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Modeling hourly air temperature based on internationally agreed times and the daily minimum temperature

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ABSTRACT: There are several fields that require knowledge of air temperature variation throughout the day, such as disease prediction or calculation of chill-hours. However, automatic meteorological stations are not always located in the vicinity to accurately monitor this variable. In this sense, models that describe the daily temporal variation of air temperature can be used to meet this demand, and transform the climatic data series of conventional meteorological stations into an estimated hourly series. The aim of this study was to adjust and validate models for the hourly air temperature variation through data obtained at internationally agreed times (0, 12 and 18 h Universal Time Coordinated: UTC) and the daily minimum air temperature. The hourly database of the automatic station was used for model adjustment and validation. Functions were adjusted based on values measured at internationally agreed times and the daily minimum air temperature for certain daily variation patterns. The air temperature estimation was performed on an hourly basis using sinusoidal and linear models. The model that presented the lowest root mean square error (RMSE) was used for the estimation. The accuracy of the air temperature estimates varied according to the time, presenting RMSE from 0.7 to 1.6 °C, with maximum mean deviation of 0.4 °C. The results of this study showcase the necessity of knowledge of the daily air temperature variation, as well as a series of data from conventional meteorological stations, which can be estimated using hourly models.

Key words: meteorological data, sinusoidal and linear models, weather station

Modelagem da temperatura horária do ar baseada nos horários convencionados internacionalmente e na mínima diária

RESUMO: Existem áreas que exigem conhecimento da variação da temperatura do ar ao longo do dia, como previsão de doenças ou cálculo de horas de frio. Porém, nem sempre há estações meteorológicas automáticas próximas para observar esta variável. Nesse sentido, modelos que descrevem a variação temporal diária da temperatura do ar podem ser utilizados para suprir essa demanda. Também, séries climáticas de dados de estações meteorológicas convencionais podem ser transformadas em séries horárias estimadas. O objetivo do trabalho foi ajustar e validar modelos para a variação horária da temperatura do ar, através de dados obtidos nos horários de medida das estações convencionais. O banco de dados horários da estação automática foi utilizado para ajuste e validação dos modelos. Funções foram ajustadas com base nos valores medidos nos horários convencionados internacionalmente (0, 12 e 18 h UTC) e na temperatura diária do ar mínima para determinados padrões de variação diária da temperatura do ar. A estimativa da temperatura do ar foi realizada para cada horário, por funções senoidais e lineares. O modelo que apresentou o menor valor da raiz do quadrado médio do erro (RQME) foi utilizado para a estimativa. A precisão das estimativas de temperatura do ar varia conforme horário, apresentando RQME de 0,7 a 1,5 °C, com desvio médio de até 0,4 °C. Os resultados deste trabalho viabilizam estudos que exijam o conhecimento da variação diária da temperatura do ar, bem como séries térmicas oriundas de estações meteorológicas convencionais, que podem ser estimadas utilizando-se modelos horários.

Palavras-chave: dados meteorológicos, modelos sinoidais e lineares, estação meteorológica

INTRODUCTION

Air temperature is a meteorological element with a high influence on plant ecosystems. Plant growth and development are closely related to the concept of thermal sum, defined as the sum of daily units above a thermal temperature, below which the plant stops developing or the development occurs at negligible rates (McMaster & Wilhelm, 1997). In addition, it also influences infections and the progress of diseases caused by plant pathogens that are influenced directly by its daily variation (Bernard et al., 2013; Desanlis et al., 2013).

Automatic weather station data are stored on an hourly scale. However, in conventional stations, observations and measurements of the various meteorological elements are performed at midnight, noon, and 6 p.m. UTC: Universal Time Coordinated (WMO, 2014).

Meteorological data obtained from automatic weather stations show a correlation with conventional weather station data (Pereira et al., 2008; Teramoto et al., 2009; Oliveira et al., 2010; Strassburger et al., 2011). Thus, it is possible to obtain models that describe the temporal variation of daily meteorological elements in automatic weather stations and apply them to the data from conventional stations.

The availability of hourly values makes it possible to model disease severity in crops, serving as a basic tool in disease forecast systems (Krause et al., 1975; Madden et al., 1978). Therefore, the knowledge of the temporal variation of air temperature is essential to alert services and for risk analysis of disease occurrence. Moreover, for the calculation of chilling-hours, it is very important to know the temperature variation at least on an hourly scale (Pola & Angelocci, 1993).

Ramos et al. (2011) sought to adjust models for the estimation of hourly air temperatures in Brazil and verified that the mean error was approximately 5 °C. Pola & Angelocci (1993) verified that sinusoidal models are more accurate for hourly temperature estimation used in chilling-hour calculations. The aim of the present study was to adjust and validate models for hourly air temperature variation based on data obtained at 0, 12 and 18 h UTC and the daily minimum air temperature.

MATERIAL AND METHODS

Weather data were obtained from an automatic weather station belonging to Instituto Nacional de Meteorologia (INMET), located in Santa Maria, RS, Brazil (29° 42' S; 53° 48' W, at an altitude of 95 m). The regional climate is a Cfa type, according to the Köppen classification—humid subtropical with hot summers, without a dry season (Alvares et al., 2013).

Hourly air temperature data were collected from January 2002 to December 2017, a total of 16 years. First, quantitative and qualitative data analyses were carried out, based on the calculation of number of days in the study period that presented failures or showed no meteorological/physical consistency, with the objective of minimizing these instances.

Functions that cover the daily trend of air temperature variation were adjusted. The value interpolation among the known points of the daily curve was tested using simple linear

interpolation and sinusoidal equations, similar to those used in the chilling-hours estimation by Pola & Angelocci (1993).

To adjust the hourly air temperature estimation models for the three internationally agreed measurement times, data of 0, 12 and 18 h UTC were used, along with the daily minimum air temperature, as it represents a moment of inflection in the daily air temperature curve, assuming a time for minimum air temperature occurrence for each season. The time assumed was the one that showed the highest frequency of occurrence in each month (Radons, 2012). From September to February, Tmin occurred most frequently at 9 h UTC and from March to August, this time was delayed, predominantly occurring at 10 h UTC.

For the best model adjustment, pre-analysis was performed for the classification of days according to the meteorological elements behavior and a different model to estimate air temperature during the early morning hours was obtained for each day type. The day-type separation criterion was based on the air temperature variation. When air temperature recorded at 12 h UTC was less than or equal to the air temperature recorded at 18 h UTC and the air temperature recorded at 0 UTC differed by 1 °C or more from the daily minimum air temperature, the day was type 1. In cases where one or both of the conditions was not met, the day was type 2.

In type 1 days, the daily minimum air temperature occurrence was considered, in terms of the respective time taken for each month. In days considered type 2, to obtain the hourly air temperature values during the period from 0 to 12 h UTC, the daily minimum air temperature occurrence in this interval was disregarded.

Once the function type to be used to estimate temperature at each time was delimited, the results made it possible to obtain the functions. Thus, from 1 to 3 h UTC, Eqs. 1 and 2 were used to estimate the air temperature depending on the daily air temperature temporal variation.

Type 1:

$$T_t = T_{00} - (T_{00} - T_{\min}) \sin \left[\left(\frac{\pi}{2} \right) \left(\frac{t}{t_{\min}} \right) \right] \quad (1)$$

Type 2:

$$T_t = T_{00} - (T_{00} - T_{12}) \sin \left[\left(\frac{\pi}{2} \right) \left(\frac{t}{12} \right) \right] \quad (2)$$

where:

- T_t - air temperature, °C, estimated for the set time t UTC;
- T_{00} - air temperature, °C, at 0 h UTC;
- T_{12} - air temperature, °C, at 12 h UTC;
- $T_{\min}$ - daily minimum air temperature, °C;
- t - set time UTC; and,
- $t_{\min}$ - UTC time considered for the occurrence of daily minimum air temperature.

From 4 h UTC to the time of occurrence of the minimum air temperature, the air temperature estimation occurred according to Eqs. 3 and 4.

Type 1:

$$T_t = T_{00} - \left[(T_{00} - T_{\min}) \left(\frac{t}{t_{\min}} \right) \right] \quad (3)$$

Type 2:

$$T_t = T_{00} - \left[(T_{00} - T_{12}) \left(\frac{t}{12} \right) \right] \quad (4)$$

From the daily minimum air temperature occurrence time until 11 h UTC, Eqs. 5 and 6 were used to estimate the air temperature.

Type 1:

$$T_t = T_{\min} + \left[(T_{12} - T_{\min}) \left(\frac{t - t_{\min}}{12 - t_{\min}} \right) \right] \quad (5)$$

Type 2:

$$T_t = T_{00} - \left[(T_{00} - T_{12}) \left(\frac{t}{12} \right) \right] \quad (6)$$

From 13 h UTC to 17 h UTC, the air temperature estimation for each time occurred according to Eq. (7).

$$T_t = T_{12} + (T_{18} - T_{12}) \sin \left[\left(\frac{\pi}{2} \right) \left(\frac{t - 12}{18 - 12} \right) \right] \quad (7)$$

where:

T_{18} - air temperature, °C, at 18 UTC.

At 19, 20 and 21 h UTC, the air temperature estimation for each time was performed by Eq. 8.

$$T_t = T_{00 \text{ n+1}} - (T_{00 \text{ n+1}} - T_{18}) \sin \left[\left(\frac{\pi}{2} \right) \left(\frac{24 - t}{24 - 18} \right) \right] \quad (8)$$

where:

$T_{00 \text{ n+1}}$ - air temperature, °C, at 0 h UTC of the following day.

At 22 h and 23 h UTC, the air temperature estimation for each time happened as described in Eq. 9.

$$T_t = T_{00 \text{ n+1}} - \left[(T_{00 \text{ n+1}} - T_{18}) \left(\frac{24 - t}{24 - 18} \right) \right] \quad (9)$$

A model test was performed by comparing the estimated values with those measured at different times. The model type that presented the lowest value of the root mean square error (RMSE) (Chai & Draxler, 2014) when testing the model and a value close to 1 in the d test (Willmott, 1981) was used for the estimation. Also, the standard error of estimation (SEE), standard deviation (SD), mean absolute error (MAE) (Chai & Draxler, 2014), and linear regression between estimated and observed air temperature were performed.

RESULTS AND DISCUSSION

It was observed that the sinusoidal functions, such as those used by Pola & Angelocci (1993), showed lower RMSE at most times (Table 1). In the morning and immediately after twilight, when air temperature changes are more pronounced, the linear function showed better performance compared with the sinusoidal function.

The times at which it was possible to obtain the minor air temperature estimation errors, indicated by a lower RMSE, were at 1 and 23 h UTC, with values of approximately 0.7 °C at both times. The highest values of RMSE, reaching 1.8 °C for 15 and 20 h UTC, resulted from estimates for the times more

Table 1. Equations utilized to estimate hourly air temperature (°C) and their respective root mean square error (RMSE), Willmott's d index, mean absolute error (MAE), standard error of estimation (SEE) and standard deviation (SD)

UTC time	RMSE		d		MAE		SEE		SD		Equation utilized
	Linear	Sinusoidal	Linear	Sinusoidal	Linear	Sinusoidal	Linear	Sinusoidal	Linear	Sinusoidal	
1	0.7	0.7	1.00	1.00	0.2	0.0	0.01	0.01	0.7	0.7	Sinusoidal
2	1.0	1.0	0.99	0.99	0.4	0.0	0.01	0.01	1.0	1.0	Sinusoidal
3	1.2	1.2	0.99	0.99	0.4	-0.1	0.02	0.02	1.1	1.2	Sinusoidal
4	1.3	1.3	0.99	0.99	0.4	-0.2	0.02	0.02	1.2	1.3	Linear
5	1.4	1.4	0.98	0.98	0.4	-0.3	0.02	0.02	1.3	1.4	Linear
6	1.4	1.5	0.98	0.98	0.4	-0.3	0.02	0.02	1.3	1.4	Linear
7	1.4	1.5	0.98	0.98	0.3	-0.3	0.02	0.02	1.3	1.5	Linear
8	1.4	1.5	0.99	0.98	0.1	-0.3	0.02	0.02	1.4	1.5	Linear
9	1.3	1.4	0.99	0.98	-0.1	-0.2	0.02	0.02	1.3	1.4	Linear
10	1.3	1.5	0.99	0.98	0.0	-0.4	0.02	0.02	1.3	1.4	Linear
11	0.9	1.3	0.99	0.99	0.2	0.8	0.01	0.01	0.9	0.9	Linear
13	1.1	1.0	0.99	0.99	-0.6	-0.1	0.01	0.01	0.9	0.9	Sinusoidal
14	1.6	1.3	0.98	0.99	-1.0	-0.1	0.02	0.02	1.3	1.3	Sinusoidal
15	1.8	1.4	0.98	0.99	-1.1	0.0	0.02	0.02	1.4	1.4	Sinusoidal
16	1.7	1.3	0.98	0.99	-1.0	0.0	0.02	0.02	1.3	1.3	Sinusoidal
17	1.2	1.0	0.99	0.99	-0.7	0.0	0.01	0.01	1.0	1.0	Sinusoidal
19	1.3	1.0	0.99	0.99	-0.8	-0.1	0.01	0.01	1.0	1.0	Sinusoidal
20	1.8	1.3	0.98	0.99	-1.1	-0.1	0.02	0.02	1.4	1.3	Sinusoidal
21	1.7	1.6	0.98	0.98	-0.8	0.3	0.02	0.02	1.5	1.5	Sinusoidal
22	1.2	1.4	0.99	0.99	-0.2	0.7	0.02	0.02	1.2	1.3	Linear
23	0.7	1.0	1.00	0.99	0.1	0.6	0.01	0.01	0.7	0.8	Linear

UTC – Universal time coordinated

distant from the agreed measurement times. The MAE values obtained were from -1.1 to 0.8 °C, SEE did not exceed 0.02, and SD varied from 0.7 to 1.5 °C.

The more distant from 0, 12, and 18 h UTC the estimation time, the higher tends to be the error. This result is in accordance with those obtained by Ramos et al. (2011). After sunrise and sunset, the estimates tend to be less precise. It should be kept in mind that, at these times, air temperature change is usually more pronounced (Tazzo et al., 2008), and equations cannot describe such a change.

At times closest to the agreed measurement times, such as 1, 23, 11 and 13 h UTC, and times of the late morning and early afternoon (from 14 to 17 h UTC), the average difference in most cases is lower than at other times, generally not exceeding 0.1 °C (Figure 1).

There is a tendency to underestimate air temperature from 0 until 3 h UTC, at times of occurrence of Tmin (9 and 10 h UTC), at 13, 14, 15, 19, 20 and 22 h UTC, which peaks at 22 h UTC (-0.2 °C) (Figure 2). On average, air temperature

UTC – Universal time coordinated

Figure 1. Mean absolute error (points) and standard deviation (bars) of air temperature (°C) estimates in relation to the measured values, at different times of the day, based on the agreed measurement time values (0, 12 and 18 h UTC) and daily minimum air temperature, from January 2002 to December 2017

** - Significant at $p \leq 0.01$ by F test

Figure 2. Relation between the estimated and observed air temperature (°C) values in the automatic station, from 1 Universal Time Coordinated (UTC) until 23 UTC, except at 0, 12 and 18 h UTC and daily minimum, in the January 2002 to December 2017 period

overestimation occurs from 4 until 8 h UTC, at 11, 16, 17, 21, and 23 h UTC, with the largest mean deviation occurring at 4 h UTC (0.4 °C).

In the period between 12 and 18 h UTC, the mean deviation, in the module, does not exceed the value of 0.1 °C, indicating that the sine function used to estimate air temperature hourly values in these times is accurate (Figure 2). However, it continues the trend of larger standard deviation values in more distant times from the agreed measurement times.

In the late afternoon and early evening, there was an underestimation in certain times and overestimation in others (Figure 1). In this period, the mean error of estimates ranged from -0.2 °C (22 h UTC) to 0.3 °C (21 h UTC). At 21 h UTC, the greatest RMSE value in relation to the average among all estimating times (1.57 °C) was verified. The average deviation obtained in this study was as much as 90% lower than those obtained by Ramos et al. (2011), because of the difference in methodology, since these authors used the spherical model.

CONCLUSIONS

1. It was possible to adjust models for hourly air temperature variation based on data obtained at 0, 12 and 18 h UTC and the daily minimum air temperature.

2. The hourly air temperature estimation accuracy varies with time, presenting an root mean squared error (RMSE) of 0.7 to 1.8 °C, with maximum mean absolute error of 0.4 °C.

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