1}^{n} (\hat{y}_{oi} - y_{bi})^2}{n} \right]^{1/2} \] (7)

(iii) The determination coefficient or squared correlation coefficient
\[ R^2 = \frac{\sum_{i=1}^{n} (\hat{y}_{oi} - y_{oi})^2}{\sum_{i=1}^{n} (y_{oi} - \bar{y}_{oi})^2} \] (8)

3. Results and Discussion
Figure 1 reveals minute-interval characteristics of relative humidity (RH), air temperature and solar radiation (SR) on a typical day (01/09/2012). The RH is observed to be fairly steady at 95-96% from the beginning of the day till around 540 minute (9:00LT). The RH started decreasing gradually along a parabolic curve, reaching a minimum of 78% at minute 810 (13:30 LT) and picking up thereafter until attaining a steady value of 95% around 1350 minute (22:30LT). The day commenced with air temperature 23.7°C, following a “parabolic track” till around 420 minute (7:00LT). Thereafter the temperature rose gradually getting to its peak 26.8°C around 900 minute (15:00 LT). Thereafter the temperature reduced gradually until it reached a steady value of 23.4°C from around minute 1320 (22:00LT) till midnight. The solar radiation is zero from the beginning of the day till early hours of the morning, around minute 405 (6:45 LT). As the sun was rising around minute 420 (7:00 LT), multi-modal sporadic rise and fall of the SR was observed until minute 1140 (19:00LT). Thereafter, the SR settled at zero until the end of the day.
Figure 1: Minute-by-minute Relative Humidity, Air Temperature and Solar Radiation on a typical day.

Figure 2a, revealed that the monthly-mean diurnal Solar Radiation (SR) in September, October and December followed the shape of a “hat”. The mean solar radiation is zero from the beginning of the day till early hours of the morning, around minute 400 (6:40 LT). Thereafter, SR increased positively and “smoothly” till around 510-minute (8:30 LT). During this period, SR was least in December and highest in October. This might be due to early hour harmattan mist usually experienced during dry season in Nigeria, thus reducing the amount of SR reaching the ground. From around minute 1120 (18:40 LT) till end of the day, the SR is zero because the sun has set by that time.

Figure 2b, revealed that the monthly-mean diurnal temperature in September, October and December followed the same shape of a “hat”. Decreasing gradually from value in the range 25.8°C to 23.9°C at beginning of the day to a turning point of 23.2 °C to 23.8 °C around 450 minutes (7:30 LT). Increasing thereafter to maximum turning point of 27.6 °C to 31.5 °C around 780 minutes (13:00 LT) to 820 minutes (13:40LT).And finally, the temperature decreased gradually later to around 24.0°C and 25.7°C at the end of the day. It was however observed that, the air temperature in October was slightly higher than that of the corresponding period in September. While that of December was higher than that of October.
Figure 2b: Diurnal air temperature for Sep., Oct. and Dec. 2012

Figure 2c showed that the monthly-mean diurnal Relative Humidity (RH) in September, October and December followed the same shape of “inverted hat”. The RH increased gradually from around 94.0% to 96.0% at the beginning of the day to maximum in the range of 97.0% to 98.5% around 450 minutes (7:30 LT) to 540 minutes (9:00 LT). Decreasing thereafter to minimum turning point of 82.0% to 68.5% around 780 minutes (13:00 LT) to 900 minutes (15:00 LT). The RH increased gradually later until the range of 93.5% to 96.0% was attained at the end of the day. The RH in December was relatively lower than that of September and October in the early period of the day till around 150 minutes (2:30 LT); relatively higher between 420 minutes (7:00 LT) and 690 minutes (11:30 LT); and drastically lower for the rest of the day.

Figure 2c: Diurnal relative humidity for Sep., Oct. and Dec. 2012

Figures 3 and 4 revealed that, the monthly-mean diurnal relative humidity, temperature and solar radiation patterns follow a typical cyclic variation over the course of the day. The variation of air temperature follows the diurnal variation of solar radiation with a certain time lag. The mean solar radiation is zero at night till early hours of the morning, and positive at day time. Mean solar radiation attains its peak of 502.22 Wm^-2 at about 14:00 Local Time (LT) under clear-sky and attains zero between sunset, 1170min (19:30 LT) and sunrise, 450min (7:30 LT). The temperature attains its peak at the same time with the peak of the solar radiation. However, a minimum state of temperature was noticed about 7:00LT, which is about half an hour before sunrise.

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Strong correlations exist among the monthly mean daily air temperature, relative humidity and solar radiation. The coefficients of correlation between relative humidity and air temperature for minute based and hourly based data are -0.99157 and -0.99141 respectively. While that for temperature and solar radiation are 0.78607 and -0.81704. It was observed that the correlations involving minute based data are slightly higher than that of hourly based; except in the case of correlation between relative humidity and solar radiation. Figures 5(a) and 5(b) showed the curves of mean monthly RH on minute-by-minute basis with Fourier and Gaussian models; and Sum of Sin Function and Exponential models fitted respectively. While Figures 5(c) and 5(d) showed the curves of mean monthly RH on hourly basis with Fourier and Gaussian models; and Sum of Sin Function and Exponential models fitted respectively. Figures 6(a) to 6(d) and 7(a) to 7(d) showed the same order as we have in figures 5(a) to 5(d) for air temperature and solar radiation respectively.
Figure 5(a): Curves of mean monthly RH on min-by-min basis with Fourier and Gaussian models

Figure 5(b): Curves of mean monthly RH on min-by-min basis with Sum of Sin and Exponential models

Figure 5(c): Curves of mean monthly RH on hourly basis with Fourier and Gaussian models
Figure 5(d): Curves of mean monthly RH on hourly basis with Sum of Sin and Exponential models

Figure 6(a): Curves of mean monthly AT on min-by-min basis with Fourier and Gaussian models

Figure 6(b): Curves of mean monthly AT on min-by-min basis with Sum of Sin and Exponential models

Figure 6(c): Curves of mean monthly AT on hourly basis with Fourier and Gaussian models
Figure 6(d): Curves of mean monthly AT on hourly basis with Sum of Sin and Exponential models

Figure 7(a): Curves of mean monthly SR on min-by-min basis with Fourier and Gaussian models

Figure 7(b): Curves of mean monthly SR on min-by-min basis with Sum of Sin models
Figure 7(c): Curves of mean monthly SR on hourly basis with Fourier and Gaussian models

Figure 7(d): Curves of mean monthly SR on hourly basis with Sum of Sin and Exponential models

The Root Mean Square Errors (RMSE) and Sum of Square Error (SSE) in estimating minute-by-minute and hourly mean daily relative humidity, air temperature and solar radiation were shown in Tables 1 and 2, respectively. These tables showed that all the radiation models tend to produce largest errors compared with other two parameters. Tables 1 and 2 revealed that the root mean square errors values of the mean monthly minute-by-minute relative humidity and temperature estimated for Ota are generally smaller compared with the corresponding values of the mean monthly hourly for Gaussian, Fourier and Sum of Sin models. On the other hand, the coefficients of determination of the mean monthly minute by minute relative humidity and temperature estimated for Ota are generally higher compared with the corresponding values of the mean monthly hourly for Gaussian, Fourier and Sum of Sin models. The models that indicate the best fit between observed and estimated values for Ota is Fourier model while the worst model is Exponential model. The best models obtained in case of minute-by-minute basis occurred when $R^2 = 0.9998$, RMSE = 0.02948 and SSE = 1.237 for air temperature; for relative humidity, $R^2 = 0.9998$, RMSE = 0.1007 and SSE = 14.43 while for solar radiation, $R^2 = 0.9997$, RMSE = 9.301 and SSE = 3.51e+005. In case of hourly basis $R^2 = 0.9991$, RMSE = 0.09226 and SSE = 0.8512 for air temperature; for relative humidity, $R^2 = 0.9984$, RMSE = 0.4976 and SSE = 1.981 while for solar radiation, $R^2 = 0.9995$, RMSE = 6.631 and SSE = 351.7. This implies that the minute by minute data fit better than the hourly data for Fourier, Gaussian and Sum of Sin Functions models with air temperature and relative humidity.
Table 1: Accuracy of models (minute-by-minute basis)

| Parameters   | S/N   | Model (min) | Goodness of fit |
|--------------|-------|-------------|-----------------|
|              |       |             | SSE  | R²   | RMSE |
| Relative Humidity | 1.   | Gaussian   | 14.7 | 0.9998 | 0.1018 |
|               | 2.   | Fourier    | 14.43 | 0.9998 | 0.1007 |
|               | 3.   | Sum of Sin Functions | 68.17 | 0.999 | 0.2187 |
|               | 4.   | Exponential | 2.455e+004 | 0.6507 | 4.133 |
| Temperature  | 5.   | Gaussian   | 1.336 | 0.9997 | 0.0365 |
|               | 6.   | Fourier    | 1.237 | 0.9998 | 0.02948 |
|               | 7.   | Sum of Sin Functions | 6.218 | 0.9988 | 0.0662 |
| Solar Radiation | 8.  | Exponential | 1443 | 0.7247 | 1.002 |
|               | 9.   | Gaussian   | 1.682e+005 | 0.9959 | 10.85 |
|               | 10.  | Fourier    | 1.23e+005  | 0.997 | 9.301 |
|               | 11.  | Sum of Sin Functions | 1.277e+005 | 0.9997 | 9.485 |

Table 2: Accuracy of models (hourly basis)

| Parameters   | S/N   | Model (hour) | Goodness of fit |
|--------------|-------|-------------|-----------------|
|              |       |             | SSE  | R²   | RMSE |
| Relative Humidity | 1.   | Gaussian   | 1.591 | 0.9987 | 0.515 |
|               | 2.   | Fourier    | 1.981 | 0.9984 | 0.4976 |
|               | 3.   | Sum of Sin Functions | 3.354 | 0.9973 | 0.7476 |
|               | 4.   | Exponential | 96.11 | 0.9235 | 2.139 |
| Temperature  | 5.   | Gaussian   | 0.1441 | 0.9985 | 0.1096 |
|               | 6.   | Fourier    | 0.08512 | 0.9991 | 0.09226 |
|               | 7.   | Sum of Sin Functions | 0.1274 | 0.9987 | 0.1457 |
| Solar Radiation | 8.  | Exponential | 5.512 | 0.9443 | 0.512 |
|               | 9.   | Gaussian   | 2621 | 0.9966 | 14.78 |
|               | 10.  | Fourier    | 351.7 | 0.9995 | 6.631 |
|               | 11.  | Sum of Sin Functions | 268.7 | 0.9996 | 9.464 |

4. Conclusion

The data set of the minute-by-minute of air temperature, relative humidity and solar radiation collected at department of physics of Covenant University, Ota, Nigeria, for September, October and December 2012 demonstrate that the three parameters are strongly correlated. The curves of mean monthly hourly values of relative humidity, air temperature and solar radiation are smoother than the mean monthly minute-by-minute values. The $R^2$ values of models fitted for minute-by-minute data sets are higher than that of hourly. And the RMSE values are lower for minute-by-minute based data than hourly based. Hence, models of minute-by-minute curves are better than the hourly based.
best fit model of mean monthly air temperature, relative humidity and solar radiation is Fourier model.

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