



Hourly Air Temperature Modeling Based on Atmospheric Pressure, Global Solar Radiation and Relative Humidity Data

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A B S T R A C T

This paper is focusing on hourly air temperature estimation model (MAT) using available meteorological measured data located in Laghouat (Algeria). The hourly air temperature defined by the present model can be calculated at any time of the day or night period based on atmospheric pressure, global solar radiation and relative humidity data. This work was compared with three published models from the literature as: Wave, Idliman and Double cosine. Fifteen months of hourly atmospheric pressure, global solar radiation, relative humidity and air temperature data collected during the period (January 2015 to March 2016) were used to test the accuracy of the various models. The analysis of the days selected randomly showed that the MAT model gave substantially good fit to the observed data. The root mean square error (RMSE) of the MAT model is less than 0.5 °C during all the period of study than the other models studied ranged in the interval (2 °C, 4 °C). The estimated results were compared to the measured ones using statistical parameters tests such as the mean bias error (MBE), the mean percentage error (MPE), the mean absolute error (MAE), the RMSE and the coefficient of determination (R^2).

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INTRODUCTION

Air temperature is an important factor in many fields in human life such as: agriculture, meteorology, hydrology, solar energy and human behavior, respectively [1, 5]. All most of the existing models in the literature based on daily minima and maxima air temperature and other parameters which are defined as: latitude, longitude, sunrise time and finally sunset time. The shape of diurnal temperature curve has been modeled with different manners from simple to complex cases. For the simple ones, are based on sine curves and the complex ones are utilizing Fourier analysis or complex energy balance [6, 7] and more complex energy budget models [8, 9]. Bilbao et al. [10] presents some stochastic models that link hourly and monthly average temperature values. Several researchers as: Hollands et al. [11] were studied the effect of neglecting the random component in hourly temperature data for various solar heat systems. The results indicate that, for random component of the hourly ambient temperature are unnecessary. Boland [12] showed that the stochastic air temperature component is critical for evaluating heating and cooling loads for passive solar applications. Knight et al. [13] proposed a

model to generate hourly ambient temperature series with the random component included without introducing discontinuities between the last hour of one day and the first hour of the next day. Knight et al. and Erbs et al. [13, 14] showed that the cumulative distribution of the normalized hourly temperature values could be represented by probability function. Amato et al. [15] discussed stochastic- dynamic models for both air temperature and solar irradiance daily time series in the climate of the Italy. Hernandez et al. [16] have developed stochastic models for predicting daily minimum air temperatures Macchiato et al. [17] have analyzed cold and hot air temperatures showed at 50 stations in southern of Italy. Many empirical models below have been used to determine solar radiation by using meteorological and geographical parameters such as: sunshine hours [18], air temperature [19], latitude [20], precipitation [21], relative humidity [22], and cloudiness [23] and maximum and minimum temperature [24].

The purpose of this work is to present a new mathematical model of air temperature based on atmospheric pressure, global solar radiation and relative humidity data. A comparison is established between the results obtained by the application of the proposal model with measured data in the site of Laghouat, Algeria. This

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work was compared with three published models from the literature as: Wave, Idliman and Double cosine. The performance of present model is objectively tested by using mean bias error (MBE), root mean square error (RMSE), mean absolute error (MAE), mean percentage error (MPE) and the coefficient of determination (R^2). The advantage of this model is the possibility to determine the hourly global solar radiation just knowing the meteorological parameters at the same hour and the application of the model is simple and we can use it elsewhere in the world.

DATA COLLECTION AND METHODS

The hourly meteorological parameters such as: atmospheric pressure, global solar radiation, relative humidity and air temperature data were used to parameterize and test the new proposed model (MAT). These hourly meteorological parameters were collected from automated weather station at university of Laghouat, Laghouat (Algeria) (latitude: 33°47'59" N, longitude: 2°51'54" E, elevation: 764 m). The period of this study was from January 2015 to March 2016. The maximum (T_{max}) and the minimum (T_{min}) air temperatures were measured hourly. Five days were selected randomly for each month and fifteen days selected randomly from each season from the period of the study.

Air temperature models

Wave model The first model (WAVE) was initially presented by De Wit et al. [25]. The WAVE model uses a cosine function for the period from the time of minimum temperature to the time of maximum temperature and another cosine function from the time of the maximum temperature to the time of minimum temperature the next day. The model fixes at 14h00 the time of the maximum temperature, and at sunrise the time of the minimum temperature. The hourly temperatures are calculated from the below equations:

For $0 \leq H < RISE$ and $14h00 < H \leq 24h00$:

$$T(H) = T_{AVE} + AMP \left(\cos(\pi H' / (10 + RISE)) \right) \quad (1)$$

For $RISE \leq H \leq 14h00$:

$$T(H) = T_{AVE} - AMP \left(\cos(\pi(H - RISE) / (14 - RISE)) \right) \quad (2)$$

Where $RISE$ is the time of sunrise (hours) and $T(H)$ is the temperature at any hour, H is time (hours), $H' = H + 10$ if $H < RISE$, $H' = H - 14$ if $H > 14h00$ and T_{AVE} and AMP are defined as:

$$T_{AVE} = (T_{Min} + T_{Max}) / 2 \quad (3)$$

$$AMP = (T_{Max} - T_{Min}) / 2 \quad (4)$$

Where T_{Min} and T_{Max} are the daily minimum and maximum air temperatures.

Idliman model The hourly air temperature is determined from the daily maximum and minimum temperature [26]. The model is given by the following expressions:

$$T_{amb} = T1 + T2 \cos((14 - AST)\pi/12) \quad (5)$$

$$T1 = (T_{Min} + T_{Max}) / 2 \quad (6)$$

$$T2 = (T_{Max} - T_{Min}) / 2 \quad (7)$$

Double cosine model (DC) This type of model uses three sinusoidal segments to connect the times of occurrence of the daily minimum and maximum air temperatures [27]. The model is presented below by the following equations:

- $1 \leq t \leq t_{Tmin}$:

$$T(y, m, d, t) = T(y, m, d) - \cos \left[\frac{\pi(t_{Tmin} - t)}{24 + t_{min} - t_{Tmax}} \right] \frac{A_T(y, m, d)}{2} \quad (8)$$

- $T_{min} \leq t \leq t_{max}$:

$$T(y, m, d, t) = T(y, m, d) + \cos \left[\frac{\pi(t_{Tmax} - t)}{24 + t_{max} - t_{Tmin}} \right] \frac{A_T(y, m, d)}{2} \quad (9)$$

- $t_{max} \leq t \leq 24$:

$$T(y, m, d, t) = T(y, m, d) - \cos \left[\frac{\pi(24 + t_{Tmin} - t)}{24 + t_{min} - t_{Tmax}} \right] \frac{A_T(y, m, d)}{2} \quad (10)$$

where $T(y, m, d)$ is the daily mean air temperature, $A_T(y, m, d)$ is the daily thermal amplitude ($^{\circ}C$), t_{Tmin} is the hour at which the hourly minimum temperature occurs, t_{Tmax} is the hour at which the hourly maximum temperature occurs, and t is the hour of the day.

New proposed model

The proposal model of hourly air temperature (MAT) is defined by the following expression:

$$T_{air} = T_{min} + \left(1 - \frac{T_{min}}{T_{max}} \right) \exp \left(\frac{I}{I_0} + \frac{P}{P_0} + \frac{(1 - RH)}{2} \right) \quad (11)$$

with T_{air} is the hourly air temperature ($^{\circ}C$); T_{min} and T_{max} are the hourly minimum and maximum air temperature ($^{\circ}C$); I_0 is the constant solar ($I_0 = 1367 \text{ W/m}^2$); I is the global solar radiation incident on a horizontal surface at the location studied (W/m^2); P_0 is the atmospheric pressure ($P_0 = 101.235 \text{ kPa}$); P is the atmospheric pressure

at the location studied (kPa); RH is the relative humidity (%).

If $T_{\max} \leq 3$ °C, the equation (11) can be written as the following expression:

$$T_{air} = T_{min} + 0.01 \times \exp\left(\frac{I}{I_o} + \frac{P}{P_o} + \frac{(1-RH)}{2}\right) \quad (12)$$

Global solar radiation (I) between sunshine hour and sunrise hour (period of night) is equal to zero ($I = 0 \text{ W/m}^2$). The global solar radiation (I) can be deduced from Equation (11) as:

$$I = I_o \times \left[-\left(\frac{P}{P_o} + \frac{(1-RH)}{2}\right) + \ln\left(\frac{T_{\max} \times (T_{air} - T_{min})}{T_{\max} - T_{min}}\right) \right] \quad (13)$$

RESULTS AND DISCUSSIONS

The accuracy of the considered models was tested by calculating the mean bias error (MBE), the mean absolute error (MAE), the root mean square error (RMSE), mean percentage error (MPE), and the coefficient of determination (R^2). The difference between the calculated (or estimated) and measured (or observed) values of air temperature is defined as:

The difference between the calculated and measured values of air temperature is defined as: In the present work, we present The radiative exchange between the transparent cover and the ground is:

$$d_i = T_{i,obs} - T_{i,est} \quad (14)$$

$T_{i,est}$ and $T_{i,obs}$ are the i th estimated and observed values of air temperature. The statistical parameters are given by the following relations.

Methods of error analysis

The mean bias error (MBE)

The test of MBE provides information on the long-term performance of models studied. A positive MBE value gives the average amount of over-estimation in the calculated values and vice versa. In general, a small MBE is desirable as given by Oliveiraa et al. [28].

$$MBE = \frac{1}{N} \sum_1^N d_i \quad (15)$$

The mean absolute error (MAE)

$$MAE = \frac{1}{N} \sum_1^N |d_i| \quad (16)$$

The root mean square error (RMSE)

The value of RMSE is always positive, representing zero in the ideal case. The normalized root mean square error gives information on the short term performance of the

correlations by allowing a term by term comparison of the actual deviation between the predicted and measured values. The smaller the value, the better is the model's performance.

$$RMSE = \left(\frac{1}{N} \sum_1^N d_i^2 \right)^{1/2} \quad (17)$$

The coefficient of determination (R^2)

$$R^2 = 1 - \left(\frac{\sum_1^N d_i^2}{\sum_1^N (Y_{iN} - \bar{Y})^2} \right) \quad (18)$$

with:

$$\bar{Y} = 1/N \left(\sum_1^N Y_{obs} \right) \quad (19)$$

where, N is the number of measurements or observations.

The mean percentage error (MPE)

A percentage error between -10% and +10% is considered acceptable as reported by Muzathik et al. [29].

$$MPE(\%) = \frac{1}{n} \sum_1^N \left(\frac{d_i}{T_{i,obs}} \right) \times 100 \quad (20)$$

Model evaluation on randomly selected days

Several models are based on daily maximum and daily minimum air temperatures to predict the hourly air temperatures. For this subsection, four days were selected randomly from the period (January 2015 to March 2016) as an example to see the behaviour of the four models studied to calculate hourly air temperatures. Hence, there are differences on temperatures between the observed and estimated temperatures for each model which can be discussed in terms of model accuracy. The magnitude of the errors for each model varied through the time of the day. The curve of MAT model gave a good estimate of the observed data during all the day. The MAT model overestimates slightly the observed data (from midnight to 9h00 and from midday to midnight). The Idliman model underestimates the observed data (from midnight to 4h00 and 20h00 to midnight) and overestimates it in the interval (from 5h00 to 20h00). The Double cosine model overestimates the observed data (from 8h00 to 24h00) and underestimates it in the interval (from midnight to 8h00), and finally, the Wave model overestimates the observed data (from midday to 24h00) and underestimates it in the interval (from midnight to midday) as shown in Fig. 1.

Comparable results were obtained for the other days as presented in Fig. 3, Fig. 5 and Fig. 7. The absolute value of the error at other times of the day (05-01-2015) was less than 1.2 °C for MAT model, 7.7 °C for Wave, 12 °C for Idliman and 14.3 °C for Double cosine as shown in Fig. 2.

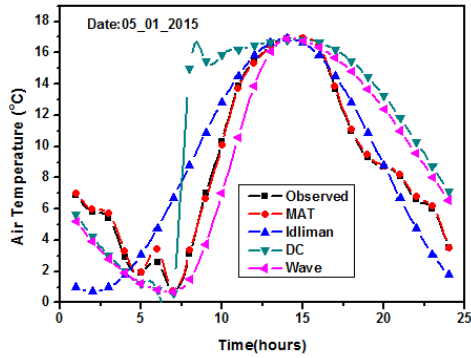


Figure 1. Hourly temperatures estimated by the four models versus time compared with observed data for a randomly selected day: 05-01-2015

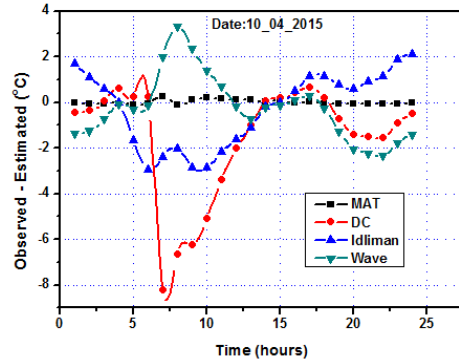


Figure 4. Comparison between the observed and estimated air temperatures as function of time for the four models studied for a randomly selected day: 10-04-2015

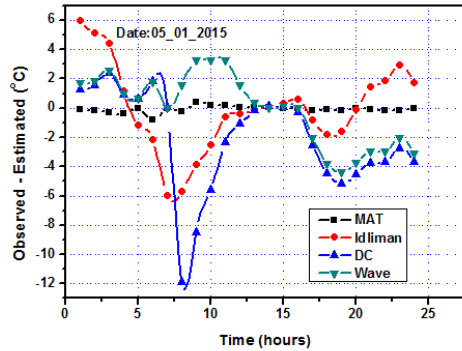


Figure 2. Comparison between the observed and estimated air temperatures as function of time for the four models studied for a randomly selected day: 05-01-2015

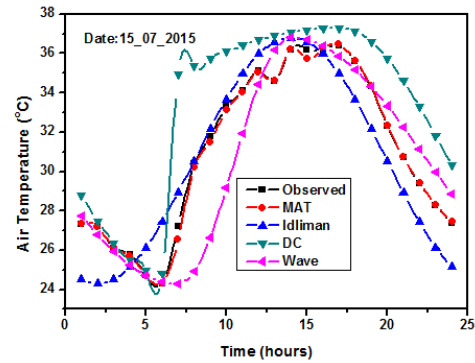


Figure 5. Hourly temperatures estimated by the four models versus time compared with observed data for a randomly selected day: 15-07-2015

The absolute value of the error at other time of the day (10-04-2015) was less than 0.4 °C for

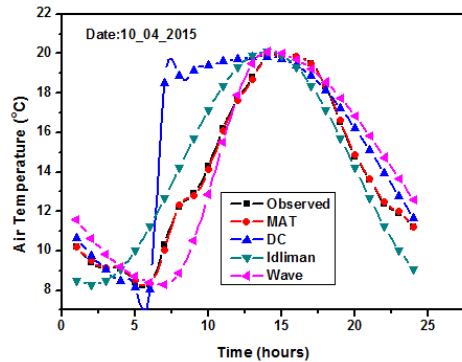


Figure 3. Hourly temperatures estimated by the four models versus time compared with observed data for a randomly selected day: 10-04-2015

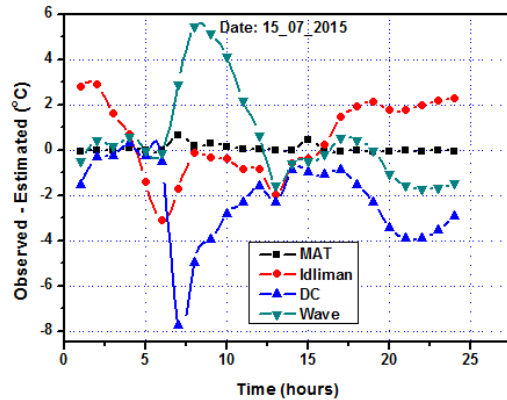


Figure 6. Comparison between the observed and estimated air temperatures as function of time for the four models studied for a randomly selected day: 15-07-2015

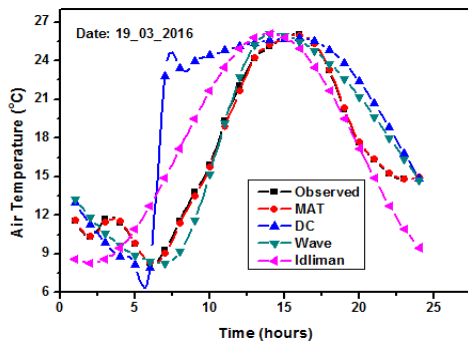


Figure 7. Hourly temperatures estimated by the four models versus time compared with observed data for a randomly selected day: 19-03-2016

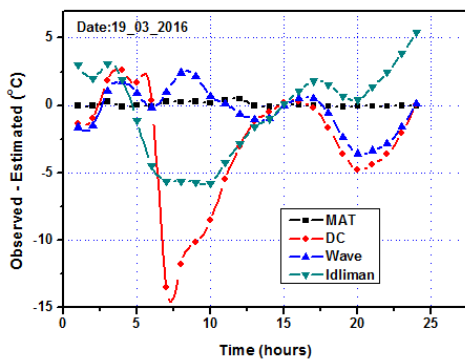


Figure 8. Comparison between the observed and estimated air temperatures as function of time for the four models studied for a randomly selected day: 19-03-2016

Fig. 4, the absolute value of the error at other time of the day (15-07-2015) was less than 1°C for MAT model but it was the largest for the other models in the interval (from 6°C to 8°C) as shown in Fig. 6. The smallest value of the absolute value of the error was at about 4h00 and 13h.00 for all models. The absolute value of the error at other time of the day (19-03-2016) was less than 0.6°C for MAT model, but it was highest for the other models in the interval (from 6°C to 16.5°C) as presented in Fig. 8.

Model evaluation of monthly mean daily air temperature

From Table 1 to Table 4 which summarize the monthly mean statistical obtained by comparing hourly air temperature calculates from each of the four models studied with observed hourly air temperature data during the period (January 2015 to March 2016). Table 1 summarises results of the monthly mean statistical for MAT model during the period (from January 2015 to March 2016). For the MAE, R² and RMSE, the values vary between the intervals (0.075 °C, 0.141 °C), (0.989, 0.998) and (0.109 °C, 0.213 °C), respectively. The coefficients of determination close to 1 for MAT model

than other three models which gave consistently a good accuracy.

TABLE 1. Error analysis for monthly mean daily air temperature for MAT model

Month	MBE	MAE	RMSE	R ²	MPE
Jan.2015	-0.032	0.111	0.147	0.998	-0.637
Feb.2015	-0.008	0.075	0.134	0.989	-0.146
Mar.2015	0.013	0.081	0.109	0.998	0.080
Apr.2015	0.050	0.102	0.144	0.998	0.232
May.2015	0.083	0.125	0.213	0.995	0.335
Jun.2015	0.071	0.107	0.163	0.998	0.263
Jul.2015	0.079	0.112	0.183	0.998	0.260
Aug.2015	0.107	0.141	0.215	0.996	0.369
Sep.2015	0.064	0.097	0.144	0.998	0.256
Oct.2015	0.045	0.083	0.125	0.998	0.244
Nov.2015	0.036	0.095	0.134	0.998	0.051
Dec.2015	0.015	0.116	0.152	0.998	-0.068
Jan.2016	0.013	0.127	0.180	0.997	-0.039
Feb.2016	0.028	0.096	0.139	0.997	0.121
Mar.2016	0.032	0.119	0.172	0.997	0.106

TABLE 2. Error analysis for monthly mean daily air temperature for Idliman model

Month	MBE	MAE	RMSE	R ²	MPE
Jan.2015	0.485	2.585	3.412	0.010	-22.737
Feb.2015	-0.052	1.102	1.398	0.071	9.309
Mar.2015	-0.211	1.595	2.059	0.339	-3.168
Apr.2015	-0.226	1.630	1.970	0.729	-1.381
May.2015	0.065	1.328	1.657	0.756	0.110
Jun.2015	0.264	1.991	2.288	0.758	0.866
Jul.2015	0.664	1.817	2.100	0.737	2.084
Aug.2015	-0.233	2.239	2.852	0.543	-0.895
Sep.2015	-0.284	1.517	1.881	0.746	-0.800
Oct.2015	0.064	1.163	1.502	0.738	0.181
Nov.2015	0.093	1.402	1.868	0.647	1.934
Dec.2015	-0.295	2.088	2.669	0.295	-7.383
Jan.2016	0.320	2.292	2.912	0.502	-3.765
Feb.2016	-0.041	1.233	1.549	0.725	-1.717
Mar.2016	-0.022	2.268	2.712	0.364	-3.459

TABLE 3.Error analysis for monthly mean daily air temperature for Double cosine model

Month	MBE	MAE	RMSE	R ²	MPE
Jan.2015	-1.781	2.489	3.308	0.328	-28.969
Feb.2015	-0.662	1.072	1.449	0.160	1.388
Mar.2015	-1.238	2.247	2.882	0.010	-14.478
Apr.2015	-1.805	2.140	3.185	0.356	-9.468
May.2015	-1.924	2.351	3.330	0.216	-8.256
Jun.2015	-2.349	2.506	3.800	0.314	-9.556
Jul.2015	-2.323	2.435	3.443	0.292	-7.687
Aug.2015	-2.436	3.138	4.218	0.012	-9.283
Sep.2015	-1.794	2.235	3.207	0.349	-7.517
Oct.2015	-1.433	1.672	2.452	0.307	-7.707
Nov.2015	-1.877	2.359	3.087	0.137	-18.056
Dec.2015	-1.482	2.198	2.875	0.335	-18.006
Jan.2016	-1.751	2.482	3.586	0.241	-20.988
Feb.2016	-1.372	1.700	2.332	0.312	-14.224
Mar.2016	-2.089	2.818	3.936	0.071	-22.425

TABLE 4.Error analysis for monthly mean daily air temperature for Wave model

Month	MBE	MAE	RMSE	R ²	MPE
Jan.2015	-0.485	1.770	2.275	0.551	0.068
Feb.2015	-0.052	0.823	1.048	0.374	5.959
Mar.2015	-0.211	1.503	1.815	0.331	-3.321
Apr.2015	0.377	1.355	1.770	0.804	1.358
May.2015	0.065	1.684	2.193	0.636	-0.075
Jun.2015	0.264	1.288	1.708	0.847	1.053
Jul.2015	0.664	1.211	1.828	0.798	2.150
Aug.2015	-0.233	2.300	2.962	0.359	-0.952
Sep.2015	-0.284	1.455	1.901	0.741	-0.725
Oct.2015	0.064	1.003	1.341	0.773	0.359
Nov.2015	0.093	1.415	1.835	0.685	2.912
Dec.2015	-0.440	1.570	2.012	0.588	-5.229
Jan.2016	0.320	1.435	1.838	0.778	4.889
Feb.2016	-0.041	1.103	1.393	0.701	0.135
Mar.2016	-0.022	1.565	2.025	0.429	-1.814

Table 2 showed that the MAE, R² and RMSE, the values vary between the intervals (1.102 °C, 2.585 °C), (0.010, 0.756) and (1.398 °C, 3.412 °C), respectively. Table 3 summarized that the MAE, R² and RMSE, the values

vary between the intervals (1.672 °C, 3.138 °C), (0.010, 0.356) and (1.449 °C, 4.218 °C). The lowest value of coefficient of determination gave lowest accuracy than all three models. Table 4 showed that the MAE, R² and RMSE, the values vary between the intervals (0.823 °C, 2.3 °C), (0.331, 0.847) and (1.048 °C, 2.962 °C). The Wave model have a good accuracy than Idliman and double cosine models because it has a higher value for R² and lower value for RMSE.

Model evaluation on different seasons

The error analysis for the four models for different seasons is also studied for objective to show the accuracy by season as shown in Fig. 9 to Fig. 12.

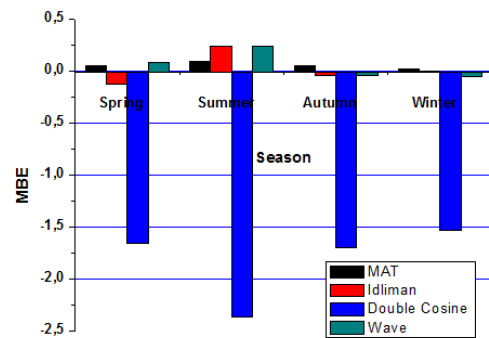


Figure 9. The mean bias error (MBE) statistical values for air temperature estimated from the four models

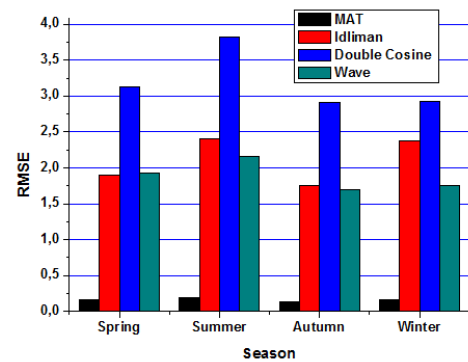


Figure 10. The root mean square error (RMSE) statistical values for air temperature estimated from the four models

Fifteen days from each season were randomly selected from January 2015 to March 2016. Once more, the MAT model performed better than the other models studied, with MBE values are ranging in interval (0.019 °C, 0.086 °C). The values of MBE and MPE are positives which indicate a tendency of MAT model to underpredict the temperature of observed data. The accuracy of all the seasons showed a better performance (R²) which is ranged between 0.997 and 0.998.

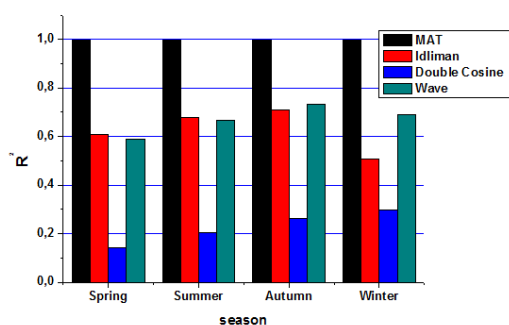


Figure 11. The determination coefficient (R^2) statistical values for air temperature estimated from the four models

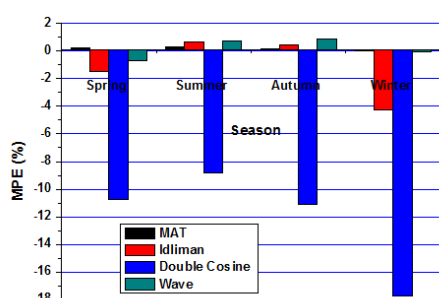


Figure 12. The mean percentage error (MPE) statistical values for air temperature estimated from the four models

Average statistics values between estimated and observed hourly temperature data for the four models during the period (january 2015-march 2016)

According to the statistical test results, it can be seen that the estimated values of monthly mean daily air temperature are in favorable agreement with the measured values of monthly mean daily air temperature for all the models except Double cosine model as shown in Table 5. It was found that, the mean bias errors, MBE, of MAT, Idliman and Wave models is in the range of acceptable values between 0.005 °C and 0.040 °C except Double cosine (-1.754 °C) with lowest RMSE values that range from 0.157 °C to 2.189 °C but the RMSE for Double cosine is equal to 3.139 °C. Also, the MPE values of MAT and Wave models are very close to zero (0.095%, 0.451%) while the values of Idliman and Double cosine models that range in the interval (-2.055%, -13.015%).

TABLE 5. Error analysis for monthly mean daily air temperature for MAT model

Model	MBE	MAE	RMSE	R ²	MPE
MAT	0.040	0.106	0.157	0.997	0.095
Idliman	0.039	1.750	2.189	0.530	-2.055
Double cosine	-1.751	2.256	3.139	0.229	-13.015
Wave	0.005	1.432	1.863	0.626	0.451

CONCLUSIONS

In this study, we presented a new proposed model (MAT) for calculating hourly air temperature basing on atmospheric pressure, global solar radiation and relative humidity data. This work was compared with three published models from the literature as: Wave, Idliman and Double cosine. Fifteen months of hourly atmospheric pressure, global solar radiation, relative humidity and air temperature data were collected during the period (January 2015 to March 2016) and were used to test the accuracy of the various models studied. Five days for each month were randomly selected for detailed analysis. The statistical tests of MBE, MAE, MPE, R² and RMSE were determined for the entire period. The analysis of the days selected randomly showed that MAT model gave substantially a good fit to the observed data. The RMSE of the MAT model is less than 0.5°C during all period of study than the other models studied ranged in the interval (2 °C, 4 °C).

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Persian Abstract

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چکیده

این مقاله با استفاده از مدل تخمینی دمای هوا در ساعت (MAT) با استفاده از داده های سنجش هواشناسی موجود در منطقه Laghouat (الجزایر) بر میانگین دمای مرطوب تمرکز دارد. دمای هوای ساعتی که توسط مدل کنونی تعریف شده است می تواند در هر زمان از روز یا شب بر اساس فشار اتمسفر، تابش خورشیدی و رطوبت نسبی محاسبه شود. این کار با سه مدل منتشر شده از ادبیات مانند: موج، Idliman و Double Cosinus مقایسه شد. برای آزمایش دقت مدل های مختلف، پانزده ماه فشار اتمسفر ساعتی، تابش خورشیدی جهانی، رطوبت نسبی و داده های هوا در طول دوره (ژانویه ۲۰۱۵ تا مارس ۲۰۱۶) مورد استفاده قرار گرفت. تجزیه و تحلیل روزهای انتخاب شده به صورت تصادفی نشان داد که مدل MAT به طور قابل توجهی مناسب با داده های مشاهده شده است. میانگین خطای مربع (RMSE) مدل MAT کمتر از ۰.۵ درجه سانتیگراد در طول دوره مطالعه نسبت به سایر مدل ها در فاصله زمانی (۲ °C، 4 °C) محاسبه شده است. نتایج برآورد شده با استفاده از آزمون های آماری پارامترهای مانند خطای میانگین خطای (MBE)، خطای متوسط (MPE)، میانگین خطای مطلق ((MAE), RMSE و ضریب تعیین (R2) مقایسه شد.
