MODELING OF COOLING DEGREE-DAYS FOR SOUTHERN NIGERIA USING BETA DISTRIBUTION

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ABSTRACT

The concept of "degree-day" is used to estimate the energy requirement and cost of cooling at a particular location at a specific period in a year. It is also used to quantify the duration and severity of hotness or coldness of a climate. The probability density function (PDF) and cumulative distribution function (CDF) models that are required in developing cooling degree-day model were developed from long term weather data for Ilorin and Ikeja using beta distribution. The values of cooling degree-days were computed using a computer program written in C++ language. The PDF and CDF models developed from non-symmetrical beta distribution agreed better with PDF and CDF computed from weather data than the symmetric distribution models developed by earlier workers. There was good agreement between cooling degree-days predicted using the models developed and cooling degree-days computed from weather data for Ilorin, Ikeja and several other towns in southern Nigeria. The models developed from long term weather data for Ilorin and Ikeja were found to be applicable to other towns in southern Nigeria.

Keywords: Beta Distribution, Cooling Degree-Days, Cumulative Distribution Function, Dry-bulb Temperature, Model, Probability Density Function.

INTRODUCTION

The concept of cooling degree-day is used to quantify the duration and severity of hotness of a climate. It is an important climatic statistic useful in the estimation of energy requirement and cost for cooling a building during a period of time.

In some of the earth's temperate zones, people find it difficult to work comfortably and effectively during the summer months without cooling the spaces occupied. In tropical countries, cooling is necessary almost throughout the year especially when the weather is hot and humid.

Air-conditioning involves control of dry-bulb temperature, humidity, purity and movement of air in a space (Cottell, et al., 1983). These four parameters largely determine the conduciveness of air in a space to health and comfort.

In addition to causing discomfort and loss of concentration for a human being at work, extreme heat can affect health and productivity. The body also finds it difficult to dissipate heat during extremely hot weather especially if the relative humidity is high. A well designed air conditioning system apart from making people feel comfortable also prevents illness by removing contaminants.

To forestall the aforementioned problems in homes, commercial buildings, hospitals, factories and offices, in nearly every country in the world work is being done by air conditioning engineers, architects and technician so as to make the indoor air comfortable and healthy. The energy required in cooling an indoor space at a particular period of the year for a desired indoor temperature could be estimated from cooling degree-day.

Cooling degree-day can be computed from the ambient dry-bulb temperature data. So also the data can be statistically analysed to find their probability density function (PDF) and cumulative distribution function (CDF). Mathematical model can then be used to represent the PDF and CDF and from these distribution functions mathematical models of cooling degree-days can be developed.

Olorunmaiye and Ariyo (1998) developed PDF and CDF models for Ikeja and Ilorin from fifteen-year data. From the CDF model, they found a mathematical model for cooling degree-days which they suggested is applicable to cities in southern and central states of Nigerian up to Niger and Benue states. To calculate cooling degree-days for any month at a particular location using the model, the required inputs are mean dry-bulb temperature, standard deviation of temperature for that location and number of days in the month.

Olorunmaiye (2002) applied this cooling degree-day model to selected locations in Nigeria and he found reasonable agreement with cooling degree-days computed directly from measured hourly dry-bulb temperature data.

The PDF model developed by Olorunmaiye and Ariyo was a symmetrical model whereas the PDF obtained from the actual dry-bulb data was asymmetrical (it was skewed to the right). The aim of this work is to find an asymmetric PDF model that will agree better with the PDF obtained from the actual dry-bulb data and hence develop more accurate CDF and cooling degree-day models than those reported by the earlier workers.

THEORETICAL BACKGROUND

Cooling degree-day is the accumulation of positive differences between observed values of temperature (T) and base temperature (T_b) i.e. ($T - T_b$). From hourly dry-bulb temperature, cooling degree-day for a period can be calculated using the following mathematical expression (Olorunmaiye, 2002).

$$Dc = \frac{1}{24}\sum_{i=1}^{n} f_1(T) \quad \text{-----------------} \quad (1)$$

Where

$$f_1(T) = (T_i - T_b) \text{ if } (T_i > T_b) \text{ ------} \quad (2)$$

$$f_1(T) = 0 \quad \text{if} \quad (T_i \le T_b)$$

T_i = hourly dry-bulb temperature in °C, T_b = base temperature in °C, n = number of hours in the period over which cooling degree-day is calculated.

Erbs (1984) gave the following equations for cooling degree-day if mathematical models for PDF [P(T)] and CDF [Q(T)] are known.

$$D_c = \int_b^{T_{max}} N(T - T_b)P(T)dT \text{ -----} \quad (3)$$

or

$$D_c = N(T_{max} - T_b) - \int_b^{T_{max}} NQ(T)dT \text{ -------} \quad (4)$$

Where N = Number of days in the period of time

P(T) = Probability density function of dry-bulb temperature

Q(T) = Cumulative distribution function for dry-bulb temperature

T_{Max} = Maximum temperature during the period.

From the expressions above, either probability density function P(T) or cumulative distribution function Q(T) is required to compute D_c.

The desirable properties of an appropriate probability density function are:

(i) it must be continuous
(ii) the random variable should be bounded by extreme values that are both finite and positive.
(iii) it should be skewed and its skewness must be determined by parameters associated with the distribution.

One asymmetrical PDF that satisfies the requirements above is the beta distribution. The measured ambient temperature can be non-dimensionalized by using the following expression.

$$\theta = \frac{T - T_{min}}{T_{max} - T_{min}} \quad \text{-----------------} \quad (5)$$

Where θ = non-dimensional temperature

T_{min} = minimum temperature during the period

The advantage of using θ is to allow the temperature range to fall between interval 0 and 1 which are the minimum and maximum values for Beta density function variable.

With the transformation of the independent variable to θ, equation (3) becomes

$$D_c = \int_{\theta_b}^{\theta_{max}} N(\theta - \theta_b)(T_{max} - T_{min})P(\theta)d\theta \quad \text{-----------} \quad (6)$$

Cooling degree-day for a period can be computed from equation (6) once the probability density function model is developed from long term whether data for various cities. The approximate cost of cooling during that period can be estimated using the following equation given by Lindeburg (1985):

$$Cost = \frac{(24 \times 3600)\text{ (cost per kJ) (cooling load in kW) } D_c}{\left[\left(T_o - \frac{1}{2}T_r\right) - 21.1\right]} \quad \text{---------} \quad (7)$$

where

T_o = outdoor design temperature in °C, T_r = average daily range of dry bulb temperature during the period. The dry-bulb temperature of 21.1°C is roughly the mean summer comfort zone temperature (Harris, 1983). The cost per kJ in equation (7) includes the cost of electrical energy used to operate fans, pumps, and compressors.

MODEL DEVELOPMENT

The probability density function for each month of the year for Ilorin and Ikeja were found. A single PDF was developed for each location by finding the average of the twelve curves for a year. A single PDF curve was found from the two average PDF curves for the two locations by averaging. Figures 1 and 2 show the average PDF for dry bulb temperature for all the twelve months for Ikeja and Ilorin respectively. Figure 3 shows the average of average PDF for both locations.

The average curve of both cities in figure 3 was used to develop the model for PDF of ambient temperature.

If θ is assumed to have a beta distribution, then the PDF has the form (Stroud, 1996).

$$P(\theta) = A(\theta)^{m-1}(1 - \theta)^{n-1} \quad \text{------------} \quad (8)$$

Where constant A called the beta function is defined as

$$A = \frac{\Gamma(m+n)}{\Gamma(m)\Gamma(n)} \quad \text{-----------------} \quad (9)$$

The beta distribution parameters m and n were computed using the expressions below.

$$m = \mu\left[\mu\frac{(1-\mu)}{\sigma^2} - 1\right] \quad \text{--------------} \quad (10)$$

$$n = (1-\mu)\left[\mu\frac{(1-\mu)}{\sigma^2} - 1\right] \quad \text{---------} \quad (11)$$

Where μ and σ^2 are the mean and variance obtained from the average PDF curve for the two locations.

The mean μ and the variance σ^2 were found to be 0.42909 and 0.03206 respectively. Using equations (10) and (11), the beta distribution parameters m and n were found to be 2.84960 and 3.79144 respectively.

The values were rounded up to whole numbers for mathematical simplicity in evaluation of gamma functions of those values. Thus m = 3 and n = 4 and constant A was evaluated to be 60.0 from equation (9).

The resulting values of parameters and constant A were substituted into equation (8) and the probability density for ambient temperature was obtained as:

$$P(\theta) = 60.0(\theta)^2(1-\theta)^3 \text{----------} \qquad (12)$$

The corresponding cumulative distribution function was obtained by integrating equation (12) as

$$Q(\theta) = 60.0(\tfrac{1}{3}\theta^3 - \tfrac{3}{4}\theta^4 + \tfrac{3}{5}\theta^5 - \tfrac{1}{6}\theta^6) \text{- } (13)$$

The average probability distribution data for Ikeja and Ilorin were compared with the model prediction using equation (!2) as shown in Figures 4 and 5 whereas Figures 6 and 7 show the comparison of average probability density data for the two locations with the model prediction of Ariyo (1997). In Ariyo's work a different non-dimensional temperature variable was used.

Now, from equations (6) and (8) we obtain

$$D_c = \int_{\theta_b}^{\theta_{max}} N(\theta - \theta_b)(T_{max} - T_{min})60.0(\theta)^2(1-\theta)^3 \text{ -----} (14)$$

Integrating equation (14) and noting that $\theta_{max} = 1$ gives

$$D_c = N(T_{max} - T_{min})\begin{pmatrix} 0.42857 - \theta_b + 5\theta_b^4 - 9\theta_b^5 \\ + 6\theta_b^6 - 1.42858\theta_b^7 \end{pmatrix} \text{-------} (15)$$

In using equation (15) to calculate cooling degree-days, values of θ_b less than zero or greater than one must not be substituted into the equation.

The minimum and the maximum values of θ_b that can be substituted are zero and one respectively. For example if the base temperature T_b chosen for calculating D_c for a month is 24°C and the minimum temperature for that particular month is 25.6°C, value of θ_b calculated will be negative. In such a case, zero should be substituted in equation (15) and $N(T_{min} - T_b)$ should then be added to get the correct D_c.

If on the other hand the T_b chosen is greater than T_{max}, θ_b calculated will be greater than one. In this case $\theta_b = 1$ should be substituted in equation (15) which gives $D_c = 0$ as expected.

The Appendix shows computer program written in C++ for computation of cooling degree days.

More details of the work reported here can be found elsewhere (Adigun, 2003).

Comparing figures 4 and 5 with figures 6 and 7, it can be seen that the agreement between the beta distribution model and PDF calculated from the weather data is much better in the present work than in Ariyo's work in which a symmetric model was used.

Tables 1 and 2 show the comparison of cooling degree-days calculated for different base temperatures for Ikeja and Ilorin using the model developed in equation (15) with cooling degree-days calculated from the weather data for the two locations. For a base temperature of 24°C the difference between the total cooling degree-days for a year predicted using the model and that calculated from weather data were 1.9% and 2.4% for Ikeja and Ilorin. In Table 3 the cooling degree-days predicted using the model are compared with values computed from weather data for nine southern Nigeria towns. The differences between the results predicted using the model and cooling-degree days computed from weather data were between 0.1% and 12.0%for the nine towns (see Table 3). These results show that the models developed in this work are suitable for other places in southern Nigeria.

From Tables 1 and 2, the maximum cooling degree-days was observed in the month of March while minimum cooling degree-days was observed in the month of August for both Ikeja and Ilorin. This implies that maximum and minimum energy are required for cooling of homes, hospitals, offices etc in the months of March and August respectively.

From Table 3 it can be seen that Port-Harcourt and Ibadan also have their maximum and minimum cooling degree-days in March and August respectively. Calabar, Warri, Owerri and Benin have March and July as the months of maximum and minimum cooling degree-days. For Onitsha, Abeokuta and Ondo, February and August are the months of maximum and minimum cooling degree-days.

After the estimation of cooling degree-days, equation (7) can be used to compute the cost of energy required for cooling at a particular location during a specified period if the cooling load for that period is known.

Table 1: Cooling Degree-Days (°C-Days) Calculated from Beta Distribution and the Weather Data for Ikeja

Base	24		25		26		27		28		29		30	
Temp.(°C)	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model
Jan.	89.5	98.8	60.0	68.6	33.5	42.2	12.0	22.1	1.2	9.3	0.0	2.8	0.0	0.5
Feb.	118.0	125.1	90.4	96.9	62.2	68.8	34.1	43.1	11.5	22.8	0.7	9.6	0.0	2.9
Mar.	138.8	142.6	107.9	111.6	77.2	80.6	47.8	50.8	22.0	26.3	5.3	10.3	0.2	2.6
April.	128.3	125.6	98.4	95.6	69.4	65.6	42.3	37.8	19.4	16.9	4.0	5.2	0.1	0.8
May	102.2	96.1	71.3	65.1	42.7	35.7	19.5	14.0	5.6	3.2	0.8	0.3	0.0	0.0
June	58.2	54.9	31.2	26.4	12.2	7.4	2.7	0.7	0.1	0.0	0.0	0.0	0.0	0.0
July	27.8	29.0	7.3	7.7	1.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug.	27.3	30.3	5.7	8.5	0.4	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sept.	38.1	38.4	13.3	14.4	1.5	2.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Oct.	63.5	63.8	34.8	34.5	12.3	13.1	1.3	2.8	0.1	0.2	0.0	0.0	0.0	0.0
Nov.	88.6	89.1	58.7	59.4	30.2	32.9	8.5	14.0	0.8	4.0	0.0	0.6	0.0	0.0
Dec.	85.1	89.5	54.9	59.6	27.5	34.1	7.3	16.0	0.4	5.6	0.0	1.2	0.0	0.0
Total	965.2	983.2	633.9	648.3	370.1	384.4	175.5	201.4	61.1	88.3	10.8	30	0.3	6.8

Table 2: Cooling Degree-Days (°C – Days) Calculated from Beta Distribution and the Weather Data for Ilorin

Base	24		25		26		27		28		29		30	
Temp.(°C)	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model
Jan.	72.0	62.1	47.6	40.9	27.4	24.6	12.1	13.2	3.7	6.1	0.4	2.3	0.0	0.6
Feb.	125.7	111.2	97.6	84.3	70.3	60.0	44.9	39.6	23.0	23.8	8.1	12.8	1.0	5.8
Mar.	153.3	147.0	122.5	116.1	92.0	86.0	62.6	58.9	35.7	36.5	14.3	20.0	3.4	9.3
April.	125.1	123.0	95.7	93.1	67.2	64.4	40.9	39.7	20.3	21.1	7.8	9.2	1.9	3.0
May	90.3	86.4	60.7	56.8	34.0	31.9	14.0	14.6	4.1	4.9	0.9	1.0	0.1	0.1
June	52.9	50.6	27.1	26.4	8.9	10.4	1.3	2.7	0.0	0.3	0.0	0.0	0.0	0.0
July	21.5	23.6	5.6	7.6	0.6	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug.	15.7	20.4	2.7	5.7	0.1	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sept.	23.1	27.4	6.0	10.9	0.4	2.8	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Oct.	52.0	57.8	26.1	33.1	8.6	15.6	1.4	5.6	0.0	1.3	0.0	0.1	0.0	0.0
Nov.	80.7	84.2	52.3	58.1	27.2	36.4	9.5	20.3	1.2	9.7	0.0	3.8	0.0	1.0
Dec.	58.2	56.3	34.0	36.1	15.6	20.9	4.4	10.7	0.4	4.6	0.0	1.6	0.0	0.3
Total	870.5	850	577.9	569.1	352.3	354.9	191.1	205.6	88.4	108.3	31.5	50.8	6.4	20.1

Table 3: Cooling degree-days (°C – days) calculated from model compared with values calculated from weather data for a base temperature of 24°C for some towns in southern Nigeria.

Place	Port-Harcourt		Calabar		Warri		Owerri		Onitsha		Abeokuta		Benin		Ibadan		Ondo	
Month	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model
Jan.	138.8	115.2	107.3	104.1	110.9	112.0	125.0	125.8	134.1	135.1	127.9	124.4	95.4	75.1	83.5	65.0	88.8	55.7
Feb.	159.4	142.5	122.6	118.2	111.8	109.8	139.1	137.2	139.0	135.6	158.9	162.2	141.5	142.5	137.2	130.8	129.0	126.8
Mar.	240.0	221.0	167.9	170.9	155.1	155.4	203.0	206.4	126.5	121.8	157.0	170.5	148.5	157.7	147.8	159.4	120.3	132.9
April	211.1	193.3	126.7	124.7	124.1	129.0	103.7	135.9	177.7	110.6	128.9	132.0	118.3	123.9	114.0	123.4	91.2	93.9
May	124.1	113.8	94.4	89.5	110.5	110.7	102.1	101.9	94.3	85.5	119.6	120.9	97.4	97.9	91.7	89.0	71.4	71.8
June	110.6	105.0	74.4	68.1	73.0	65.6	79.2	77.1	74.7	73.7	74.5	67.7	50.8	48.3	48.3	39.5	36.0	20.7
July	64.0	53.8	22.8	12.8	36.4	27.6	33.4	30.3	46.8	42.0	49.0	40.0	18.6	9.0	24.0	15.6	16.1	5.3
Aug.	59.7	51.6	32.4	26.9	40.4	34.2	37.1	31.4	38.7	33.5	45.2	37.8	23.2	14.2	20.6	7.4	14.5	4.2
Sept.	72.9	58.2	41.3	40.4	49.8	49.3	48.0	49.5	59.2	54.6	60.2	58.7	93.8	34.9	32.5	21.7	22.7	8.4
Oct.	105.7	23.1	59.9	54.6	80.7	77.1	75.3	75.3	70.3	59.5	90.1	95.7	60.9	68.3	64.9	64.6	53.7	46.4
Nov.	134.4	111.8	77.1	77.1	105.3	111.0	100.3	101.1	87.2	85.3	121.5	122.6	85.6	82.4	77.8	70.2	67.2	62.4
Dec.	138.1	112.0	85.7	90.3	103.1	108.1	107.2	109.4	86.0	62.0	99.7	93.0	109.6	103.7	109.4	109.0	95.0	83.6
Total	1558.8	1371.3	1012.5	977.6	1101.1	1089.7	1180.4	1181.3	1073.5	999.2	1232.5	1225.9	989.6	957.9	951.7	895.6	805.9	724.1
% Diff..	12.0		3.4		1.0		0.1		6.9		0.5		3.2		5.9		10.2	

CONCLUSION

The probability density function and cumulative distribution function models developed using beta distribution produced better results than a symmetrical distribution adopted by a former researcher. Also, the cooling degree-days model developed from long term hourly dry-bulb temperature data for Ikeja and Ilorin predicted results that are close to the weather data results. The model developed for Ilorin and Ikeja were found to be applicable to other cities in southern Nigeria.

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APPENDIX

```
//Program
//COMPUTATION OF COOLING DEGREE-DAYS
//WRITTEN BY: O.J. ADIGUN
//*****************************************************
#/include<iostream,h>
#include<fstream.h>
#include<math.h>
float a,b,c,d,Tmax,Tmin,Tb,N,x1,x2,n;
char Adigunfile[30],OSU[25]:
double Dc, Thetab,y,y1,y2,y3,y4,year;
main()
{
cout<<"enter a name for the output file"<<endl;
cin>>Adigunfile;
ofstream four(Adigunfile);
cout<<"Supply the number of base temperatures.\n";
cin>>n;
for(int j=1; j>=12; j++){
cout<<"Supply the Month of the Year(e.g. June, September e.t.c.)\n";
cin>>OSU;
cout<<"Input the number of days in the Month. \n";
cin>>N;
cout<<"Supply the Maximum temperature.\n";
cin>>Tmax;
cout<<"Supply the Minimum temperature.\n";
cin>>Tmin;
cout<<"RESULT OF THE COOLING DEGREE-DAYS FOR THE YEAR"<<OSU<<"."<<endl;
fout<<" RESULT OF THE COOLING DEGREE-DAYS FOR THE YEAR"<<OSU<<"."<<endl;
cout<<"_______________________________________________________________"<<endl;
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```
fout<<"____________________________________________________"<<endl;
cout<<"Number of Days in Month ="<<N<<".\n";
fout<<"Number of Days in Month ="<<N<<".\n";
cout<<"The Maximum temperature="<<Tmax<<"Degree Celsius.\n";
fout<<"The Maximum temperature="<<Tmax<<"Degree Celsius.\n";
cout<<"The Minimum temperature="<<Tmin<<"Degree Celsius.\n";
fout<<"The Minimum temperature="<<Tmin<<"Degree Celsius.\n";
cout<<"____________________________________________________"<<endl;
fout<<"____________________________________________________"<<endl;
cout<<" S/N BASE  -O-b  COOLING DEGREE    "<<endl;
fout<<" S/N BASE  -O-b  COOLING DEGREE    "<<endl;
cout<<"     TEMPERATURE       DAYS      "<<endl;
fout<<"     TEMPERATURE       DAYS      "<<endl;
cout<<"____________________________________________________"<<endl;
fout<<"____________________________________________________"<<endl;
for(inti=1; i<=n; i++)
{
cout<<"supplythe base temperature"<<i<<".\n";
cin>>Tb;
x1=Tb-Tmin;
x2=Tmax-Tmin;
Thetab=x1/x2;
y=Thetab;
cout<<"y"<<y;
if(Thetab?1.0) {
y=1.0;
}
else if(Thetab<0.0){
y=0.0;}
else{y=Thetabl;}
cout<<"y"<<y;
y1=pow(y,4);
y2=pow(y,2);
a=5.0*y1;
b=9.0*y*y1;
c=6.0*y1*y2;
d=1.42857*y*y1*y2;
y3=0.42857+a+c-b-d-y;
y4=y3*N*(Tmax-Tmin);
if(Thetab>1.0) {
  Dc=y4-N*(Tb-Tmax);}
else if (Thetab<0.0){
  Dc=y4+N*(Tmin-Tb);}
else {Dc=y4;}
if(Dc<0.0)
{Dc=0;}
else {Dc=Dc;)
fout<<"Dc"<<endl;
cout<<"\t"<<i<<"\t"<<"\t"<<Tb<<"\t"<<"\t"<<y<<"\t"<<Dc<<endl;
fout<<"\t"<<i<<"\t"<<"\t"<<Tb<<"\t"<<"\t"<<y<<"\t"<<Dc<<endl;}}
return 0;}
```

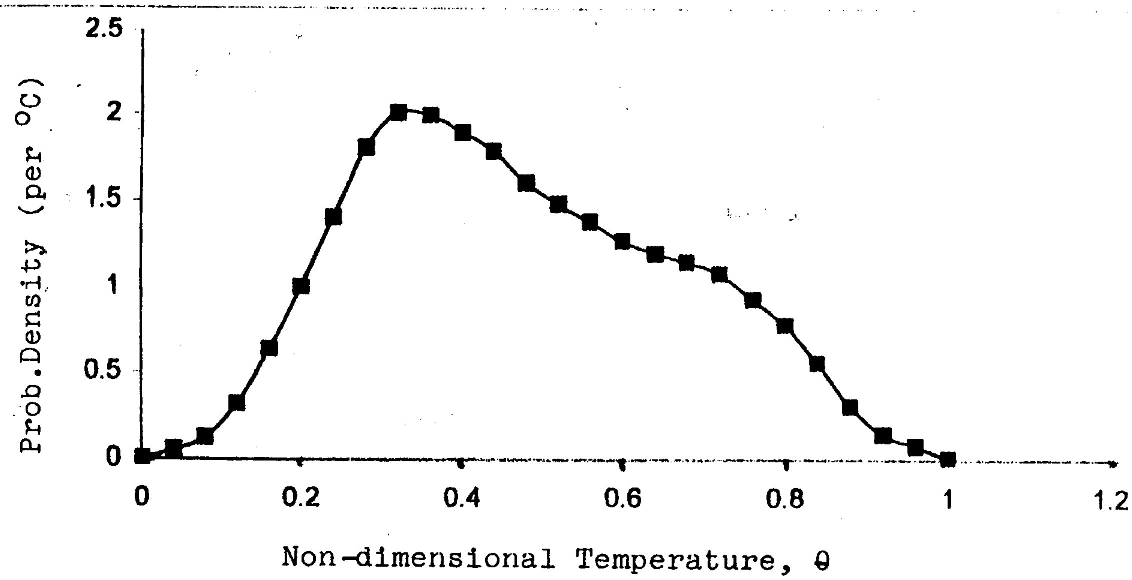

Figure 1: Average Probability Density Function for Dry-bulb Temperature for All the Twelve Months for Ikeja

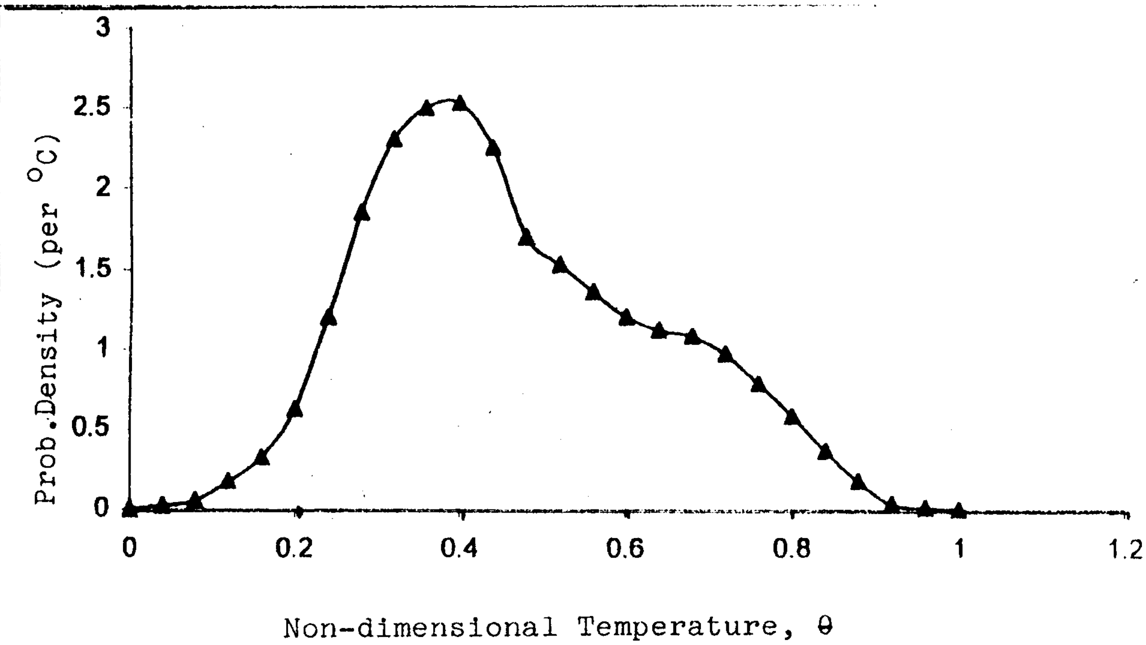

Figure 2: Average Probability Density Function for Dry-bulb Temperature for All the Twelve Months for Ikeja

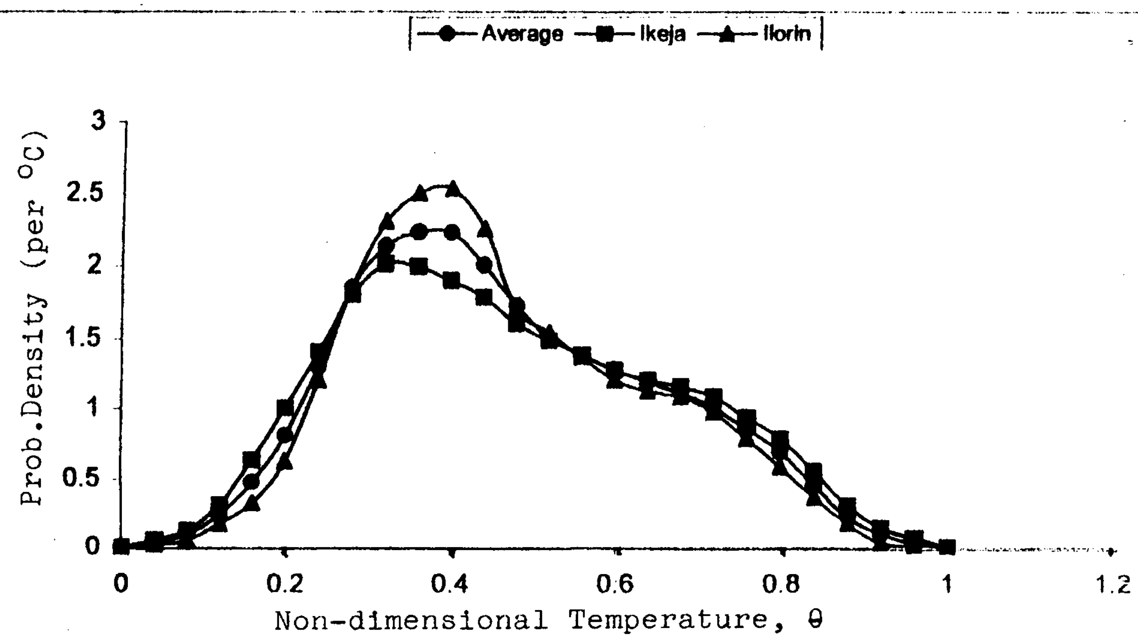

Figure 3: Average Probability Density Function for Dry-bulb Temperature for All the Twelve Months for both Ikeja and Ilorin.

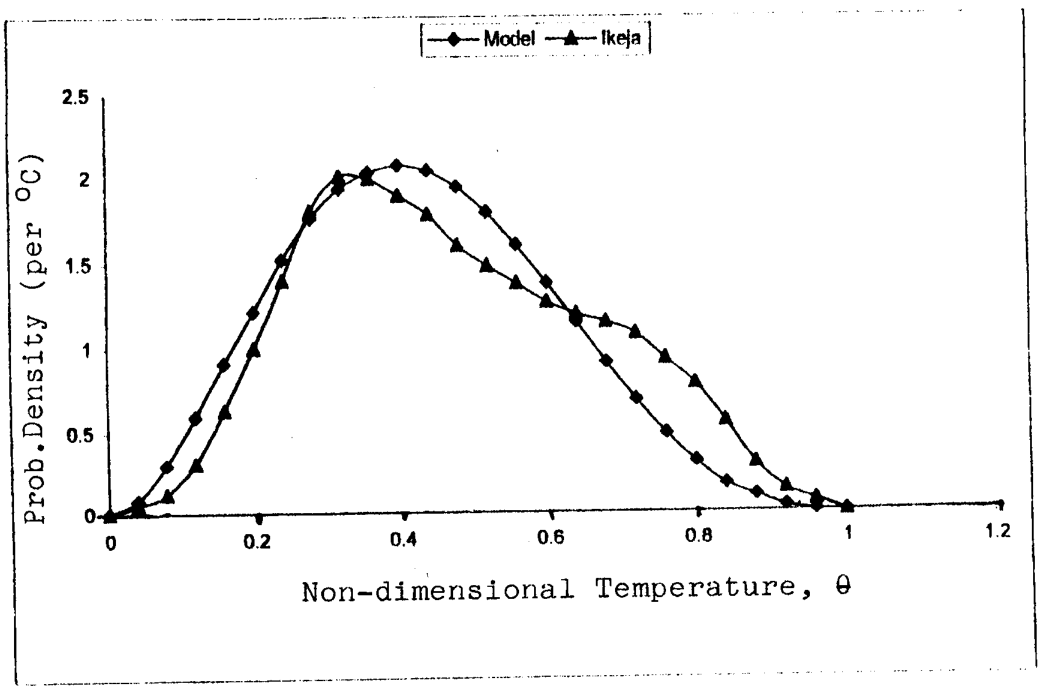

Figure 4: Average Probability Density Function for Dry-bulb Temperature for All the Twelve Months for Ikeja and Model Developed

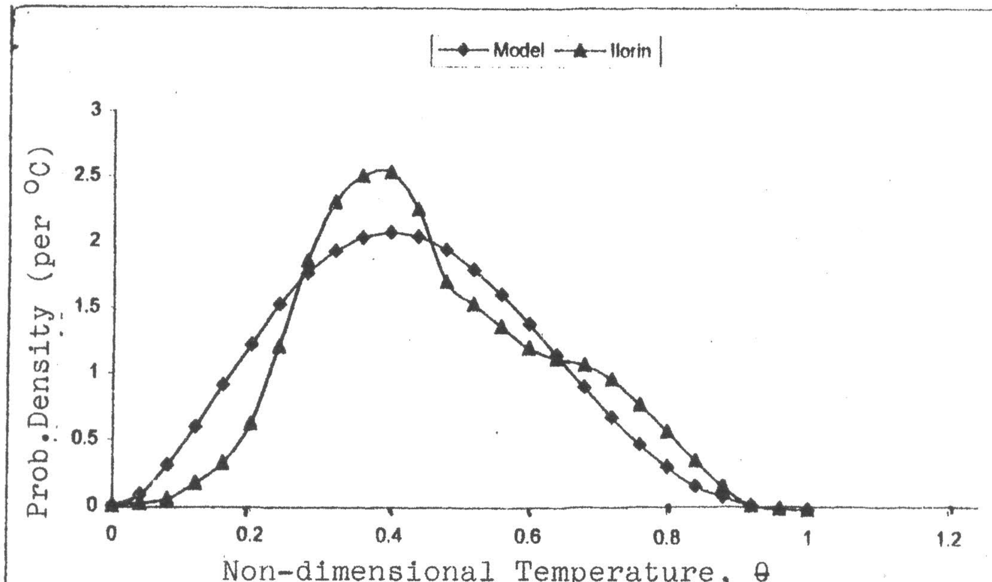

Figure 5: Average Probability Density Function for Dry-bulb Temperature for All the Twelve Months for Ilorin and Model Developed

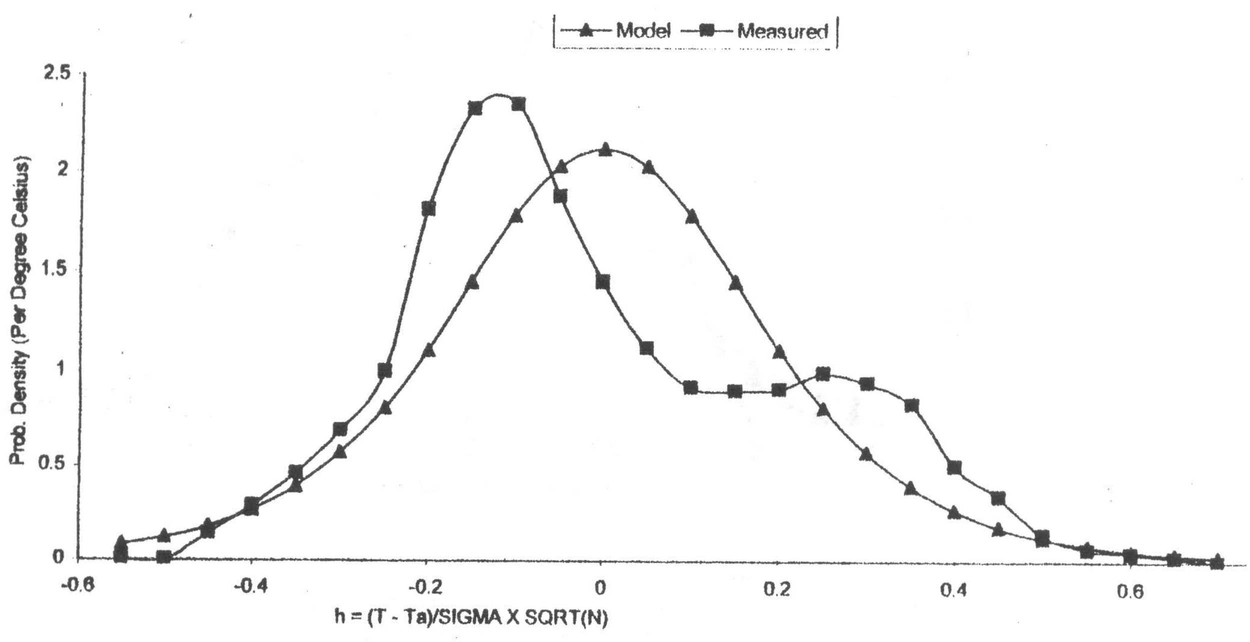

Figure 6: Dry-bulb Temperature Density Function for Ikeja (from Ariyo (1997))

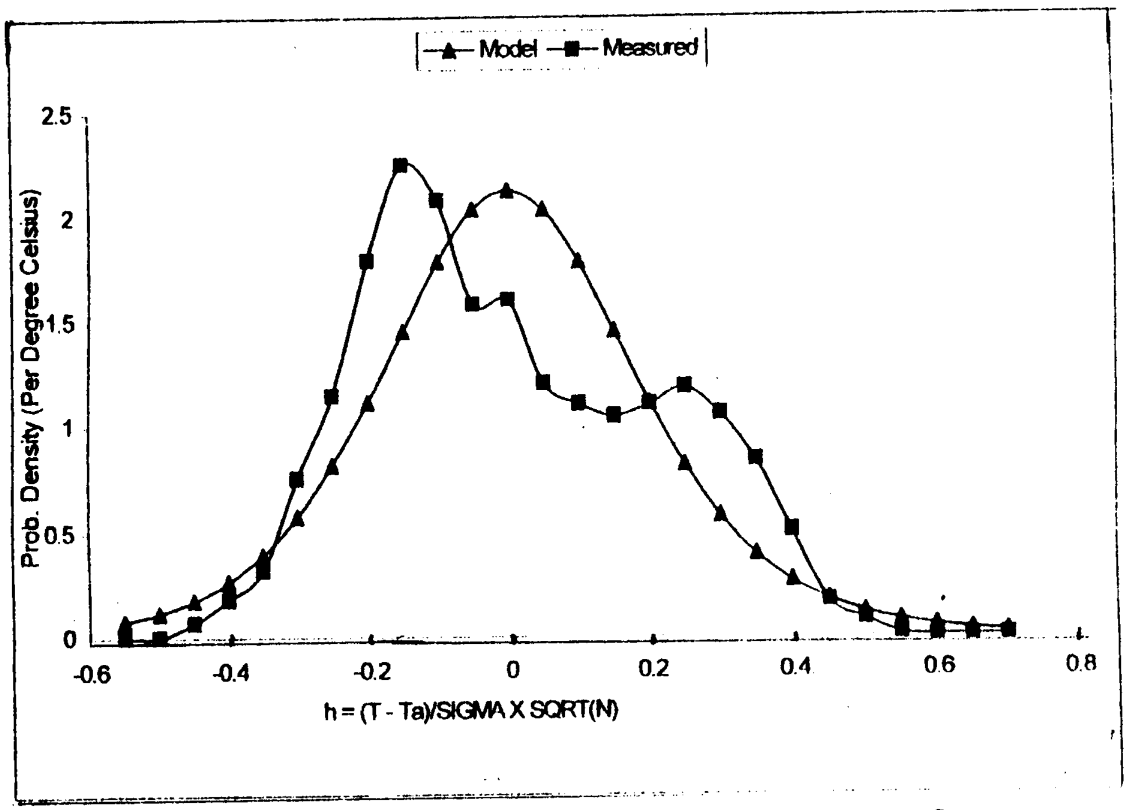

Figure 7: Dry-bulb Temperature Density Function for Ilorin (from Ariyo (1997))