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THE NOCTURNAL THERMODYNAMICS OF AMAZONIAN ECOSYSTEMS

Termodinâmica Noturna dos Ecossistemas Amazônicos

La Termodinámica Nocturna de los Ecosistemas Amazónicos

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Abstract: The purpose of this article is to establish a non-empirical theoretical model for the nocturnal cooling of Amazonian ecosystems with the aim of better understanding the thermodynamics of such ecosystems**.** The nocturnal features of temperature in five different ecosystems in the Brazilian mazon region have been studied, namely deep forest, medium forest, transitional forest, savannah (Cerrado) and a seasonally flooded forest (Brazilian Pantanal). Over the course of one year, micrometeorological data, specifically air temperature and humidity, were analysed. It has been observed that temperature in all ecosystems decreases at a rate of 0.9°C/h at the beginning of the night. The above rate is coherent with the theoretical cooling rate expected in conditions of “dry” air, i.e., when humidity does not exert a significant influence on the ecosystem thermodynamics. Data analysed revealed that when relative humidity is higher than approximately 85% in the middle of the night, the cooling rate drops down more than one order of magnitude until the end of the night, in all ecosystems. This means that the water present in the air effectively releases energy into the environment. Since hypothetically the effect is produced by the coalescence of clusters of two water molecules, the amount of energy necessary to produce the effect corresponds to a coalescence rate of 10^{22} clusters per cubic meter per hour, a very small quantity to be properly detected by latent heat flux measurement systems.

Keywords: Hourly temperature modelling. Forest thermodynamics. Nocturnal cooling rate. Heat flux. Entropy.

Resumo: O objetivo deste artigo é estabelecer um modelo teórico não-empírico para o resfriamento noturno dos ecossistemas amazônicos dentro do escopo de compreender melhor a termodinâmica de tais ecossistemas. As características noturnas de temperatura em cinco diferentes ecossistemas da Amazônia brasileira foram estudadas, a saber, floresta profunda, floresta média, floresta de transição, savana (Cerrado) e uma floresta sazonalmente inundada (Pantanal). Durante um ano, foram analisados dados micrometeorológicos, especificamente temperatura e umidade do ar. Foi observado que a temperatura em todos os ecossistemas diminui a uma taxa de 0,9 °C/h no início da noite, que é coerente com a taxa de resfriamento teórica esperada em condições de ar “seco”, ou seja, quando a umidade não exerce influência significativa na termodinâmica do ecossistema. Os dados analisados revelaram que quando a umidade relativa é superior a aproximadamente 85% no meio da noite, a taxa de resfriamento cai mais de uma ordem de magnitude até o final da noite, em todos os ecossistemas. Isso significa que a água presente no ar efetivamente libera energia para o meio ambiente. Como hipoteticamente o efeito é produzido pela coalescência de aglomerados de duas moléculas de água, a quantidade de energia necessária para produzir o efeito corresponde a uma taxa de coalescência de 10^{22} aglomerados por metro cúbico por hora, uma quantidade muito pequena para ser devidamente detectada por sistemas de medição de fluxo.

Palavras-chave: Modelagem de temperatura. Termodinâmica de ecossistemas. Taxa de resfriamento noturno. Fluxos de calor. Entropia.

Resumen: El objetivo de este artículo es establecer un modelo teórico no empírico para el enfriamiento nocturno de los ecosistemas amazónicos en el marco de una mejor comprensión de la termodinámica de dichos ecosistemas. Se estudiaron las características nocturnas de la temperatura en cinco ecosistemas diferentes de la región amazónica brasileña, a saber, selva profunda, selva media, selva de transición, sabana (Cerrado) y selva estacionalmente inundable (Pantanal brasileño). Durante un año se analizaron datos micrometeorológicos, en concreto temperatura y humedad del aire. Se ha observado que la temperatura en todos los ecosistemas desciende a razón de 0,9 °C/h al comienzo de la noche. La tasa anterior es coherente con la tasa de enfriamiento teórica esperada en condiciones de aire “seco”, es decir, cuando la humedad no ejerce una influencia significativa en la termodinámica del ecosistema. Los datos analizados revelaron que cuando la humedad relativa supera aproximadamente el 85 % en medio de la noche, la tasa de enfriamiento desciende más de un orden de magnitud hasta el final de la noche, en todos los ecosistemas. Esto significa que el agua presente en el aire libera efectivamente energía al medio ambiente. Dado que hipotéticamente el efecto se produce por la coalescencia de cúmulos de dos moléculas de agua, la cantidad de energía necesaria para producir el efecto corresponde a una tasa de coalescencia de 10^{22} cúmulos por metro cúbico por hora, una cantidad muy pequeña para ser detectada adecuadamente por calor latente. sistemas de medida de flujo de calor latente.

Palabras clave: Modelado de temperatura horaria. Termodinámica forestal. Tasa de enfriamiento nocturno. Flujo de calor. Entropía.

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1. INTRODUCTION

Tropical ecosystems have an important role in global climate and specifically in low atmosphere thermodynamics (CHAMBERS; ARTAXO, 2017; SCOTT *et al*., 2018; O'CONNEL *et al*., 2018; KOOPERMAN *et al*., 2018). However, several aspects of the thermodynamic role of tropical forests and other ecosystems are not well known. For example, results on the balance of energy fluxes, measured by documented and widely employed methods, do not reach closure in most research reported in the literature (FOKEN, 2008) for all ecosystems in general. Therefore, the study of thermodynamic processes coupled to different tropical ecosystems is important in order to improve our knowledge of the influence of these systems on global climate.

Research by de Paulo, de Paulo and de Decker (2015) has reported that air temperature is one of the micrometeorological variables that carries on more information on ecosystem dynamics. Although this variable has been measured at several points on the Earth's surface for centuries, at present there is no reliable mathematical expression that describes the hourly behaviour of the variable, with exception of semi-empirical formulations or numerical approaches (CESARACCIO *et al*., 2001; SOUZA *et al*., 2011; REICOSKY *et al*., 1989; FLOYD; BRADDOCK, 1984; GEURTS, 1983; PARTON; LOGAN, 1981; JOHNSON; FITZPATRICK, 1977; WALTER, 1967). Most models are based on a mathematical representation of a series of sinusoidal and exponential functions for daily air temperature and or even other sinusoidal functions for night-time temperature. Consequently, there is no thermodynamic explanation for the hourly evolution of air temperature explicitly established in scientific literature. The purpose of this article is to establish a non-empirical theoretical model for the nocturnal cooling of Amazonian ecosystems within the scope of better understanding the thermodynamics of such ecosystems.

Current study has found certain similarities in thermodynamic parameters for several Brazilian tropical ecosystems, specifically in the nocturnal period, which may allow the construction of a universal model for the thermodynamics of these ecosystems. The main result is that, during the night, in the five studied ecosystems, the temperature decreases with an overall rate of 0.9°C per hour when the relative humidity is lower than 85% and the cooling rate drops down to less than 0.1°C/h when it is higher than 85%.

2. METHODS

Measurements of air temperature (T) and relative humidity (RH) were conducted by automated sensors in five different Brazilian ecosystems: deep forest, border forest, transitional forest, savannah and Pantanal. The main characteristics of each ecosystem are described below.

In the deep forest, the measurements were made in a 60 m tower in São Gabriel da Cachoeira (0.15N; 66.45W), one of the few segments of the Amazon Forest untouched by human activities. The average rainfall at this site in the rain forest lies between 3,000 and 3,500 mm per year (SÁ et al., 2012).

The border forest site lies in the Rebio-Jaru Reserve (61.56 W; 10.46 S). The mean canopy height is 33 m. The site lies inside the Amazon Forest, but close to agricultural zones (approximately 50 km) with intense anthropic transformation, where the average rainfall rate (2100 mm/y) is considerably lower than that in the deep forest (ANDRADE et al., 2009).

Measurements in the transitional forest were made in a 40 m tower, in an ecosystem within a region between the Amazon Forest and the *cerrado* (Brazilian savannah), in a farm (*Macaraí*) in the municipality of Sinop (55.19 W; 11.25 S) (ANDRADE et al., 2009). Mean rainfall is 2000 mm/y and the ecosystem is characterized by a dry (June-August) and a wet season (December-March), with an approximately 28 m high canopy (PRIANTE FILHO et al., 2004).

The cerrado site lies in an abandoned pastureland on a farm (*Miranda*) in the neighbourhood of the city of Cuiabá MT Brazil (56.02W, 15.72S). The site is characterized by a dry and a wet season with mean rainfall of 1200 mm/y (PALACIOS et al., 2015).

Finally, the Pantanal site (56.41W, 16.50S) lies within a seasonally flooded area, in a place called Baia das Pedras, with a dry (July-November) and a flooded period (December-June). Rainfall is approximately 1500 mm/y, 80% of which occurs during the wet season. The vegetation constitutes a kind of successional forest, with mean height of 6m (DALMAGRO et al., 2019).

All measurements were made from a few meters above the canopy by automated systems, collecting data every 10 min (for deep forest and Pantanal) and every 30 min (for border forest, transitional forest and Cerrado). Details on the equipment may be found in the references cited in current section. Analysed data correspond to 2008 for the deep forest (São

Gabriel da Cachoeira) and the border forest (Jaru); 2002 for the transitional forest (Sinop); 2013 for the Cerrado (Miranda farm); 2012 and 2013 for Pantanal (Baia das Pedras).

The data were chosen in order to use time series with the maximum possible consistency, in periods when the equipment worked well. This issue is important because, frequently, data collection fails for several reasons: action of animals and insects, adverse weather conditions, need for recalibration and accumulation of dirt. Consequently, the periods to which the data refer in the different ecosystems are different, which, in principle, could suggest some bias due to the possible dependence of local thermodynamics on climate variability. However, despite the great diversity of the ecosystems in terms of time of data acquisition, rainfall, type of soil, insolation, mean vegetation height and density, the analysed data suggests uniformity in the basic thermal dynamics for all ecosystems during the nocturnal period, as will be described below.

The first step to construct a model for nocturnal ecosystem thermodynamics was to consider a condition where the influence of humidity was unimportant, called *dry* in current paper.

3. RESULTS

3.1 The Dry Model

The dry model for temperature considers that temperature variation is closely related to the balance between incoming solar radiation and the outcoming infrared radiation, as it is done in the case of several classic global models (HOUGTHON, 2002; NICOLIS; PRIGOGINE, 1989), leading to the following equation:

$$\rho_a c_a \frac{dT}{dt} = \alpha R - \gamma \sigma T^4 \qquad (1)$$

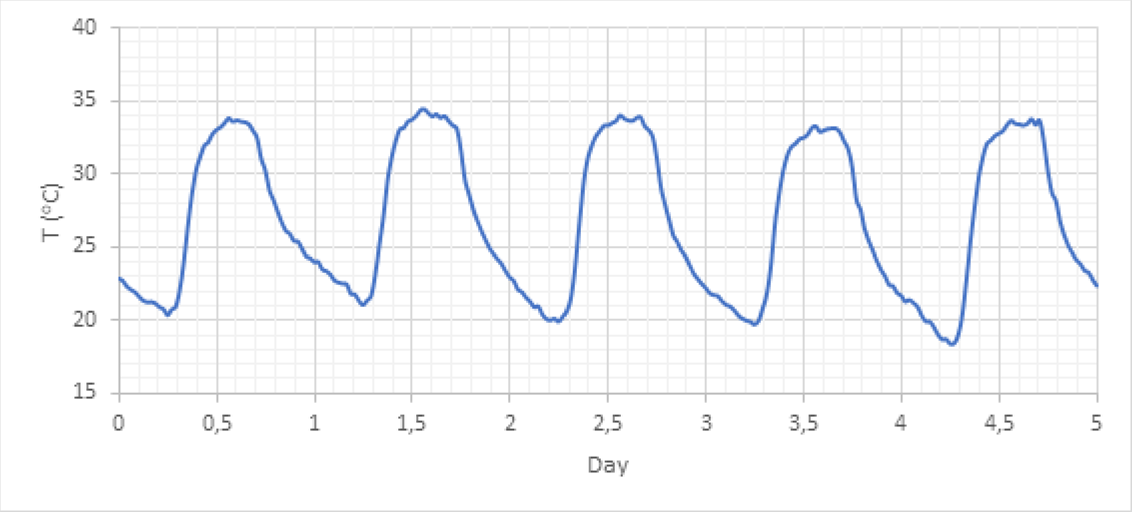
where ρ_a is the air density (1.184 Kg/m^3); c_a is the specific heat of the dry air (1012 J/Kg°C); R (W/m^2) is the incoming solar net radiation flux, discounted the reflected fraction (the radiation that is effectively absorbed by the air or ecosystem); T (K) is air temperature; σ (5.67×10^{-8} W m^{-2} K^{-4}) is the Stefan Boltzmann Constant; α and γ are two adjustable parameters. This equation is attained in conditions that the effect of transfer of energy by wind is negligible, as well as by rain and clouds.

The term on the left side of the equation is related with the sensible heat variation, while the last term on the left side corresponds to the Stefan Boltzmann law. The dimension of the equation is J/m^3 (energy density), α and γ are given in m^{-1}. Consequently, the physical meaning of these two parameters is concerned with extinction coefficients of radiation in the air.

In order to estimate the rates of α and γ for these Brazilian ecosystems, data from one ecosystem within an intermediate latitude (Sinop) were taken into account. At this location, the conditions valid for eq. 1 are attained due to the low wind intensity (GRECO et al., 1992) and absence of precipitation leading to low humidity conditions in the middle of year (PRIANTE FILHO, et al. 2004). The choice of a specific ecosystem, in a specific period, may represent some limitation in the face of possible climate changes and long-distance influence, such as those characterized by El Niño conditions. However, within conditions of low humidity, the behavior of nocturnal thermodynamics is characterized by robust universality, as the results below indicate.

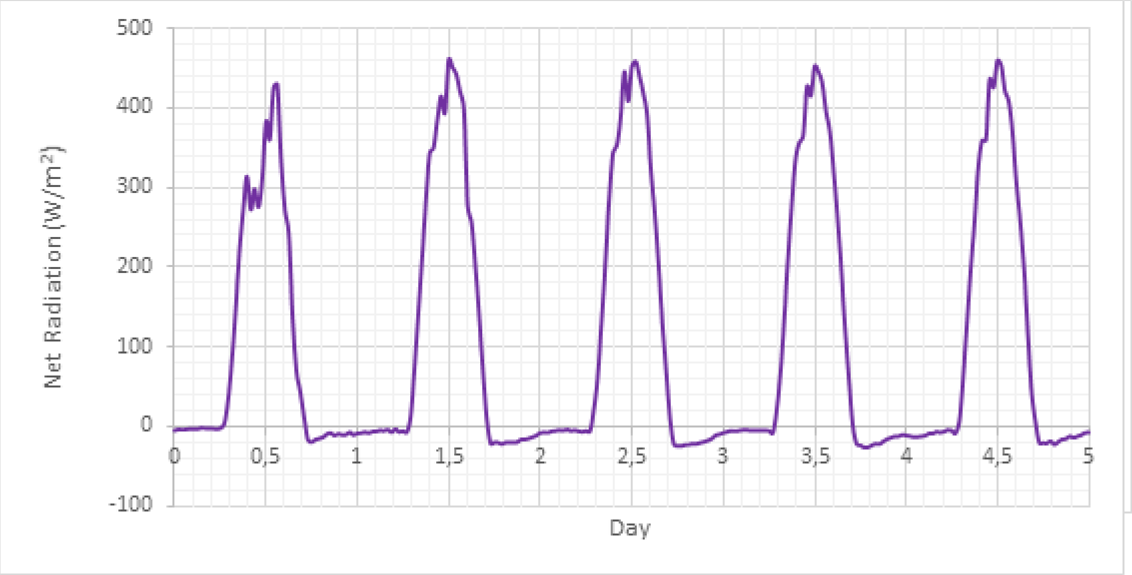
In Figures 1 and 2, the experimental values of temperature and net radiation correspond to the first days of June 2002, in Sinop. June is a month characterized by very low rainfall rates and low humidity. The experimental data show that the temperature increases when radiation increases, but the maximum value of the two variables is not reached at the same hour of the day. Maximum temperature is attained at approximately 2 or 3 p.m., while maximum radiation occurs at noon.

Figure 1 - Experimental temperature measured in Sinop on the first five days of June 2002.



Source: Elaborated by the authors (2022).

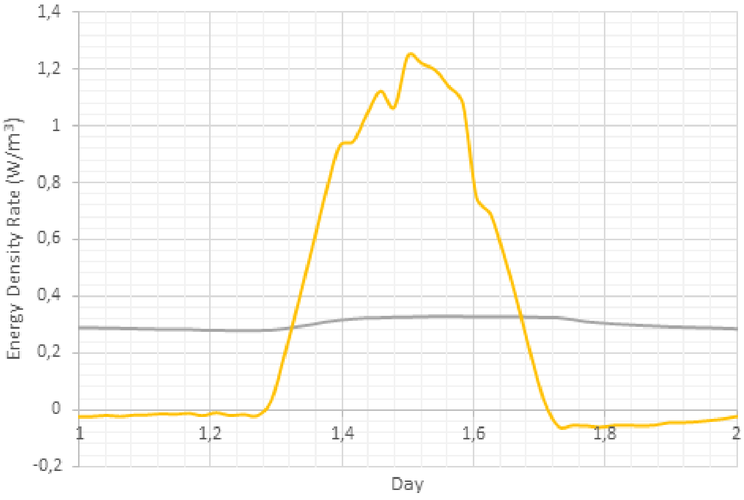
Figure 2 - Experimental net radiation measured in Sinop on the first five days of June 2002.



Source: Elaborated by the authors (2022).

Temperature has daily maximum and minimum rates which do not vary very much from one day to another, suggesting a very stable behaviour. Otherwise, Equation 1 is not linear and has fixed points when $\alpha R = \gamma\sigma T^4$. However, R is always lower than σT^4, but if α and γ have suitable rates, as Figure 3 reveals, this condition is attained twice a day.

Figure 3 - Comparison between $\alpha R \text{ and } \gamma\sigma T^4$ for June 2, 2002.

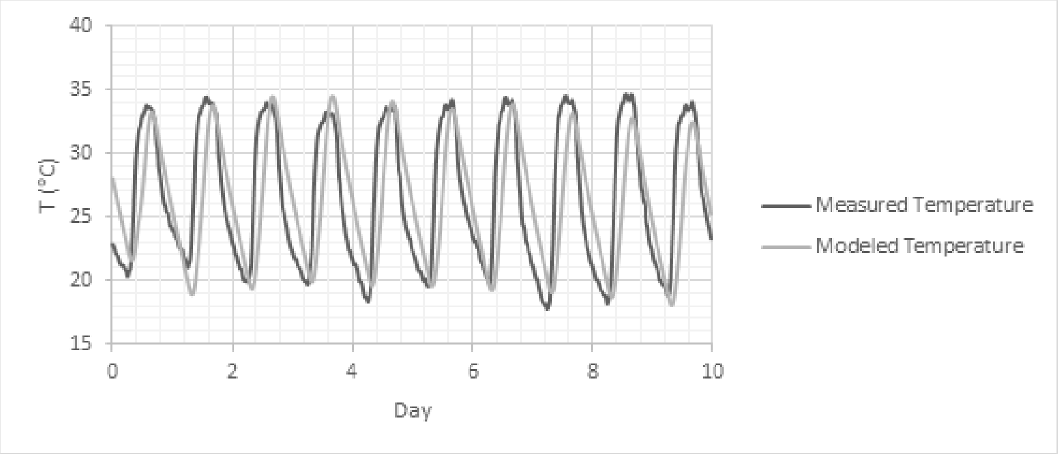


Source: Elaborated by the authors (2022).

Suitable values of α and γ may be obtained by taking into account that instants of time corresponding to maximum and minimum temperature rates are equal to the instants of time when $\alpha R = \gamma\sigma T^4$. For the experimental data of temperature measured in Sinop in June 2002, these values are 2.7 x 10^{-3} and 6.5 x 10^{-4} m^{-1} respectively.

A computational algorithm was prepared to calculate numerically the time evolution of temperature, using Equation 1. The algorithm admits the experimental rates of R calculating interactively the expected temperature rates along the time. Figure 4 shows a time series of temperature thus modelled and compared with experimental values of the variable for the first days of June 2002, in Sinop.

Figure 4 - Model´s temperature compared with experimental values between June 1 and June 10, 2002.



Source: Elaborated by the authors (2022).

As may be perceived in this figure, there is a similar pattern between experimental and theoretical features. The model reproduces the periodicity, the amplitude of temperature variation and approximately the instants of time with maximum and minimum temperature during the day. Consequently, the main model constituted by the equation may be a good approximation for real data, taking into consideration that these data are concerned to a real open system. However, there are differences between current temperature and values given by the model: during the first half of the day experimental values increase faster than the theoretical ones, whilst on the second half of the day the theoretical values decrease more linearly.

Equation 1 is a nonlinear differential equation that cannot be solved analytically because R varies with time. However, at night, when R is zero as a good approximation, it is possible to obtain an analytical solution. In this condition, Equation 1 is reduced to:

$$(\rho_a c_a)\frac{dT}{dt} = -\gamma\sigma T^4 \qquad (2)$$

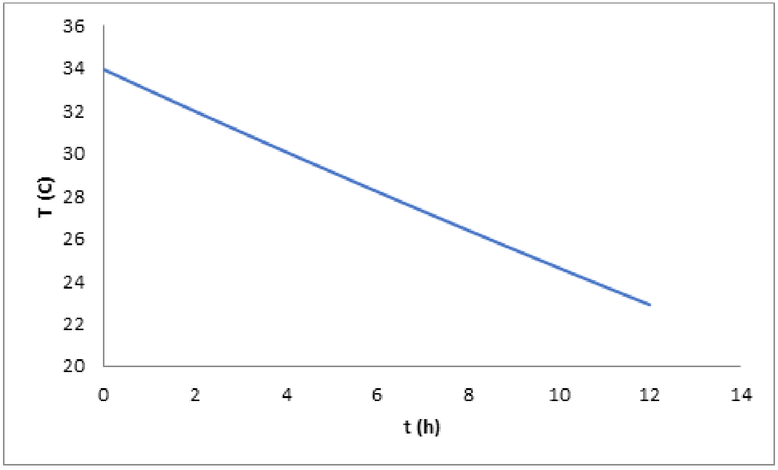
By direct integration, temperature may be considered a function of time:

$$T(t) = \sqrt[3]{\frac{\rho_a c_a T_0^3}{3\gamma\sigma t T_0^3 + \rho_a c_a}} \qquad (3)$$

where T_0 is the temperature in the beginning of the night and t is the time counted from the instance when temperature is T_0.

Figure 5 shows temperature in function of time, following Equation 3. Despite the nonlinear Equation 3, the behaviour of temperature in the interval between 20 and 40ºC is almost linear, corresponding to a cooling rate of about 0.9ºC/hour, for γ=6.5x10^{-4} m^{-1}.

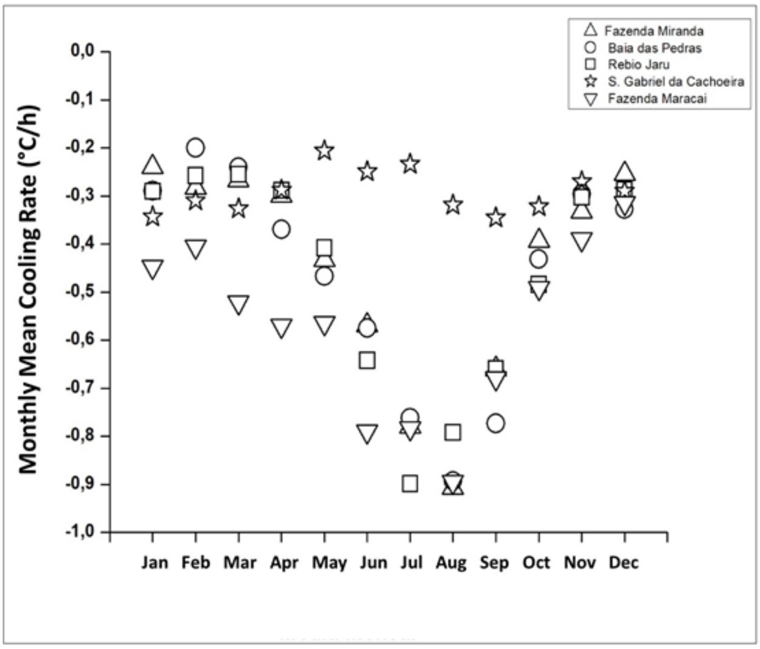
Figure 5 - Temperature forecasted by the dry model during the night.



Source: Elaborated by the authors (2022).

It is expected that during the night relative humidity increases with time. Consequently, the cooling rate of 0.9 °C/h should be more realistic in the beginning of night when relative humidity is low. Otherwise, during the dry season in the central regions of South America, when the precipitation is low, the above cooling rate may be detected practically every night. This may be observed in Figure 6, where the mean cooling rate between 19 pm and 5 am is given for each month of the year and for each ecosystem under analysis.

Figure 6 - Mean cooling rate (°C/h) between 19 pm and 5 am, in Fazenda Miranda, Cerrado (2013), Baía das Pedras (2012 and 2013), Rebio Jaru (2008), S. Gabriel da Cachoeira (2008) and Fazenda Maracaí, Sinop (2002).

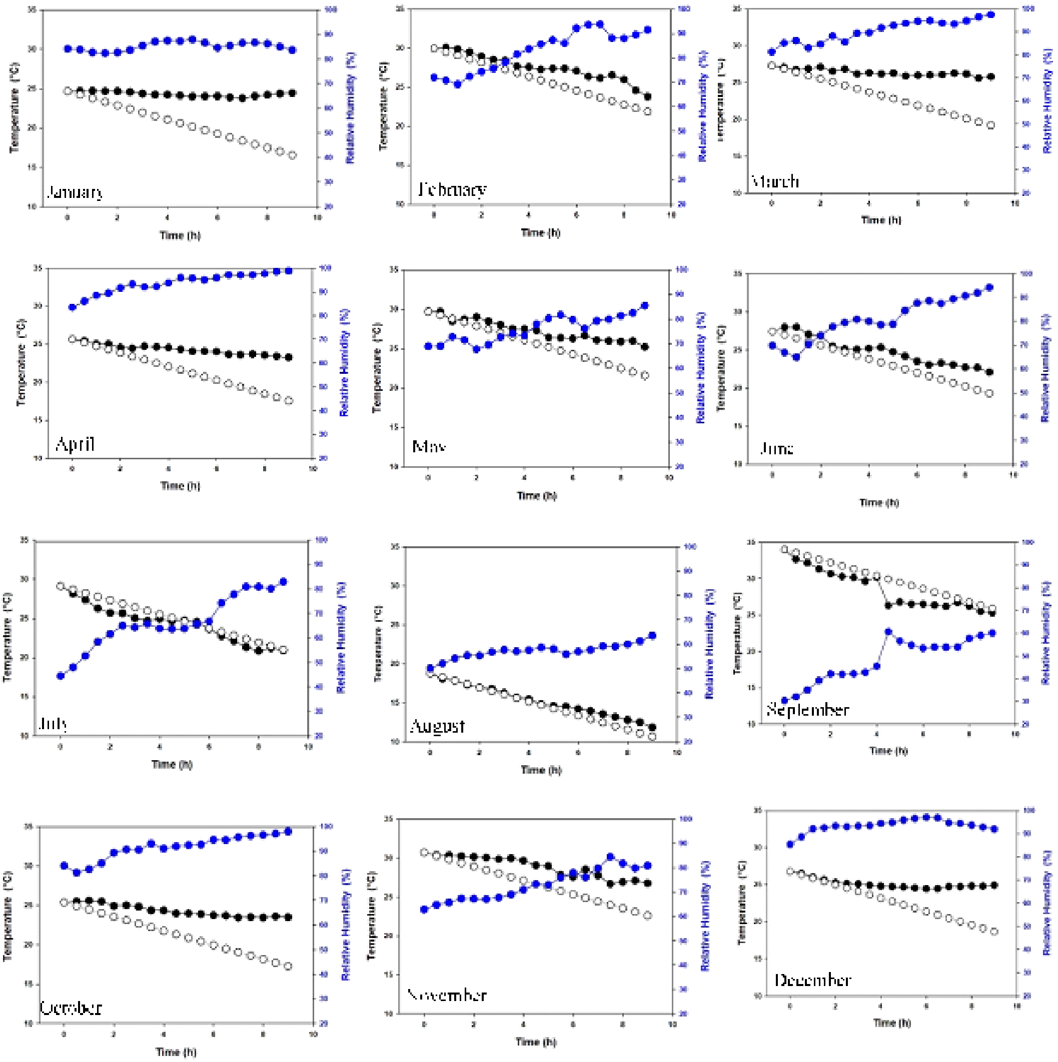


Source: Elaborated by the authors (2022).

3.2. The Effect of Humidity

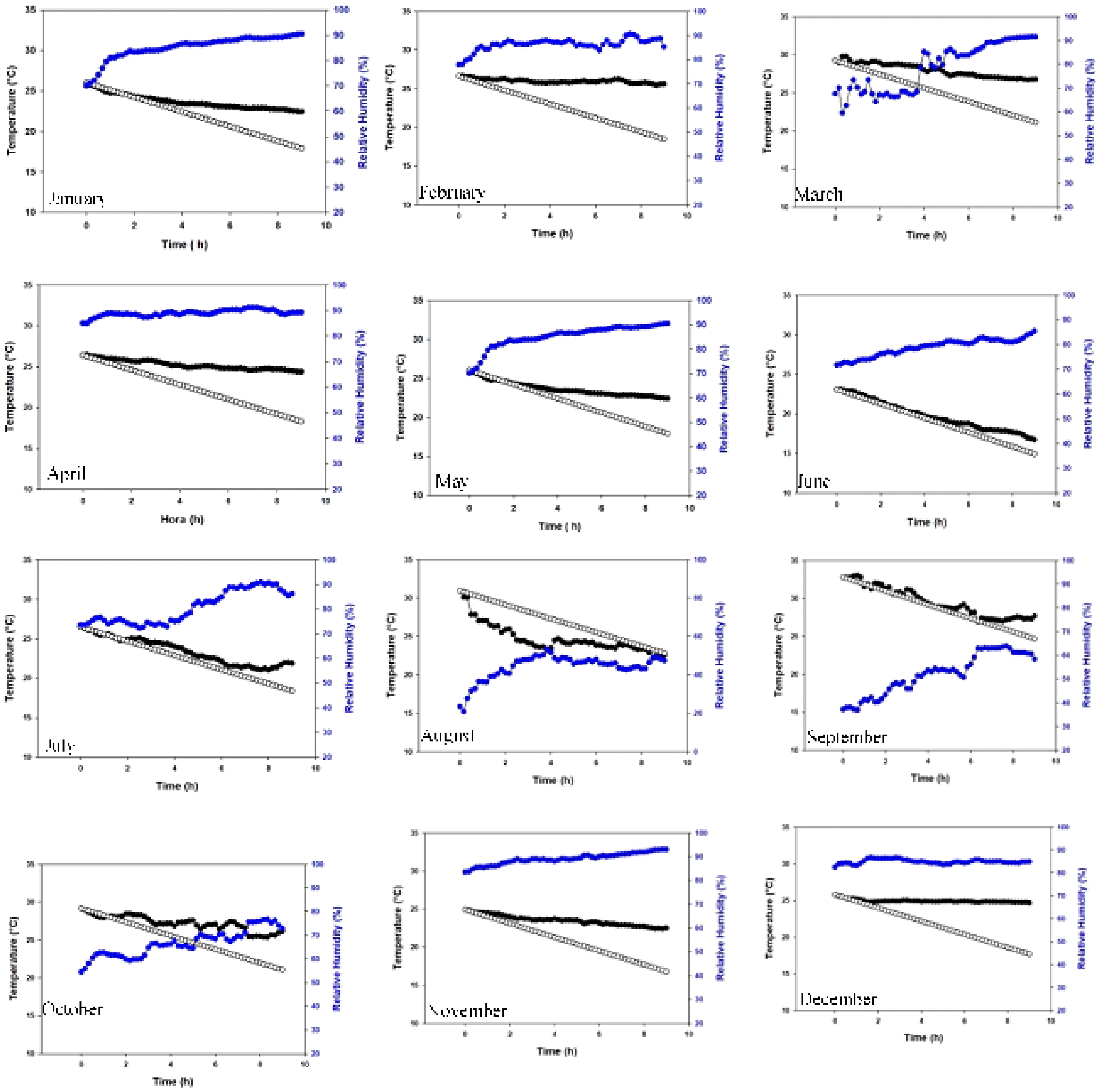
The dry cooling rate may actually be observed in the beginning of the night in most of the days for all ecosystems. Figures 7, 8, 9, 10 and 11 provide the nocturnal temperature variation in one day (chosen randomly) for each month of the year in Cerrado, Pantanal, Border Forest, Deep Forest and Transitional Forest respectively, compared with the dry cooling rate. Initial time was 8:00 pm when solar radiation may be considered negligible throughout the year for all ecosystems. The above-mentioned figures also demonstrate the time evolution of relative humidity.

Figure 7 - The nocturnal variation of temperature in Miranda farm (savannah). Experimental values (black dots), theoretical dry cooling (white dots) and experimental values of relative humidity (blue).



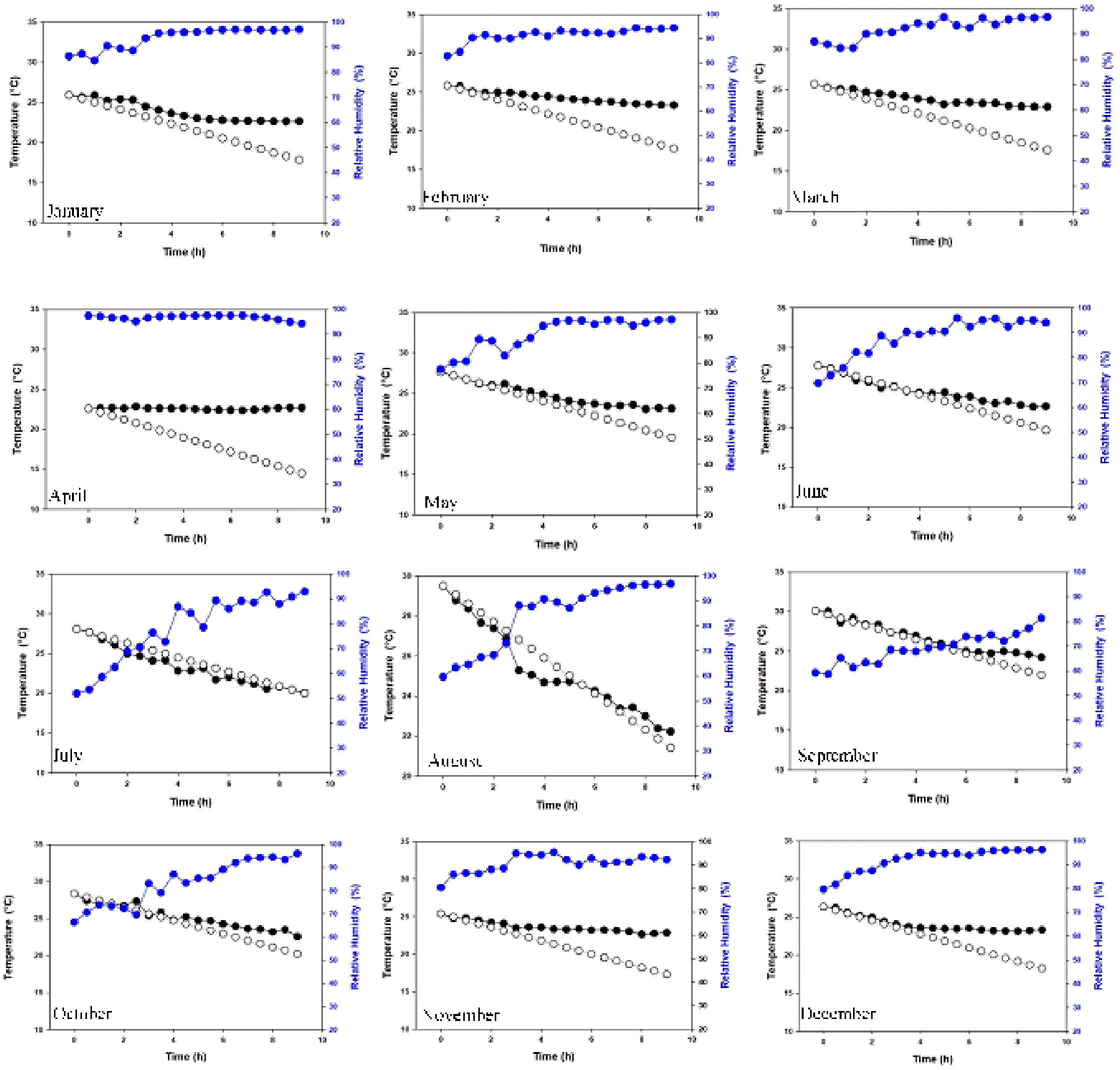
Source: Elaborated by the authors (2022).

Figure 8 - The nocturnal variation of temperature in Baia das Pedras (Pantanal). Experimental values (black dots), theoretical dry cooling (white dots) and experimental values of relative humidity (blue).



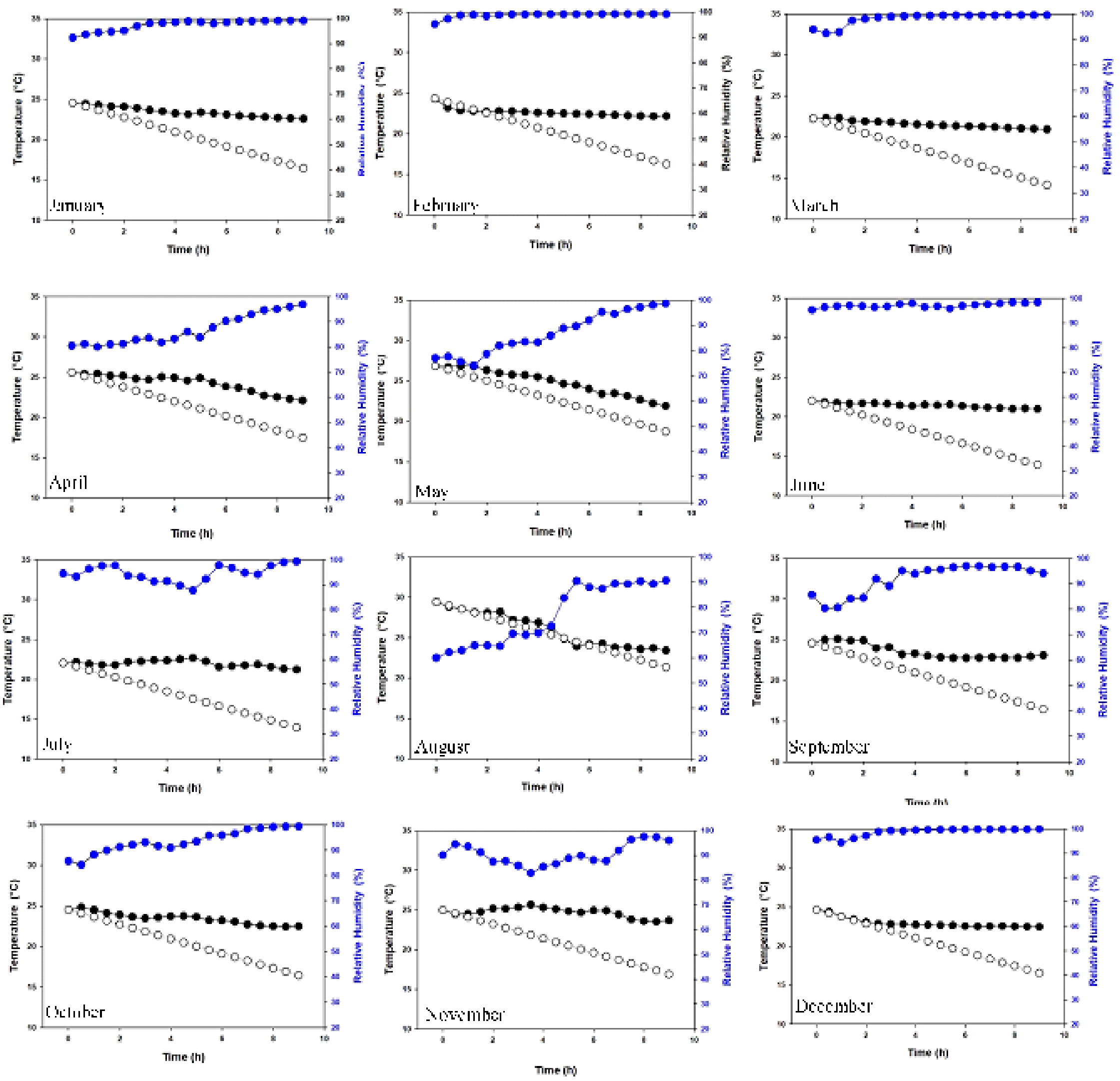
Source: Elaborated by the authors (2022).

Figure 9 - The nocturnal variation of temperature in Rebio-Jaru (Border Forest). Experimental values (black dots), theoretical dry cooling (white dots) and experimental values of relative humidity (blue).



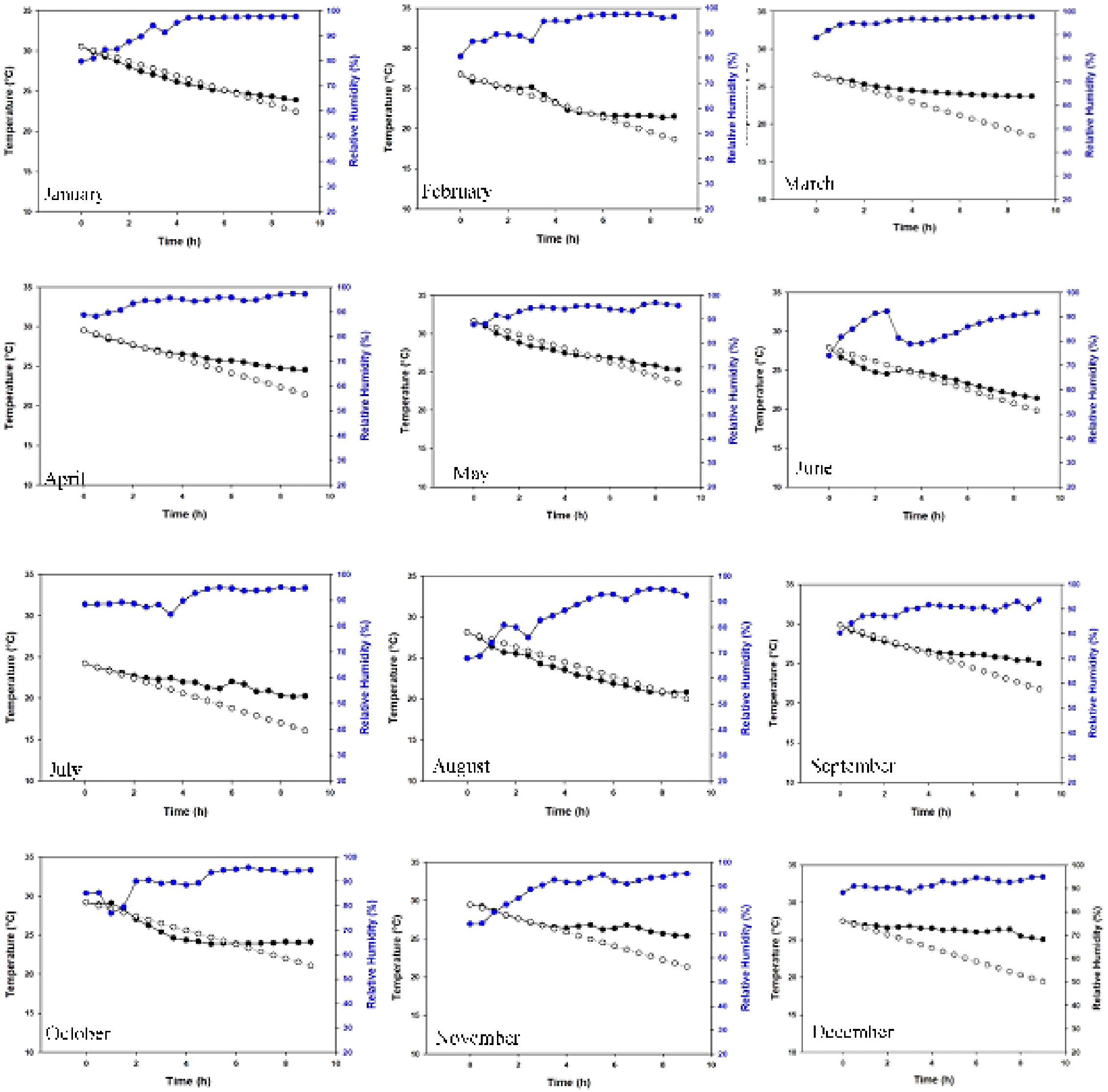
Source: Elaborated by the authors (2022).

Figure 10 - The nocturnal variation of temperature in São Gabriel da Cachoeira (Deep Forest). Experimental values (black dots), theoretical dry cooling (white dots) and experimental values of relative humidity (blue).



Source: Elaborated by the authors (2022).

Figure 11 - The nocturnal variation of temperature in Maracaí farm (Transitional Forest). Experimental values (black dots), theoretical dry cooling (white dots) and experimental values of relative humidity (blue).



Source: Elaborated by the authors (2022).

The observed cooling rate in the beginning of the night in most days is compatible with 0.9°C/h. It may also be observed that in all the cases where the above was not verified, the relative humidity was high, typically higher than 85%. Therefore, all given data may be compatible with the following statements:

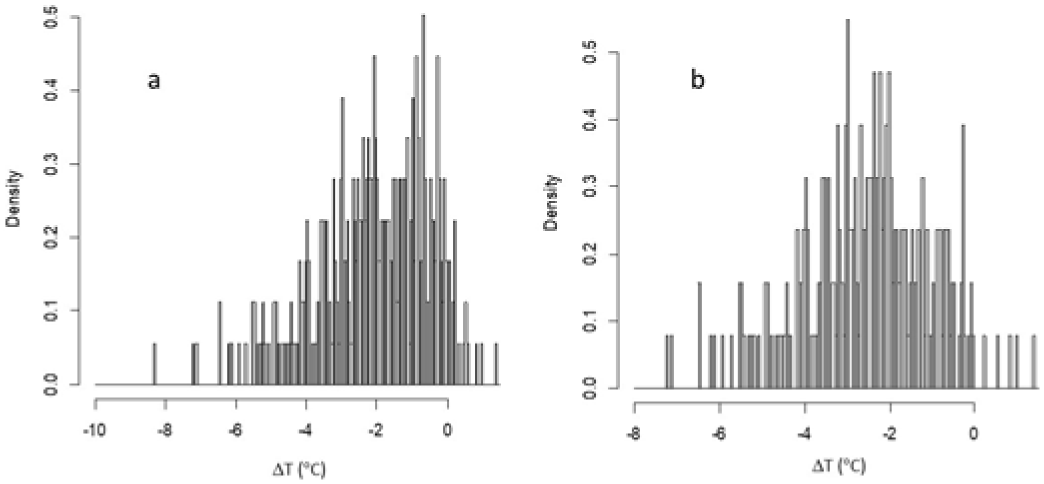
1. when relative humidity is lower than 85%, the nocturnal cooling rate is 0.9°C/h.
2. when relative humidity is higher than 85%, the nocturnal cooling rate drops to rates significantly lower than 0.9°C/h.

Although 85% is only a reference rate, the data point out that there is a fundamental difference between the thermodynamics in tropical ecosystems for relative humidity which may be lower and higher than a transitional interval around 85%. We may say that, around 85%, there is a *phase transition* in the thermodynamic process.

Prior to discussing the transition phase, let us show that, statistically, the cooling rate of 0.9°C/h may be considered for relative humidity lower than 85%. Figures 12, 13, 14, 15 and 16 provide the distribution of difference between the temperature measured at 8 pm and the temperature measured at 11 pm, taking into consideration (a) all available data and (b) relative humidity lower than 85%. Consequently, if the cooling rate is 0.9°C/h, the expected difference of temperature is (11 – 8) x 0.9 = 2.7°C. As it can be seen in the figures, for all ecosystems, the temperature difference is close to 2.7°C for RH < 85%. The mean values are (-2.52 ± 0.10), (-2.78 ± 0.10), (-2.74 ±

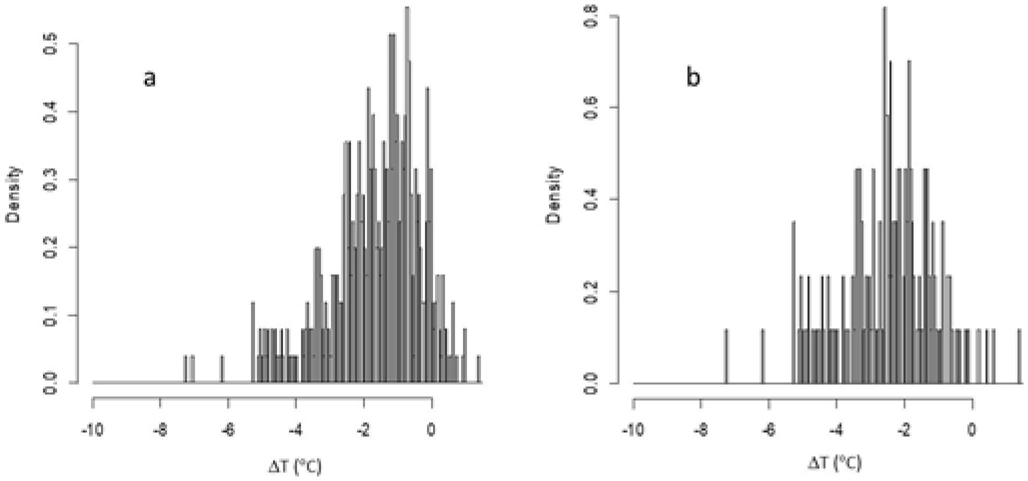
0.11) and (-2.25 ± 0.42) for Baia das Pedras, Miranda farm, Rebio-Jaru and Maracai farm, respectively. In the case of S. Gabriel, the statistic rates are low because rarely relative humidity is low in the deep Amazon Forest. On the contrary, in Miranda, which is very dry in the middle of the year, there are several days that satisfy the condition of RH < 85%.

Figure 12 - Distribution of values of the difference between the temperature at 8 p.m. and 11 p.m. for all analysed data in Miranda farm (savannah), for any condition of relative humidity (a) and for RH < 85% (b).



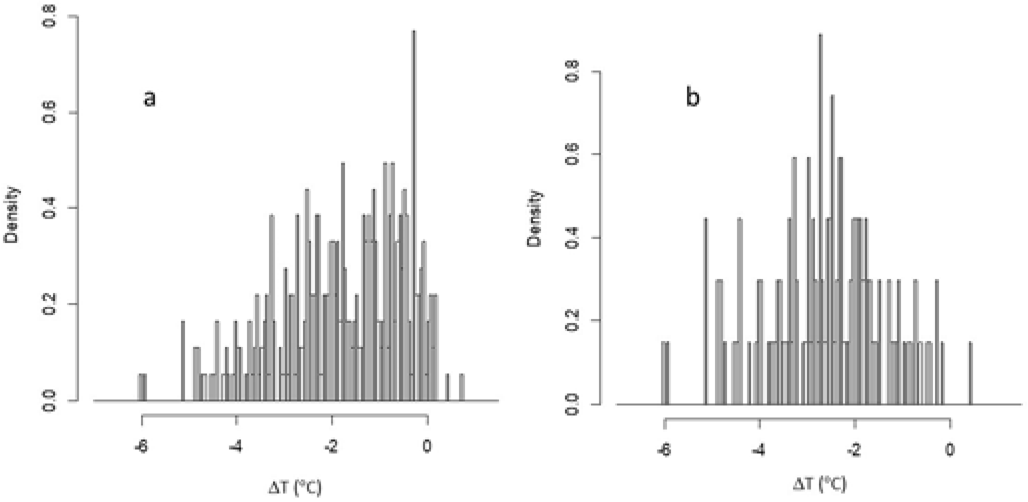
Source: Elaborated by the authors (2022).

Figure 13 - Distribution of values of the difference between the temperature at 8 p.m. and 11 p.m. for all analysed data in Baia das Pedras (Pantanal), for any condition of relative humidity (a) and for RH < 85% (b).



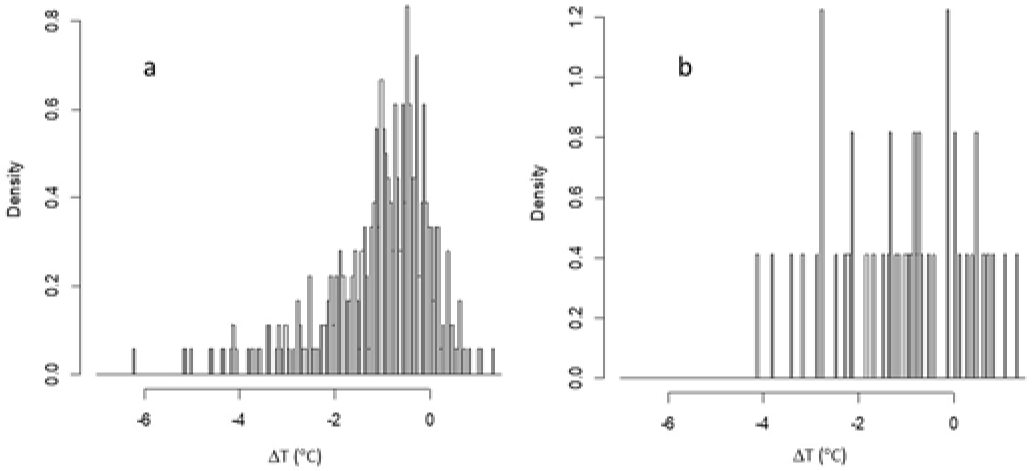
Source: Elaborated by the authors (2022).

Figure 14 - Distribution of values of the difference between the temperature at 8 p.m. and 11 p.m. for all analysed data in Rebio-Jaru (Forest), for any condition of relative humidity (a) and for RH < 85% (b).



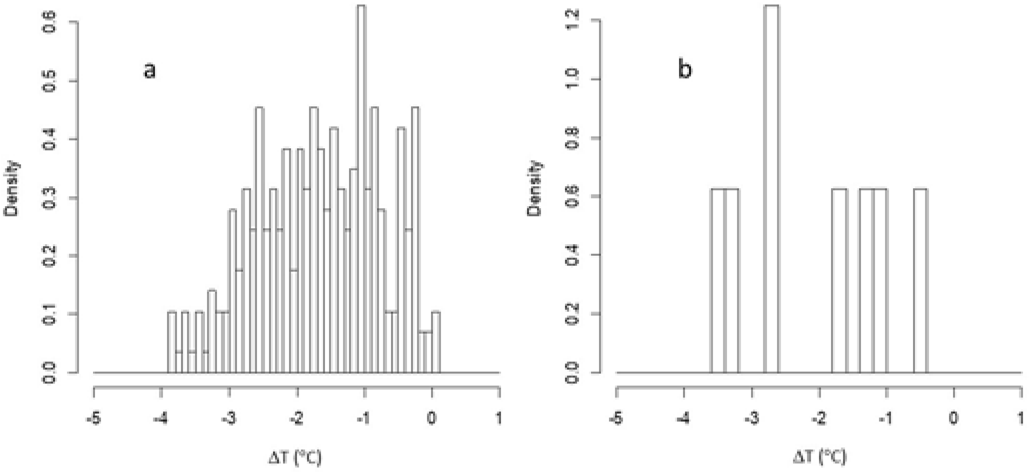
Source: Elaborated by the authors (2022).

Figure 15 - Distribution of values of the difference between the temperature at 8 p.m. and 11 p.m. for all analysed data in São Gabriel da Cachoeira (Deep Forest), for any condition of relative humidity (a) and for RH < 85% (b).



Source: Elaborated by the authors (2022).

Figure 16 - Distribution of values of the difference between the temperature at 8 p.m. and 11 p.m. for all analysed data in Macaraí farm (Transitional Forest), for any condition of relative humidity (a) and for RH < 85% (b).



Source: Elaborated by the authors (2022).

The strong depletion of the cooling rate when RH is higher than 85% may be a consequence of the clustering of small amounts of water molecules liberating energy into the air. Since the cooling rate for RH > 85% is negligible when compared with 0.9°C/h, it is possible to estimate the coalescence rate of water molecules that compensate the dry cooling rate (rh < 85%) by the following expression:

$$\rho_{air} c_{air} \left(\frac{dT}{dt}\right)_{dry} = \dot{n}\varepsilon$$

where ρ_{air} is the air density; c_{air} is the specific heat; $\left(\frac{dT}{dt}\right)_{dry}$ corresponds to 0.9°C/h; $\dot{n}$ is the coalescence rate of molecules; ε is the bonding energy. Considering also that the predominant process in coalescence is the clustering of two water molecules and that the bonding energy is roughly 5 kcal/mol (XANTHEAS, 2000), $\dot{n}$ is roughly 3 x 10^{22} $m^{-3}h^{-1}$.

The order of magnitude of this number (10^{22}) is very important. It is low when compared with the Avogadro number, or rather, only a few fractions of the amount of water molecules in the air are required to produce the effect of minimizing the cooling rate. The clustering of water molecules behaves effectively as a latent heat flux. In the micrometeorological knowledge area, latent heat flux is commonly measured by the technique of eddy covariance (BALDOCCHI, 2003), detecting the variation of the amount of water vapor by a sensor equipped with an infrared beam. It is hard to believe that this kind of sensor could detect such small variations (10^{22}) distinguishing clusters of two water molecules from free individual ones. This means that one should consider the possibility of the occurrence of serious limitations in measuring latent heat flux by eddy covariance. This may partially explain the difficulties with the balance energy closure in micrometeorology (FOKEN, 2008).

The entropy flux is another important factor. Results of current research indicate that the period of more intensive exporting entropy flux is at the beginning of the night, during the dry cooling thermodynamic process. Since plant growth is a self-organizing process corresponding to a significant reduction in the entropy of the ecosystem matter, it depends on substantial amount of entropy flux exportation. Consequently, from the thermodynamic point of view, the most favourable period for the growth of plants in Amazonian region is in the beginning of the night. Several research works on this theme have been reported in the literature (NUSINOW et al., 2011; STITT; ZEEMAN, 2012; GRAF at al., 2010; NOZUE at al., 2007).

4. CONCLUSION

The temperature model presented in current analysis is based on variables that are usually measured in micrometereological research. The goal was to describe the temporal behaviour of temperature within a 24-hour period in conditions of low humidity. Employing the experimental data model, a dry cooling rate of 0.9ºC/h was obtained, which is consistent with the experimental data at the beginning of the night. However, during the night, the cooling rate drops to rates below 0.1ºC/h when the relative humidity is higher than 85%. Therefore, water concentration exerts a fundamental role in ecosystem thermodynamics. The above may be due to the coalescence of water molecule clusters.

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