

SYNTHESIZING SEQUENCES OF HOURLY AMBIENT TEMPERATURE DATA

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***Abstract**. Sequential meteorological data are necessary to execute simulations of energy conversion systems that are sensitive to climatic variations. Especially solar energy conversion systems are strongly dependent on values of solar radiation and ambient temperature. In many places where we wish to apply a simulation procedure, sequential meteorological data are not known. On the other hand, averaged climatological data, as monthly values of solar radiation, of mean temperature and of maximum and minimum temperatures are obtained easily. The present work proposes a methodology to synthesize ambient temperature data in hourly sequence from monthly averaged data with use of computational procedures. The results are compared with sequential measured data in several Brazilian cities, demonstrating that the methodology is adequate.*

***Keywords.** Environmental Temperature, Ambient Temperature, Sequential Temperature, Meteorological Data Synthesizing.*

1. Introduction

A lot of engineering procedures make use of sequential meteorological data. The need for hourly sequential data are especially remarkable to the preparation of the input data for software that simulate time dependent behavior on systems whose operation is susceptible to the meteorological data. Among these applications there are programs to simulate the behavior of alternative energy conversion systems. In this environment appeared the need for searching methods to supply these data.

In general the objectives of the computational simulations of alternative energy conversion systems include the study of the behavior of the system along the time and it should contemplate all the possible situations. As these systems are strongly sensitive to the meteorological variations, the use of monthly typical days or the use of averaged climate data is not enough to embrace the true conditions to which the systems will be submitted. On the other hand, it is impossible to foresee the future hourly-frequency meteorological data for long periods, remaindering to use the data of the past (believing that the meteorological behavior comes repeating) or to invent data that have a statistical meaning and sequential characteristics so that produce the same effects of the natural data. Because the measured data exist only in few places, we chose the second alternative.

It is important to understand that the sequential data have to contemplate the several situations that could happen and have to present a frequency of events similar to that presented by the nature. If there is a coupling between two different meteorological data, this coupling should be respected. The sequence of data finally should consist of a plausible data set that bring from the simulations results as those that would be found if measured data were used as the input of the same procedure.

The meteorological data that are necessary for solar energy conversion systems simulation are: horizontal solar radiation, ambient temperature and, with less influence in the simulation results, the wind speed. These data are unfortunately not available in hourly sequences, with exceptions of very few places in Brazil. On the other hand, climatological data of monthly averaged values are known. Because of this, the Solar Energy Laboratory of UFRGS has already been developing in the last years synthesizing techniques for solar radiation data in hourly basis, starting from monthly averaged data.

The first effort in this direction (in UFRGS) was the adaptation of the method of the Markov Transition Matrices (Aguiar et alii, 1988) through the proposing of matrices elaborated partially with Brazilian solar radiation data (Krenzinger and Macagnan, 1988). The use of this method allows the user to generate sequences of daily solar radiation data from only the monthly averaged solar radiation values and the information of the local latitude. The sequences are synthesized firstly in the form of daily clearness index and then multiplied by the horizontal daily extraterrestrial solar radiation, in order to produce daily horizontal solar radiation data. The Markov matrices are square matrices where each element (i, j) represents the probability of a transition from the clearness index state i to the state j. A random computer generated number is used to draw the column j from a given row i, establishing a clearness index state j. The chosen state is then the next row i = j and a new random number is generated to proceed the synthesizing of the desired stochastic series.

From the daily solar radiation sequence, an hourly solar radiation sequence can be estimated using other stochastic model. In 1979, Collares-Pereira and Rabl presented an equation to correlate the mean hourly solar radiation to the daily solar radiation as a function of the hour angle and the sunset hour angle. This study is internationally recognized as a very accurate method to find the mean hourly radiation. Actual hourly radiation profiles follow this behavior only for clear sky conditions. For partially cloudy days, a stochastic component can be added, as proposed in Krenzinger 1994 and Krenzinger and Rauter, 1998.

The present work proposes a methodology to synthesize ambient temperature data sequences starting from known climatic data and from hourly solar radiation values previously synthesized. These solar radiation data are needed as prerequisite, because we believe that there is a coupling between solar irradiance and ambient temperature. We first present few methods proposed by other authors, selecting the procedures that seemed more appropriate and combining these procedures into a new method adapted for the data that are effectively easy to find in Brazil.

2. Stochastic Temperature Models

There are several models proposed in the literature for synthesizing temperature data aiming to supply tools for agricultural sciences, for the weather risk market and other practical applications. Some of these models use the past historical time temperature series observed at a locality and the resulting statistical information for generating future temperature sequences, as in Dischel, 1999, but these are not the kind of models that we need.

According to Lasnier and Ang, 1990, the ambient temperature can be modeled by a sinusoidal function taking into account the daily maximum and minimum temperature. The Eq. (1) shows their model:

$$T(t) = 0.5\left[T_{\max}(day) + T_{\min}(day) + \left(T_{\max}(day) - T_{\min}(day)\right)sin\left(\frac{2\pi(t-t_p)}{24}\right)\right] \tag{1}$$

where T(t) is the ambient temperature at the time t (in hours), T_{max}(day) is the maximum ambient temperature of the day, T_{min}(day) is the minimum ambient temperature of the day and t_p is an adjust time to slide the daily profile to its actual position.

The model used in the software *METEONORM* (Remund and Kunz,1997) is based on the assumption that the amplitude of the temperature variation during daytime is approximately proportional to the amplitude of the daily global radiation profile. In order to obtain a final temperature profile, the radiation profile suffer a transformation involving stretching, time displacement and smoothing of the radiation profile. After the sunset, the temperature variation is extrapolated till sunrise. There are conversion factors that have to be determined individually for each climatic situation. The resulting profile is then subjected to perturbations based on a first order autoregressive procedure. In this procedure, the day-to-day temperature slope depends on total daily radiation and on time of year.

Perhaps the more relevant face of the model used in *METEONORM* is the basic assumption, but it does not make use of important data that are easily available for the most localities, such as the maximum and minimum monthly averaged temperatures.

3. Limits and Trends,

For the development of the algorithm proposed in this work we looked for a mean of producing hourly sequences of ambient temperature data, using known climatic data and without depending on unavailable statistical data. The data in which the methodology should be based are: locality latitude, monthly mean temperature, monthly mean of the maximum temperatures, monthly mean of the minimum temperatures, daily maximum solar irradiance and the day length. We perform a process of looking for correlations between temperature profiles and these known data. This process was accomplished comparing graphs of the data from 9 of the 14 cities studied by Goulart et al, 1998. Table 1 presents the latitudes for that and other sites mentioned in this paper. Some of the main observations are reported through the Figs (1) to (5).

Table 1 – Latitudes of the sites mentioned in this work

SITE	LATITUDE	SITE	LATITUDE	SITE	LATITUDE
BELÉM	1°23’	FORTALEZA	38°32’	SALVADOR	12°54’
BRASÍLIA	15°52’	MACEIO	9°31’	SÃO LUIS	2°35’
CURITIBA	25°31’	PORTO ALEGRE	30°00’	SÃO PAULO	23°37’
FLORIANÓPOLIS	27°40’	RIO DE JANEIRO	22°50’		

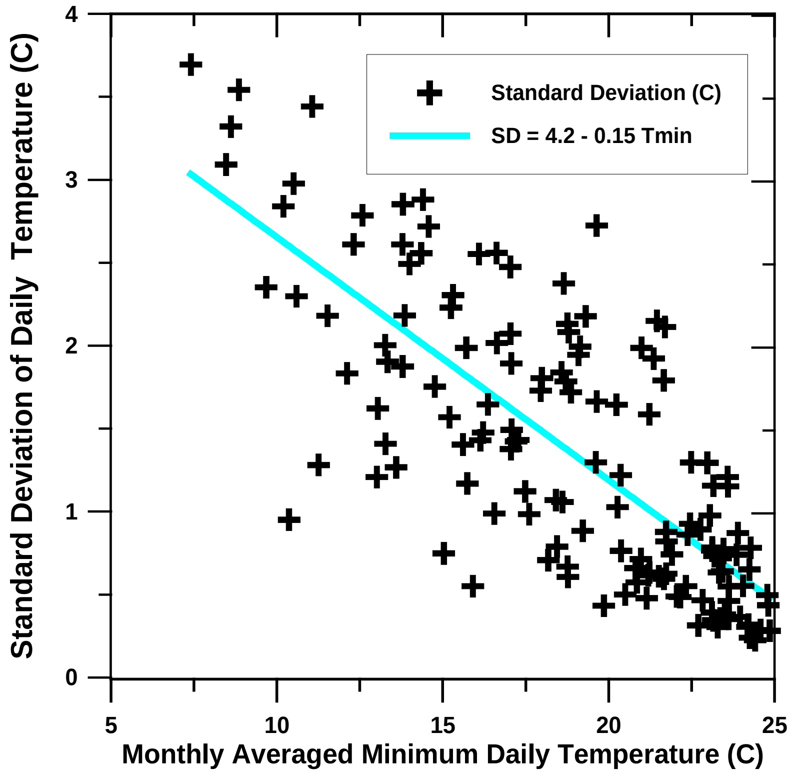

Figure 1. Dependence on the monthly averaged minimum daily temperature of the standard deviation of daily mean ambient temperature to the monthly mean ambient temperature, for 108 months in 9 cities.

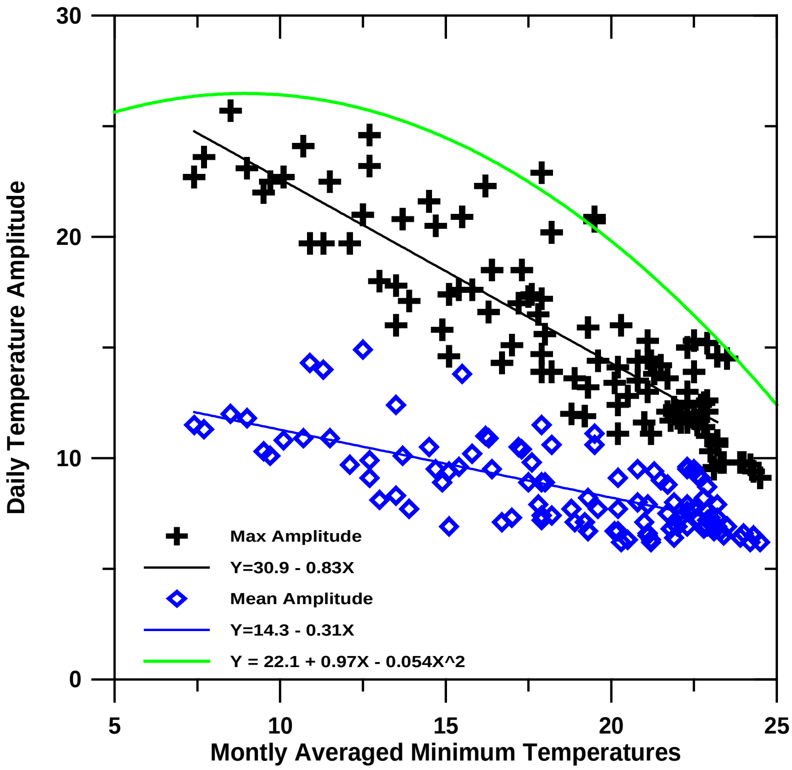

Figure 2 Dependence on the monthly averaged minimum daily temperature of the daily temperature amplitude, showing the maximum daily amplitude for each month and the mean amplitude for each month. The straight lines are the mean root square fits of the monthly values and the parabolic green curve represents the superior limit for maximum daily temperature amplitude.

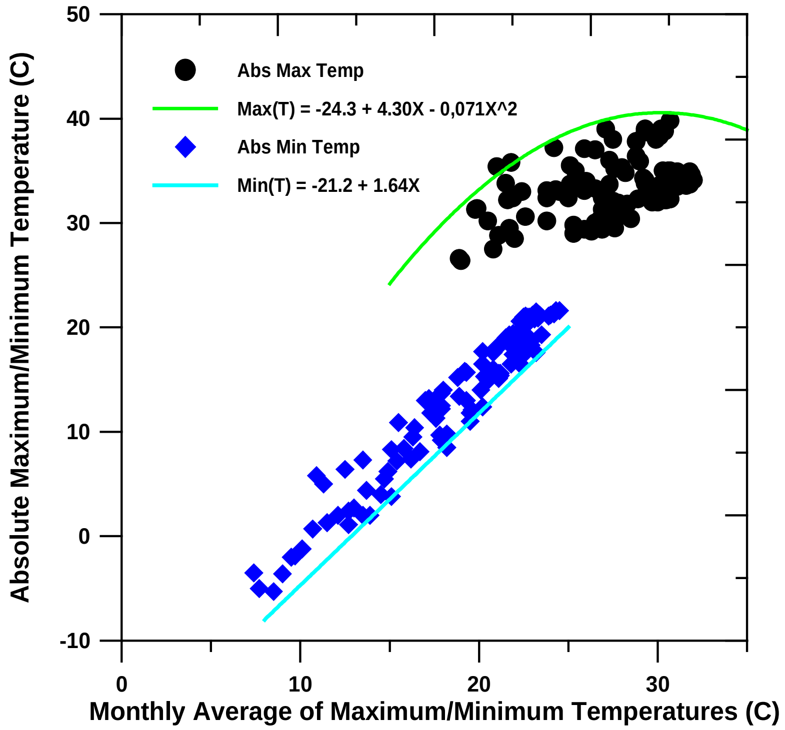

Figure 3. Values of the absolute maximum temperature (black dots) plotted in function of the monthly average of the daily maximum temperature and values of the absolute minimum temperature (blue dots) plotted in function of the monthly average of the daily minimum temperature. The lines represent equations used for limiting the generated temperatures in each day.

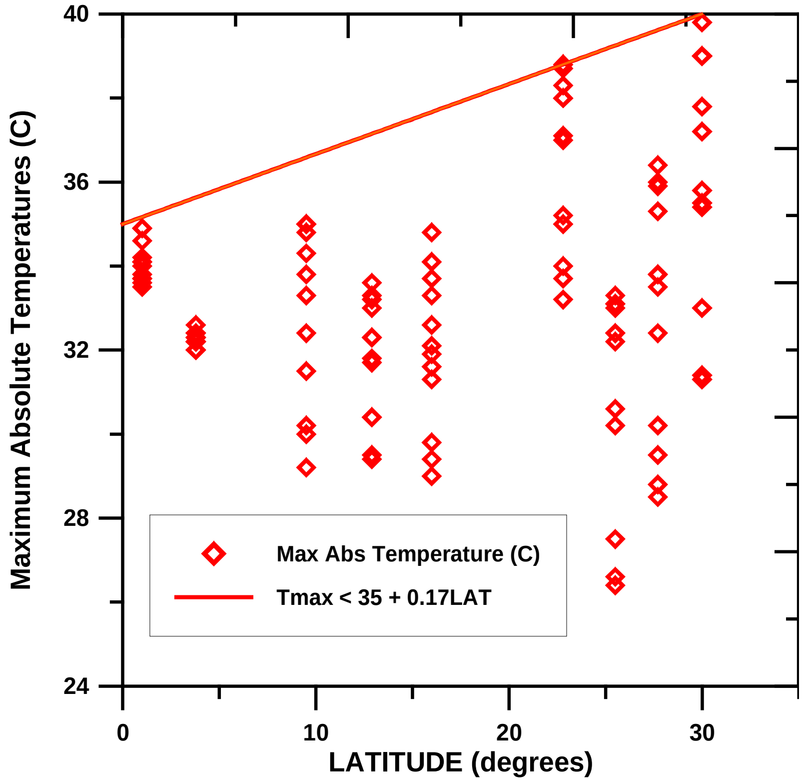

Figure 4. Maximum absolute ambient temperature for each month plotted in function of the site latitude. The straight line represents an equation used for limiting the generated temperatures in each day

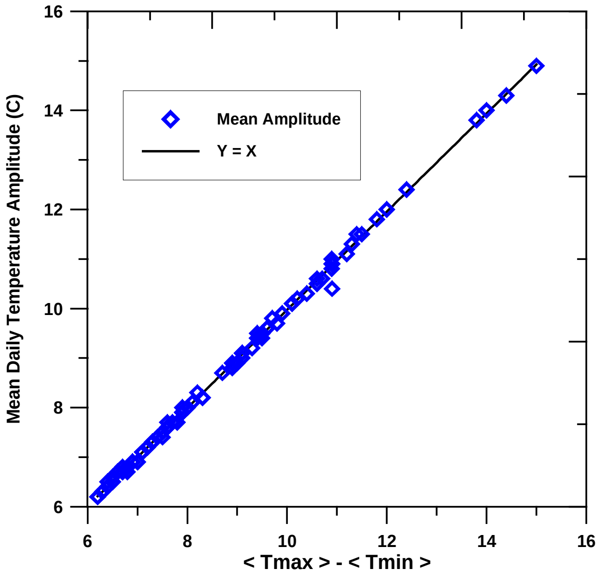

Figure 5. Linear correlation between the mean daily temperature amplitude and the difference between the monthly averaged maximum temperatures and the monthly averaged minimum temperatures

The studied data were from the following Brazilian cities: Belém, Brasília, Curitiba, Florianópolis, Fortaleza, Maceió, Porto Alegre, Rio de Janeiro and Salvador. The following observations and assumptions are remarkable:

- It is reasonable to distribute daily sequences with a gaussian function for each month.
- The dispersion of the daily temperatures in one month depends on the monthly mean of the minimum temperatures. In the months in which the monthly mean of the minimum temperatures is high, the dispersion is smaller.
- The monthly averaged daily amplitude of the temperature variation has a perfect straight-line correlation with the difference between the monthly average of the maximum daily temperatures and the monthly average of the minimum daily temperatures.
- The absolute maximum ambient temperature depends on the latitude and is possible to establish an equation for limiting the maximum daily temperature. In spite of that we found also a similar dependence for the absolute minimum ambient temperature, the limit equation could not be established because surely there is the influence of the locality altitude combined.
- The absolute maximum ambient temperature depends on the monthly average of the maximum temperature and is possible to establish an equation for limiting the maximum daily temperature.
- The absolute minimum ambient temperature depends on the monthly average of the minimum temperature and is possible to establish an equation for limiting the minimum daily temperature.

4. Proposed Algorithm

Using the above information and combining ideas from Lasnier and Ang and the *METEONORM* methods, we developed a novel model for synthesizing first daily sequences and then hourly sequences. We assumed that

- The mean daily temperature evolve along the year nearly the extraterrestrial solar radiation evolution, maintaining a gaussian day-to-day characteristic.
- The daytime amplitude of the temperature variation is correlated with the amplitude of the daily irradiance profile.
- The daily profile follows a periodic function with the minimum temperature at the sunrise time and the maximum trend temperature near 15h in solar time, besides the irradiance influence.
- There is a small random term to be added to the ambient temperature

The following sequence describes the development of a temperature series. To begin we need data about the latitude, sequences of hourly horizontal solar global radiation and $\langle T_{min}\rangle$,$\langle T_{max}\rangle$ and $\langle T_{mean}\rangle$ respectively giving the monthly averaged minimum, maximum and mean ambient temperature.

The procedure is performed for each month in the year. After selected the month, we have to generate a mean daily temperature sequence. In order to do this, we firstly define a daily base temperature as in Eq. (2). H_o(day) is the extraterrestrial solar radiation for the considered day and H_o(month) is the monthly averaged daily extraterrestrial solar radiation.

$$T_{base}(day) = \langle T_{mean}\rangle \frac{1}{3}\left[2 + \left(\frac{H_o(day)}{H_o(month)}\right)\right] \tag{2}$$

Using this base temperature, the daily mean temperature T_{meam}(day) is obtained by adding χ, a normal distributed random variable, as seen in Eq.(3). The standard deviation SD for the χ variable is given by the Eq.(4) after observing Fig.(1).

$$T_{mean}(day) = T_{base}(day) + \chi \tag{3}$$

$$SD = 4.2 - 0.15\langle T_{\min}\rangle \tag{4}$$

From the correlation presented in Fig. (5), we can calculate the mean daily amplitude $<A_{mean}>$ Eq. (5)::

$$\langle A_{mean}\rangle = \langle T_{\max}\rangle - \langle T_{\min}\rangle \tag{5}$$

In Fig. (4) there were two correlations, one for the maximum daily amplitude in each month $<A_{max}>$ and the other for the mean daily amplitude in each month $<A_{mean}>$. In order to propose an init value to $<A_{max}>$ we considered an intermediate correlation, obtained from a balance of 2/3 for the correlation of maximum amplitude resulting Eq.(6):

$$\langle A_{\max}\rangle = 25 - 0.42\langle T_{\min}\rangle + \frac{\delta}{2} \tag{6}$$

where δ is a random variable uniformly distributed between –1 and +1.

Proceeding this task, we compute, from the solar radiation sequences, the values of the maximum solar radiation for each day, $I_{max}(day)$, and the monthly average of these values, $<I_{max}>$. We also compute the maximum value of solar radiation in whole the month, denoted as $I_{max}(month)$. We then calculate the daily amplitude of temperatures using Eq. (7). Note that now we are working at daily level

$$A(day) = \left(I_{\max}(day) - \langle I_{\max}\rangle\right)\left(\frac{\langle A_{\max}\rangle - \langle A_{mean}\rangle}{I_{\max}(month) - \langle I_{\max}\rangle}\right) + \langle A_{mean}\rangle + \delta \tag{7}$$

and this result is submitted to the limit imposed by Eq.(8) from Fig. (2).

$$A(day) < 22.1 + 0.97\langle T_{\min}\rangle - 0.054\langle T_{\min}\rangle^2 \tag{8}$$

The next step is the evaluation of the maximum temperature in the day $T_{max}(day)$ by adding a half of daily amplitude to the mean daily temperature, as done in Eq(9)

$$T_{\max}(day) = T_{mean}(day) + \frac{A_{\max}(day)}{2} \tag{9}$$

being this result submitted to the limits imposed by Eq.(10) and Eq.(11), respectively from Figs (4) and (3).

$$T_{\max}(day) < 35 + 0.17|LAT| \tag{10}$$

$$T_{\max}(day) < -24.3 + 4.3\langle T_{\max}\rangle - 0.071\langle T_{\max}\rangle^2 \tag{11}$$

The hourly temperature is then estimated by adding a periodic term, a solar term and a random term to the base term. In order to link the mean temperature of a day with the mean temperature of the next day in the sequence, we use a linear interpolation, given in Eq.(11). The base of the temperature that will be developed along the day gather an empiric term (the last one) for the purpose of adjust the mean final result. From here, the model will introduce some variables in hour level.

$$T_{base}(t) = T_{mean}(day) + (t+1)\left(\frac{T_{mean}(day+1) - T_{mean}(day)}{24}\right) - \left[1 + 0.155A(day)\right] \tag{12}$$

The periodic term is evaluated depending on the time of the day. The sunrise time t_{sr} is computed and for time before this we use Eq(13) and for time after t_{sr} we use Eq(14). The curve resulting of this periodic term is shown in Fig. (6) for a day where the mean temperature is 23.3ºC and the amplitude is 15ºC.

if $t < t_{sr}$ then $$PT(t) = \frac{A(day)}{4}\left[\frac{1}{2} + COS\left(\frac{(20+t)}{(20-t_{sr})}\frac{\pi}{2}\right)\right] \tag{13}$$

else $$PT(t)=\frac{A(day)}{8}\left[COS\left(\frac{(16-t)}{(15-t_{sr})}\frac{\pi}{2}\right)+COS\left(\frac{(14-t)}{(13-t_{sr})}\frac{\pi}{2}\right)\right] \quad (14)$$

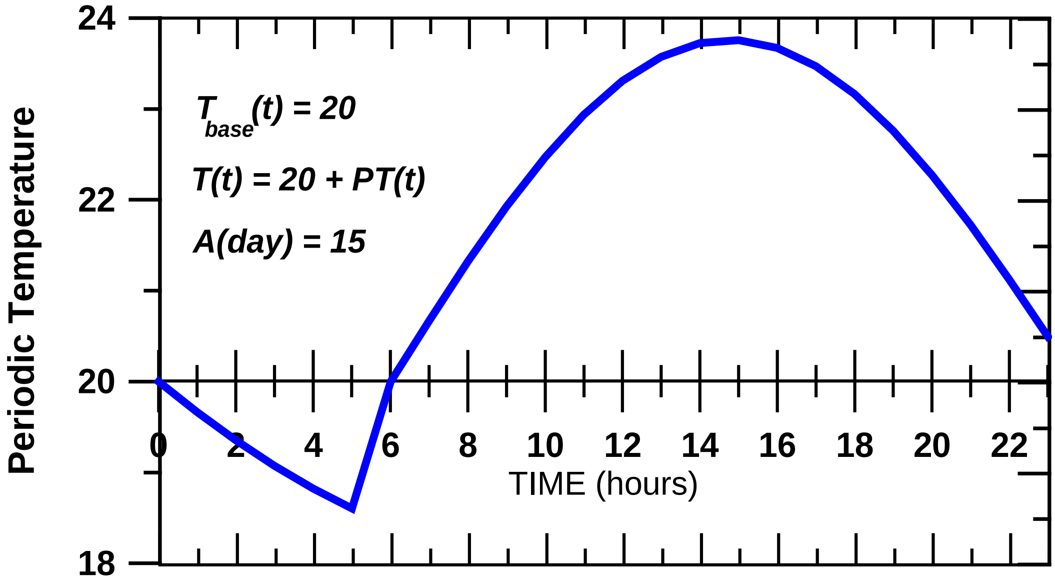

Figure 6. Periodic function used to determine the periodic term in the temperature synthesizing. In this example the base temperature remain constant $T_{base}(t)$ = 20ºC and the temperature amplitude was considered $A(day)$ = 15ºC.

The Solar Term $ST(t)$ is then evaluated through a simple proportion equation conferring the maximum temperature to the time of the maximum solar radiation delayed by one hour. The delta (Δ) in Eq.(15) is only a recurrent term, which value is null in the first iteration.

$$ST(t)=\left(\frac{T_{\max}(day)-[T_{base}(t)+PT(15)]}{I_{\max}(day)}+\Delta\right)I(t-1) \quad (15)$$

Now, using the three defined terms we add the random one and obtain the hourly temperature in Eq.(16)

$$T(t)=T_{base}(t)+PT(t)+ST(t)+\frac{\delta}{2} \quad (16)$$

The hours are denoted from 0 to 23. After scan all the 24 hours in the day, a comparison between the mean value used in the input of the daily procedure and the resulting mean temperature gives the opportunity of repeating the daily generation, while is not obtained a convergence less than 0.5ºC. This iteration is carried out through Eq.(17).

$$IF\cdots\left(T_{mean}(day)-\sum T(t)/24\right)<0.5\cdots THEN\cdots\Delta=\Delta+\frac{T_{mean}(day)-\sum T(t)/24}{I_{\max}(day)}\cdots RETURN \quad (17)$$

The daily series is again submitted to the limits imposed by Eq.(10) and Eq.(11), and the monthly averaged generated data is evaluated and compared to the input data, being possible to iterate again from Eq.(6), but in general this is not necessary. The proceeding is repeated for all the months in a year and then the task is over.

5. Results and comparison with measured data.

The proposed algorithm can be easily applied to any locality in Brazil (and in foreign localities with similar latitudes) preceded by the solar radiation series generation. The computer interface developed to use this method allows the user to produce meteorological files handling a mouse in front of the computer.

The method was employed to generate hourly sequences for 8 cities in Brazil: Belém, Brasília, Curitiba, Florianópolis, Fortaleza, São Paulo, São Luis and Porto Alegre, in order to verify the statistical quality of the synthetic series. Figure 7 shows the temperature profiles along the whole year for Porto Alegre and Belém, comparing the synthetic series with the hourly data from TRY (Test Reference Year) files obtained from reference TRY-UFSC. The TRY files are natural sequences selected from that measured ones in order to represent the climate for project purposes.

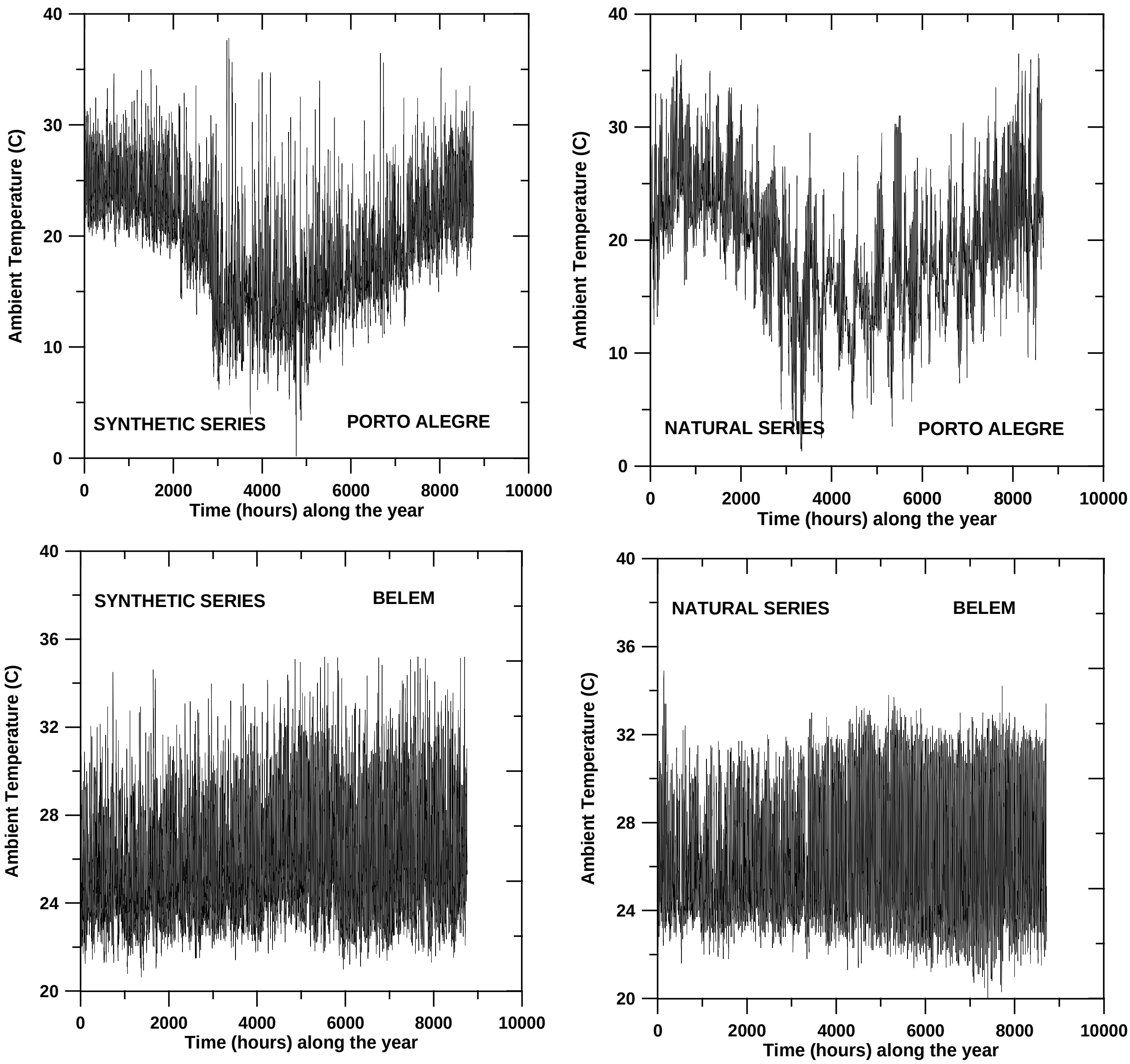

Figure 7. Temperature profiles for Porto Alegre and Belém as synthesized with the presented algorithm (left) and respective natural profiles as recorded in TRY files (right).

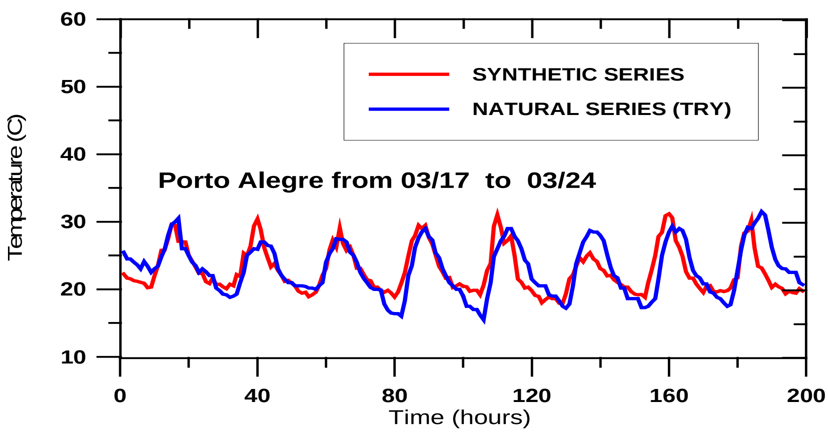

Figure 8. Comparison for Porto Alegre zoomed to 200 hours.

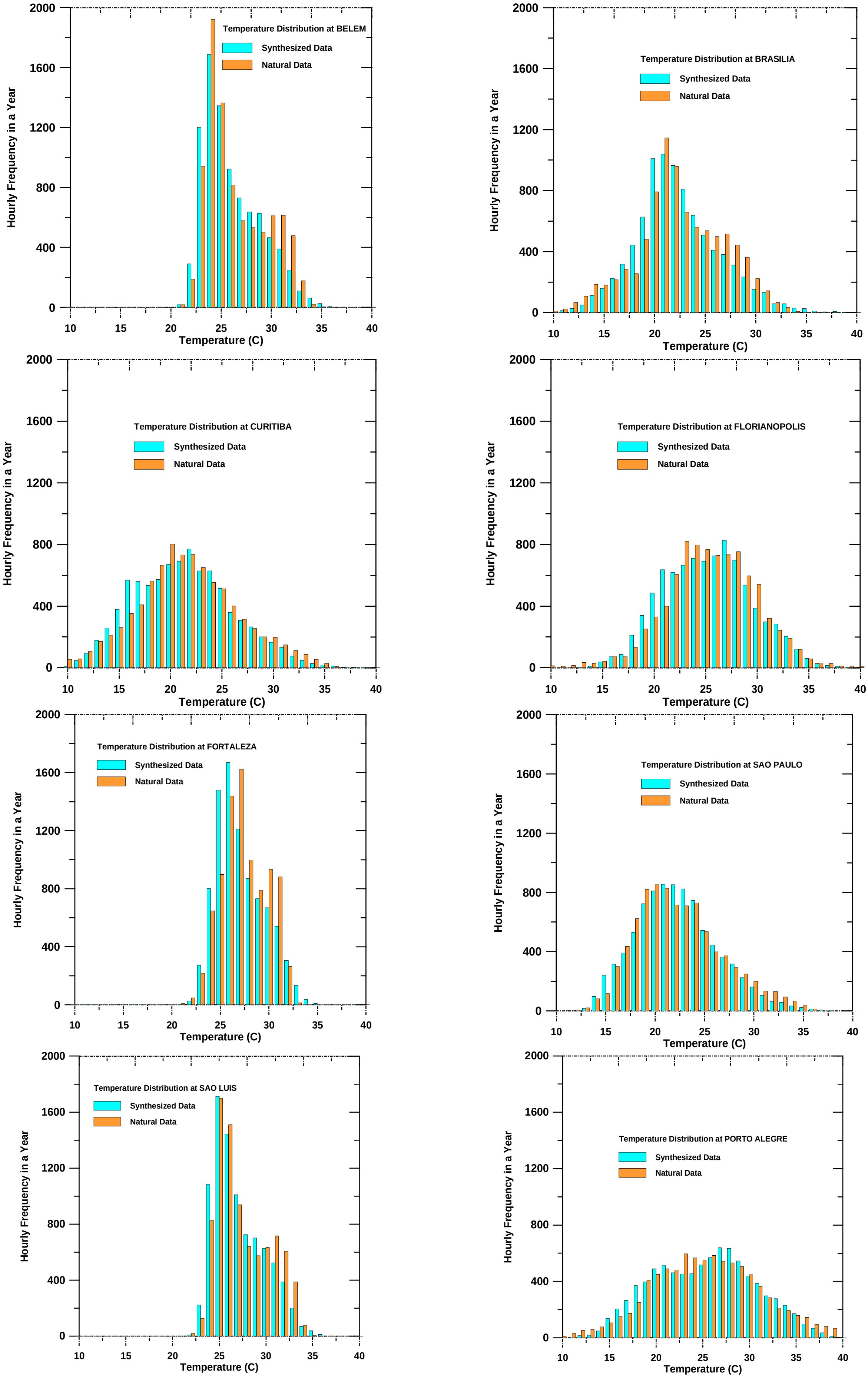

Figure 9 Comparison of the frequency of the hourly temperatures along a year for 8 cities in Brazil. Green bars are frequencies from synthesized data and orange bars are frequencies from natural data (TRY files).

Figure 8 shows a short part of the synthetic sequence represented in Fig.(7) for Porto Alegre, with the time scale zoomed to 200 hours, from march 17th to march 24th . Note that the TRY file does not provide the solar radiation data used for the synthesizing, so we are not expecting that the temperature amplitude coincide but only comparing the form of the daily profile. Figures 7 and 8 show that the proposed is a good method for data generation.

The same TRY files were used for the frequency comparison of Fig.(9). The eight graphs are constructed with frequency bars for ambient temperatures distributed in one degree Celsius steps. The vertical and horizontal scales are purposely fixed respectively in 2000 occurrences and 10 to 40 Celsius degrees in order to help the reader to note the climate diversity .The agreement is very good for sites with very different climates and latitudes, showing the universal characteristic of the model. Fortaleza, that shows the worst case in this comparison, present a displacement of only 1ºC, which would disappear in a 3^{o}C step bars graph.

6. Conclusions

We developed a methodology to synthesize ambient temperature data in hourly sequence from given monthly averaged daily solar radiation and minimum, maximum and mean ambient temperatures. The results were compared with recorded natural sequences showing very good agreement and demonstrating that the methodology can be used for several different climates and latitudes.

7. Acknowledgement

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