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FREQUENCY OF METEOROLOGICAL VARIABLE FOR REFERENCE EVAPOTRANSPIRATION CALCULATION IN BRAZIL USING CLUSTER ANALYSIS

Frequência de registros de variáveis meteorológicas para o cálculo da evapotranspiração de referência no Brasil por análise de agrupamento

Frecuencia de registros de variables meteorológicas para el cálculo de la evapotranspiración de referencia en Brasil mediante análisis de conglomerados

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Abstract: Irrigation management relies on the estimation of reference evapotranspiration (*ETo*). The objective was to characterize meteorological variables under different recording frequencies and climate classifications and to determine the minimum recording frequency for calculating *ETo*. Data were collected at 15-minute intervals from three weather stations located in Aw, Cfa, and Cwa climate regions from their installation through 2022. Nine recording frequencies were simulated to estimate *ETo* (Penman-Monteith method). Descriptive and cluster analyses (Agglomerative Hierarchical Clustering using the farthest neighbor method) were performed. Groups were formed based on 70% similarity. Statistical analyses were conducted using R and Microsoft Excel, with a significance level of 0.05. The Cwa climate exhibits the highest temperature, while the Cfa climate shows the highest relative humidity. Solar radiation is highest in the Aw climate, and wind speed is highest in the Cfa and Aw climates; consequently, *ETo* is highest in the Aw climate. The minimum recording frequency for *ETo* calculation is 2 hours for the Aw and Cfa climates and 4 hours for the Cwa climate. Adopting a two-hour recording interval across these climates and meteorological variables reduces data volume by 87.5%. Reliable estimates can be obtained with lower recording frequencies, and cluster analysis proves effective in determining these frequencies, providing valuable insights for companies offering irrigation management services.
Keywords: Sampling frequency. Time series. Evapotranspiration.

Resumo: O manejo da irrigação depende da estimativa da evapotranspiração de referência (*ETo*). O objetivo foi caracterizar as variáveis meteorológicas sob diferentes frequências de registro e classificações climáticas e determinar a frequência mínima de registro para calcular a *ETo*. Os dados foram coletados a cada 15 minutos em três estações meteorológicas localizadas nas regiões climáticas Aw, Cfa e Cwa, desde a sua instalação até 2022. Nove frequências de registro foram simuladas para estimar a *ETo* (método de Penman-Monteith). Realizou-se análises descritivas e de agrupamento (Método Hierárquico Aglomerativo do vizinho mais distante). Os grupos foram formados a partir de 70% de semelhança. As análises estatísticas foram realizadas com os softwares R e Microsoft Excel, adotando probabilidade de erro de 0,05. O clima Cwa apresenta a maior temperatura e o Cfa a maior umidade relativa do ar. A radiação solar é maior no clima Aw e a velocidade do vento no Cfa e Aw, sendo a *ETo* maior no Aw. A frequência mínima para o cálculo da *ETo* é de 2 horas nos climas Aw e Cfa, e de 4 horas no Cwa. A adoção de registros a cada duas horas para os diferentes climas e variáveis meteorológicas, reduz em 87,5% o volume de dados. Estimativas confiáveis podem ser obtidas com

menor frequência de registros e a análise de agrupamento mostra-se eficiente para defini-la, fornecendo subsídios para empresas que oferecem serviços de manejo da irrigação.
Palavras-chave: Frequência de amostragem. Séries temporais. Evapotranspiração

Resumen: La gestión del riego depende de la estimación de la evapotranspiración de referencia (*ETo*). El objetivo fue caracterizar las variables meteorológicas bajo diferentes frecuencias de registro y clasificaciones climáticas y determinar la frecuencia mínima de registro para calcular la *ETo*. Se recopilaron datos cada 15 minutos en tres estaciones meteorológicas ubicadas en las regiones climáticas Aw, Cfa y Cwa, desde su instalación hasta 2022. Se simularon nueve frecuencias de registro para estimar la *ETo* (método de Penman-Monteith). Se realizaron análisis descriptivos y de conglomerados (método jerárquico aglomerativo del vecino más lejano). Los grupos se formaron en base a una similitud del 70%. Los análisis estadísticos se realizaron utilizando el software R y Microsoft Excel, adoptando una probabilidad de error de 0,05. El clima Cwa presenta la temperatura más alta y el Cfa la humedad relativa más alta. La radiación solar es mayor en el clima Aw y la velocidad del viento es mayor en los climas Cfa y Aw, siendo la *ETo* mayor en el clima Aw. La frecuencia mínima para calcular la evapotranspiración de referencia (*ETo*) es de 2 horas en climas Aw y Cfa, y de 4 horas en climas Cwa. La adopción de registros cada dos horas para diferentes climas y variables meteorológicas reduce el volumen de datos en un 87,5%. Se pueden obtener estimaciones fiables con registros menos frecuentes, y el análisis de conglomerados demuestra ser eficiente para definir esta frecuencia, lo que resulta útil para las empresas que ofrecen servicios de gestión de riego.
Palabras clave: Frecuencia de muestreo. Series temporales. Evapotranspiración

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1. INTRODUCTION

Agriculture faces the challenge of ensuring food supply in the face of continued global population growth, which is expected to exceed 9 billion people by 2050, requiring a 70% increase in food production (Wang, 2022). However, it is known that agricultural productivity is limited worldwide by abiotic stresses, such as water deficit, which affects the growth and development of agricultural crops (Santos; Carlesso, 1998; Zarei, 2022), resulting in a significant impact on global food production.

Irrigation has been one of the main strategies for ensuring global food security. Brazil ranks among the ten countries with the largest areas equipped for irrigation, holding sixth place with 8.2 million hectares. (FAO, 2024). To guarantee high productivity, simply acquiring and installing an irrigation system is not enough. Ideally, proper irrigation management should be implemented, determining when and how much to irrigate, whether based on plant, soil, and/or climate factors (Báez *et al*., 2020). Proper management prevents yield losses due to excessive or insufficient water application (Kheir *et al*., 2021), it ensures greater agricultural production, financial profitability for producers, and environmental sustainability.

In climate-based irrigation management, evapotranspiration is one of the key components of the water balance in agricultural ecosystems, alongside precipitation and irrigation (Brito *et al*., 2020). Maximum crop evapotranspiration (*ETm*) can be determined by the product of reference evapotranspiration (*ETo*) and the crop coefficient (*Kc*). *ETo* is understood as the evapotranspiration that occurs on a grassed surface, completely covering the soil, during active growth and without soil water restrictions (Pereira *et al*., 2002). It is influenced by solar radiation, air temperature, relative humidity, and wind speed. Therefore, it is also considered a climatic parameter and can be estimated from meteorological data obtained through automatic weather stations (Sentelhas; Gillespie; Santos, 2010). Among the available methods, the Penman-Monteith (FAO-56) method (Allen *et al*., 1998) is globally recognized as the standard and considered one of the most accurate (Abeysiriwardana; Muttil; Rathnayake, 2022).

Automatic weather stations enable the measurement and recording of various meteorological variables at high frequency (Pereira *et al*., 2008), generating large volumes of data that require greater memory storage capacity. In Brazil, the National Institute of

Meteorology alone manages a total of 564 automatic weather stations (INMET, 2025). On the other hand, using lower collection frequencies, with few daily observations, can compromise the accuracy of the data obtained (Hupet; Vanclooster, 2001). Therefore, the appropriate approach is to determine the minimum frequency for recording meteorological variables, reducing the dataset to a minimum without loss of information.

The application of multivariate analysis techniques has been used to analyze climate data series, with the purpose of reducing the size of the dataset and improving its interpretation (Gebert; Kist; Virgens Filho, 2018). Cluster analysis is a technique that groups similar characteristics into homogeneous groups, with greater heterogeneity between the groups (Andrade *et al*., 2021; Melo; Souza, 2021; Santos; Sousa; Leite, 2022).

n agriculture, cluster analysis has been used to determine the minimum frequency of observations of meteorological variables in canola cultivation (Engers, 2023). However, this is one of the few studies aimed at defining the ideal sampling frequency for micrometeorological variables measured within specific crop canopies. Consequently, there is a scientific gap regarding the definition of the minimum recording frequency required to calculate reference evapotranspiration across different climatic regions.

Given the above, this work aimed to characterize the dataset of meteorological variables under different recording frequencies and climatic classifications, and to determine the minimum recording frequency of meteorological variables measured by meteorological stations, in order to represent the accuracy of field conditions for the purpose of calculating reference evapotranspiration.

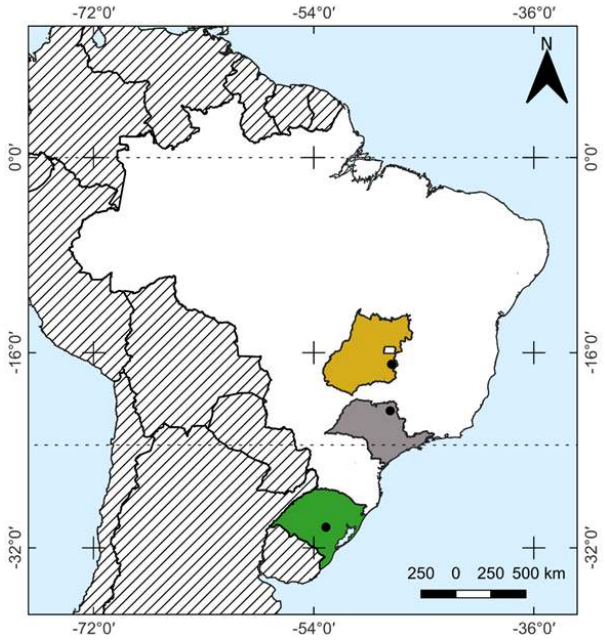
2. MATERIAL AND METHODS

2.1. Characterization of the study área

Meteorological data were obtained from automatic weather stations belonging to the company Irriga Global (Irriga Global, 2023). Meteorological data on air temperature (°C), relative humidity (%), wind speed (m s^{-1}), and incident global solar radiation (W m^{-2}) were used from three weather stations located in the states of Goiás (GO), Rio Grande do Sul (RS), and São Paulo (SP), in Brazil, as described in Table 1 and illustrated in Figure 1. Data were collected

daily, at 15-minute intervals, from the date of establishment of each weather station until December 2022 (Table 1).

Figure 1 - Geographic location of meteorological stations (filled circles) located in the states of Rio Grande do Sul (green), São Paulo (gray) and Goiás (yellow), Brazil.



Source: Prepared by the authors (2024).

Table 1 - Geographic location, climate type according to the Köppen climate classification, and data period collected from weather stations.

Meteorological stations	Geographic coordinates			Climate	Data Period
	Latitude	Longitude	Altitude		
Cristalina/GO[1]	-16° 58' 5.3"	-47º 38' 47.8"	976 m	Aw	11/05/2003 - 12/31/2022
Cachoeira do Sul/RS	-30° 17' 40.6"	-53º 00' 37.2"	137 m	Cfa	08/28/2009 - 12/31/2022
Nuporanga/SP	-20° 45' 13.9"	-47º 45' 7.6"	767 m	Cwa	05/13/2009 - 12/31/2022

[1]GO: Goiás; RS: Rio Grande do Sul; SP: São Paulo; Aw: tropical with a dry winter; Cfa: humid subtropical, without a defined dry season and with a hot summer; Cwa: humid subtropical, with a dry winter and a hot summer.

Source: Prepared by the authors (2025).

The weather stations are located in regions with distinct climate classifications (Table 1). According to the Köppen classification, the municipality of Cristalina has an Aw type climate, defined as tropical with a dry winter, where the air temperature in the coldest month is ≥ 18 °C and the rainfall in the driest month is < 60 mm. The municipality of Cachoeira do

Sul/RS has a Cfa climate, called humid subtropical, without a defined dry season and with a hot summer, and Nuporanga/SP has a Cwa climate, humid subtropical, with a dry winter and a hot summer. Both have air temperatures in the warmest month > 22 °C and in the coldest month ranging from -3 °C to < 18 °C. However, rainfall in the driest month is > 40 mm in Cfa and < 40 mm in Cwa (Alvares *et al*., 2013).

First, flaws were identified, and invalid data were identified and excluded from the meteorological data series. Finally, all days that did not have 96 daily observations were excluded from the dataset, either due to flaws or invalid values. Thus, the total number of meteorological data records for each meteorological variable used in this study was 377,184 records in Cristalina, 349,536 records in Cachoeira do Sul, and 367,872 records in Nuporanga. These numbers correspond, respectively, to 56.16%, 74.70%, and 76.92% of the total number of records expected in the established period for each location.

Data exclusion was necessary to simulate different recording frequencies and ensure the consistency of the calculations. Despite the flawed data and this exclusion, 56.16, 74.70, and 76.92% of the expected records were preserved for Cristalina, Cachoeira do Sul, and Nuporanga, respectively, representing a sufficient amount of data.

Based on the 15-minute recording frequency that comprises the original dataset, nine recording frequencies for each meteorological variable were simulated across different climate classifications. These frequencies were obtained by averaging the previous periods, starting at 00:00 Brasília time (UTC -3). The simulations included records at 30 min, 1 h, 2 h, 3 h, 4 h, 6 h, 8 h, 12 h, and 24 h intervals, corresponding to the means of the previous 2, 4, 8, 12, 16, 24, 32, 48, and 96 fifteen-minute records, respectively (Engers, 2023).

2.2. Estimation of reference evapotranspiration (*ETo*)

For each of the recording frequencies and climate classifications, the daily reference evapotranspiration (*ETo* mm dia^{-1}) was estimated using the Penman-Monteith method, recommended by the Food and Agriculture Organization of the United Nations (FAO) (Allen *et al*., 1998) (Equation 1):

$$(1) \qquad ET_o = \frac{0.408.\Delta.(R_n\text{-}G)+\gamma.\left(\frac{900}{T+273}\right).u_2.(e_s\text{-}e_a)}{\Delta+\gamma.(1+0.34.u_2)}$$

where Δ is the slope of the saturation vapor pressure curve of air at the mean daily air temperature (kPa °C^{-1}); R_n is the net radiation at the surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (3% of R_n, MJ m^{-2} day^{-1}); T is the mean daily air temperature (°C); u_2 is the mean daily wind speed (m s^{-1}); γ is the psychrometric constant (0.0662 kPa °C^{-1}). e_s is the saturation vapor pressure of the atmosphere (kPa); e_a is the partial vapor pressure of the atmosphere (kPa).

The saturation vapor pressure in the atmosphere (e_s, kPa) was determined considering the mean daily air temperature (T, °C) (Equation 2) and the partial vapor pressure in the atmosphere (e_a,, kPa) considering e_s (kPa) and the mean relative air humidity (RH, %) (Equation 3) (Tetens *et al*., 1930):

$$(2) \qquad e_s = 0.6108.10^{\left(\frac{7.5.T}{237.5+T}\right)}$$

$$(3) \qquad e_a = \frac{RH.e_s}{100}$$

The tangent to the saturation vapor pressure curve of air for the mean daily air temperature (Δ, kPa °C^{-1}) was determined considering both e_s (kPa) and T (°C) (Equation 4):

$$(4) \qquad \Delta = \frac{4098.e_s}{(237.5+T)^2}$$

The net radiation on the surface (R_n, MJ m^{-2} day^{-1}) was determined according to the equation described by Brunt-Penman, with the last term of the equation n/N substituído por $K_{\downarrow}/K_{O\downarrow}$ (Pereira; Villa Nova; Sediyama, 1997) (Equation 5):

$$(5) \qquad R_n = K_{\downarrow}.(1\text{-}R)\text{-}\left(\varepsilon.\sigma.T^4\right).\left(0.56\text{-}0.0797.\sqrt{e_a}\right).\left(\frac{1{,}35.K_{\downarrow}}{0{,}75.K_{o\downarrow}} - 0{,}35\right)$$

where, $K_{\downarrow}$ is the mean daily incident global solar radiation (MJ m^{-2} day^{-1}); R is the surface reflectivity (0.23 on a grassy surface); ε is the emissivity (0.95); σ is the Stefan-Boltzmann constant (4.9x10^{-9} MJ m^{-2}day^{-1}K^{-4}); T is the mean daily air temperature (K); e is the partial vapor pressure in the atmosphere (mmHg); $K_{O\downarrow}$ is the global solar radiation flux density incident at the top of the atmosphere (MJ m^{-2} day^{-1}) (Equation 6).

$$(6) \qquad K_{O\downarrow} = 37{,}6.\left(d/D\right)^2.\left[\frac{\pi}{180}\right].H.sen\,\emptyset.sen\,\delta + cos\,\emptyset\,.\,cos\,\delta\,.sen\,H$$

where, $(d/D)^2$ is the ratio of the mean Earth-Sun distance to the distance on a specific day (Km) (Equation 7); *H* is the hour angle at sunrise or sunset (°) (Equation 8); Ø is the latitude (°); δ is the solar declination (°) (Equation 9), with *n* being the Julian day.

$$(7)\quad (d/D)^2 = 1+0{,}033\ cos(n.360/365)$$

$$(8)\quad H = arccos[-1(tg\ Ø.tg\ \delta)]$$

$$(9)\quad \delta = 23{,}45\ sen\left[\left(\frac{360}{365}\right).(284+n)\right]$$

2.3. Statistical analysis

Descriptive analyses (*boxplots*) were performed for the different meteorological variables and recording frequencies. For the cluster analysis, the hierarchical agglomerative complete-linkage method was used. Initially, Euclidean distances were calculated according to Equation (10).

$$(10)\quad dij = \sqrt{\sum_{v=1}^{p} (X_{iv}-X_{jv})^2}$$

where, *dij* is the Euclidean distance between record frequencies *i* and *j*; X_{iv} and X_{jv} correspond to the values of Variable *v* for record frequencies *i* and *j*, respectively; *p* is the number of dimensions.

Subsequently, the linkage distance between two groups G_1 e G_2 was determined using the farthest neighbor method (*complete linkage*), considering the maximum Euclidean distance, as shown in Equation (12):

$$(11)\quad d\ (G_1, G_2) = \max_{i \in G_1, j \in G_2} dij$$

where, $d\,(G_1,G_2)$ is the Euclidean distance between record frequencies G_1 and G_2; *dij* é à distância euclidiana entre as frequências de registro *i* e *j*.

The groups were formed based on a 70% similarity threshold, adopted as the cutoff point on the dendrogram to identify recording frequencies exhibiting behavior similar to the original data frequency. This threshold was deemed appropriate by Lúcio *et al*. (2006), as it allowed for the formation of groups characterized by high internal homogeneity and high heterogeneity between them. The aim was to select the frequency with the longest recording

interval that was grouped in the cluster where the 15-minute frequency (original data) was present (Engers, 2023).

Statistical analyses were performed with a significance level of 0.05 probability of error, using R software (*version* 4.3.1) (R Core Team, 2025) and Microsoft Office Excel®. The following functions and packages were used: the '*ggplot*' function from the '*ggplot2*' package, the '*desc_stat*' function from the '*metan*' package, the '*hclust*' function with the '*complete*' method from the '*stats*' package, the '*dist*' function with the '*euclidean*' method; and the '*fviz_dend*' function from the '*factoextra*' package.

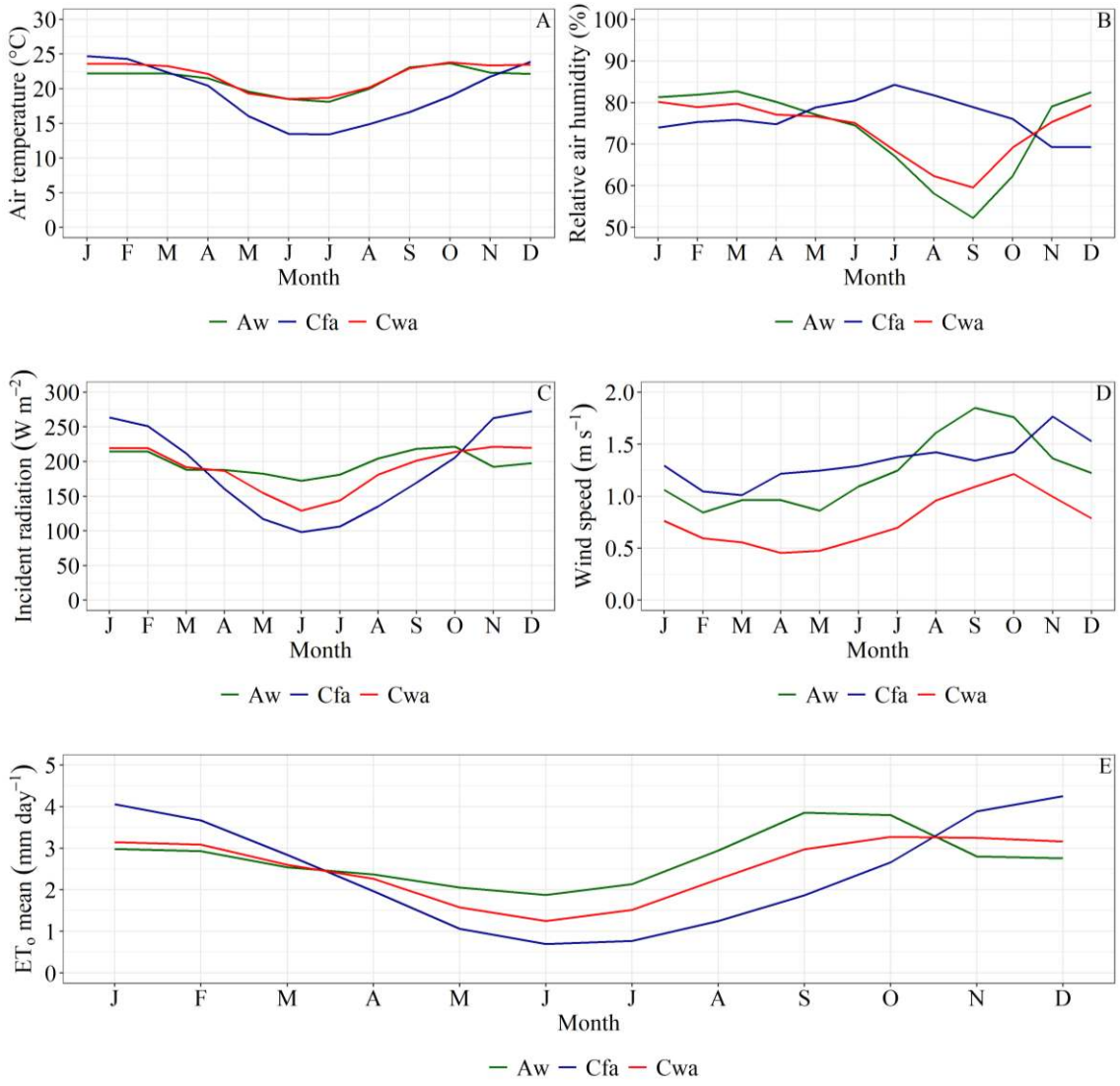
3. RESULTS AND DISCUSSION

Mean values for air temperature and incident global solar radiation were lower during winter and higher in summer in all climatic regions, with greater thermal amplitude (Figure 2A) and in annual solar radiation (Figure 2C). Mean relative air humidity increased in winter, exceeding 80% in the Cfa climate, while in the Aw and Cwa climates it decreased at the end of winter and beginning of spring, remaining below 70%. A greater annual amplitude was observed in the Aw climate (Figure 2B).

Regarding wind speed, the highest mean values were concentrated from spring onwards, followed by a decreasing trend, with the lowest values identified at the end of summer and the beginning of autumn in all locations (Figure 2D). The mean values of *ETo* showed different rates in the three locations, increasing during the spring and summer months, and decreasing throughout autumn and winter (Figure 2E).

The mean annual *ETo* curves are influenced by other meteorological variables. Periods of greater availability of solar energy, air temperature, wind speed, and lower relative humidity lead to an increase in the evaporative demand of the atmosphere, and consequently, in the *ETo* rate (Lemos Filho *et al*., 2010; Shi *et al*., 2023; Tagliaferre *et al*., 2015). Similar annual variations were observed in the Southeast, Midwest (Lemos Filho *et al*., 2007), and Southern regions of Brazil (Hallal *et al*., 2013).

Figure 2 - Mean values of air temperature (°C) (A), relative air humidity (%) (B), incident global solar radiation (W m^{-2}) (C), wind speed (m s^{-1}) (D) and reference evapotranspiration (*ETo*, mm day^{-1}) (E) throughout the months of the year in the climate classifications Aw (green line), Cfa (blue line) and Cwa (red line), from the date of foundation of the meteorological stations until 2022.

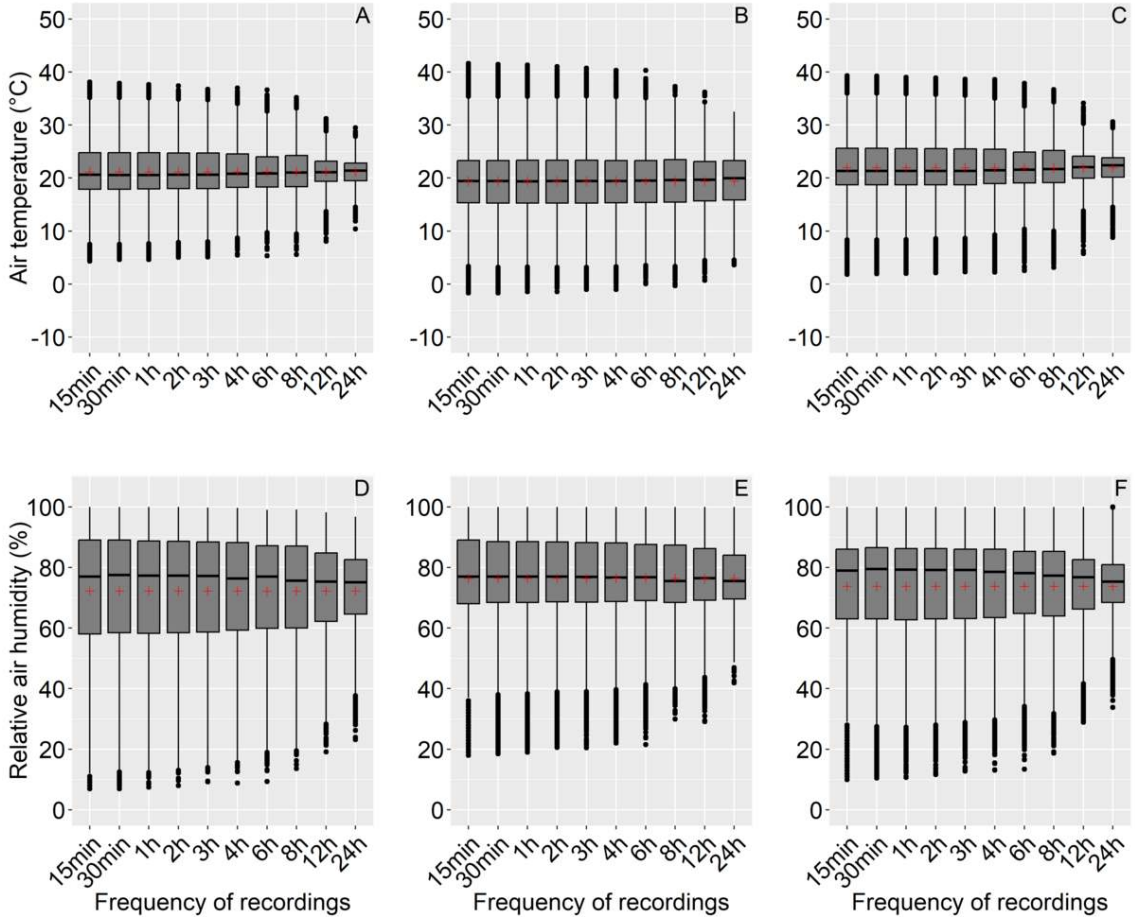


Source: Prepared by the authors (2024).

Descriptive analysis of air temperature meteorological data across different frequencies showed that mean values were highest in climate type Cwa (21.9 °C) (Figure 3C), followed by Aw (21.2 °C) (Figure 3A), and lowest in Cfa (19.4 °C) (Figure 3B), where greater variability was also observed, with readings below 0 °C or above 40 °C, not verified in the other regions. On the other hand, mean relative humidity values were highest in climate type Cfa (76.4%), also showing less dispersion among the data and less amplitude between extreme values (Figure 3E). In Cwa and Aw, mean values were 73.8% (Figure 3F) and 72.2% (Figure 3D), respectively, with greater variability identified among the data from the latter. Furthermore,

for both meteorological variables and regardless of the type of climate, recording frequencies with few observations throughout the day resulted in less data variability, since they were defined based on means. Furthermore, for both meteorological variables and regardless of the climate type, recording frequencies with few observations throughout the day resulted in lower data variability, since they were defined based on averages.

Figure 3 - Descriptive analysis of the different frequencies of recording air temperature (°C) in the climatic classifications Aw (A), Cfa (B) and Cwa (C), and relative air humidity (%) in the climatic classifications Aw (D), Cfa (E) and Cwa (F), from the date of foundation of the meteorological stations until the year 2022. *Boxplot* (5, 25, 50, 75 and 95%), mean (+) and outliers (solid circles).



Source: Prepared by the authors (2024).

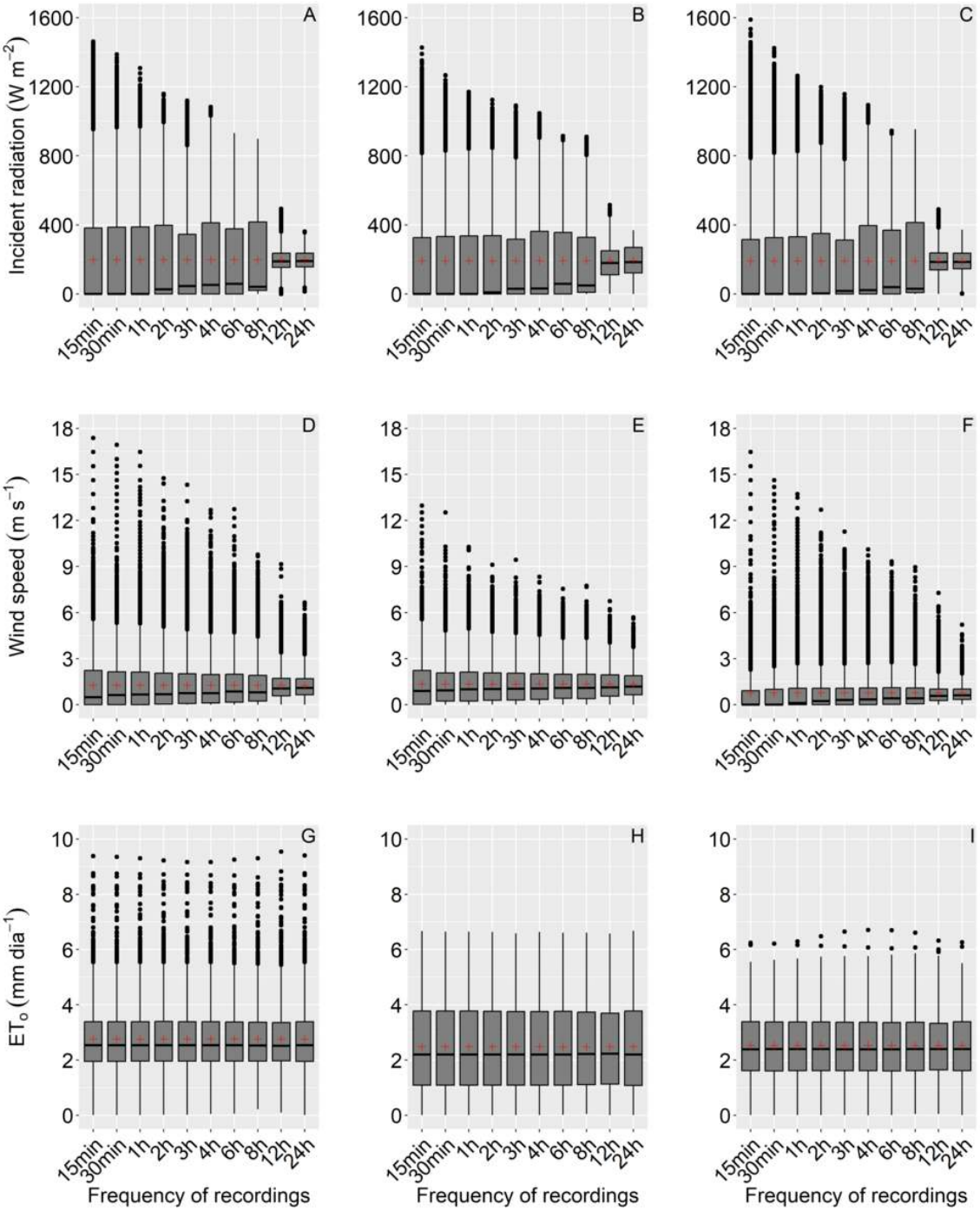
Descriptive analysis is a fundamental technique for obtaining preliminary knowledge of the distribution of a dataset in order to visually explore the information in the data series, detecting atypical behaviors and observations (Andrade *et al*., 2021; Cunha Filho *et al*., 2022). In the Cfa climate, mean temperatures were lower and more variable than in other regions, possibly due to latitude, a factor that influences the annual temperature range. In regions

further from the Equator, in southern Brazil, this range is greater than in the Central-West and Southeast regions (Varejão-Silva, 2006).

Relative humidity was higher in Cfa, with low data dispersion. Daily, this variable has an inverse relationship with air temperature, decreasing as the temperature increases. The increase in air temperature is due to the availability of energy on the soil surface, and relative humidity decreases as a function of air heating (Costa; Leal; Carmo Júnior, 2004; Radons *et al*., 2020). Annually, periods with higher relative humidity values are related to higher rainfall and/or lower air temperatures (Biscaro, 2007). The Central-West region of Brazil is characterized by a monsonic rainfall regime, with a dry period in winter and a rainy period in summer, during which there is high relative humidity, while the South region has an isohygroscopic regime with rainfall well distributed throughout the year (Buriol *et al*., 2006; Carvalho *et al*., 2022), where the highest values of relative humidity are generally concentrated in winter. This pattern can vary due to the El Niño Southern Oscillation (ENSO) phenomenon, which interferes not only with rainfall distribution but also with relative humidity, being high in southern Brazil in El Niño years and low in La Niña years (Streck et al., 2008).

Considering incident global solar radiation, the mean values were highest in climate Aw (197.5 W m^{-2}) (Figure 4A) and lowest in Cfa (191.6 W m^{-2}) (Figure 4B) and Cwa (190.2 W m^{-2}) (Figure 4C). In this case, the median values are also noteworthy; they were zero for all climatic regions at the most frequent recording intervals, indicating that approximately half of the observations corresponded to periods with no solar radiation. Regarding wind speed, the means were highest in climate type Cfa (1.3 m s^{-1}) (Figure 4E) and Aw (1.3 m s^{-1}) (Figure 4D) and lowest in Cwa (0.8 m s^{-1}) (Figure 4F). Regarding *ETo*, the mean values were higher in the Aw climate (2.8 mm day^{-1}) (Figure 4G), and lower in the Cwa (2.5 mm day^{-1}) (Figure 4H) and Cfa (2.5 mm day^{-1}) (Figure 4I) climates.

Figure 4 - Descriptive analysis of the different recording frequencies of incident global solar radiation (W m^{-2}) in the climate classifications Aw (A), Cfa (B) and Cwa (C), wind speed (m s^{-1}) in the climate classifications Aw (D), Cfa (E) and Cwa (F), and reference evapotranspiration (*ETo*, mm day^{-1}) in the climate classifications Aw (G), Cfa (H) and Cwa (I), from the date of foundation of the meteorological stations until the year 2022. *Boxplot* (5, 25, 50, 75 and 95%), mean (+) and outliers (solid circles).



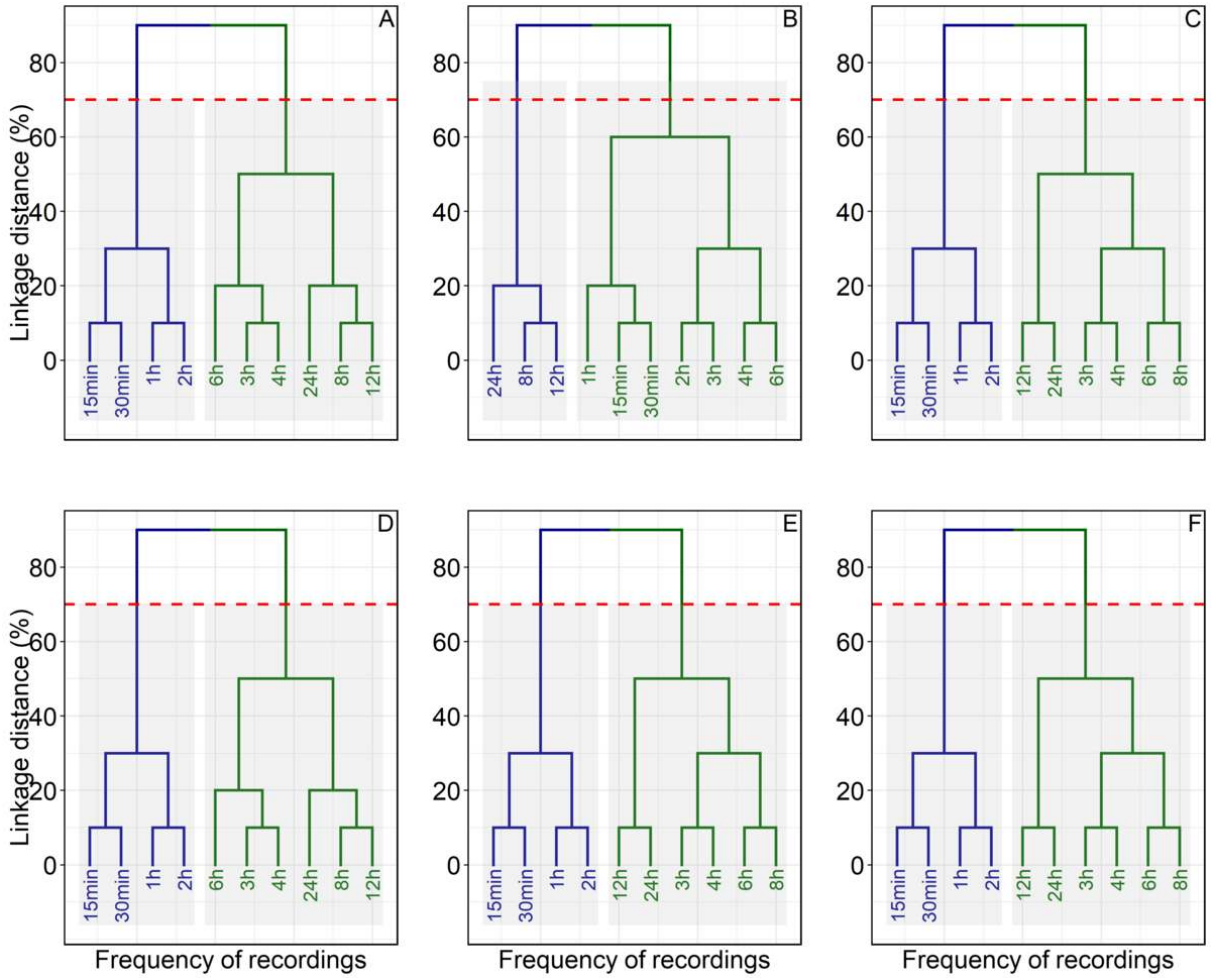
Source: Prepared by the authors (2024).

Regarding the incidence of solar radiation, it was observed that the median values were zero for the different regions and recording frequencies. During nighttime periods, the shortwave balance is zero, meaning there is no incident or reflected solar radiation from the

surface (Bergamaschi; Bergonci, 2017). Furthermore, during the day, cloud cover can impact the variability of incident solar radiation, since under cloudy conditions, it is lower compared to its intensity on clear days (Kejna; Uscka-Kowalkowska; Kejna, 2021). Annual variations can occur due to the Earth-Sun distance and the angle of incidence, which depends on latitude, solar declination, and time of day (Bergamaschi; Bergonci, 2017). Wind speed is higher during the morning and afternoon periods and lower during the night (Araújo; Lucena, 2024). In Brazil, variations can occur depending on the region and the season, generally the strongest winds are recorded at the beginning of spring and the weakest at the beginning of summer (Biscaro, 2007). Furthermore, wind speed and direction can vary due to the pressure gradient force, the Coriolis force, centripetal acceleration, and frictional force (Varejão-Silva, 2006).

Cluster analysis for all meteorological variables resulted in the formation of two groups for all climate classifications. For air temperature in climate types Aw (Figure 5A) and Cwa (Figure 5C), Group I was composed of four recording frequencies (15 min, 30 min, 1 h, and 2 h) and formed with 30% similarity, while Group II included six intervals (3 h, 4 h, 6 h, 8 h, 12 h, and 24 h) which, with 50% similarity, were grouped to form the group. The original frequency was present in the first grouping, defining a recommended minimum data collection interval of 2 hours for these climate types. On the other hand, in Cfa (Figure 5B), Group I was composed of only three recording frequencies (8 h, 12 h, and 24 h) and formed with 20% similarity, while Group II was larger and included seven intervals (15 min, 30 min, 1 h, 2 h, 3 h, 4 h, and 6 h), which clustered together at 60% to form the group. In this case, the original frequency was found in the second cluster, resulting in a minimum interval of 6 hours for data collection.

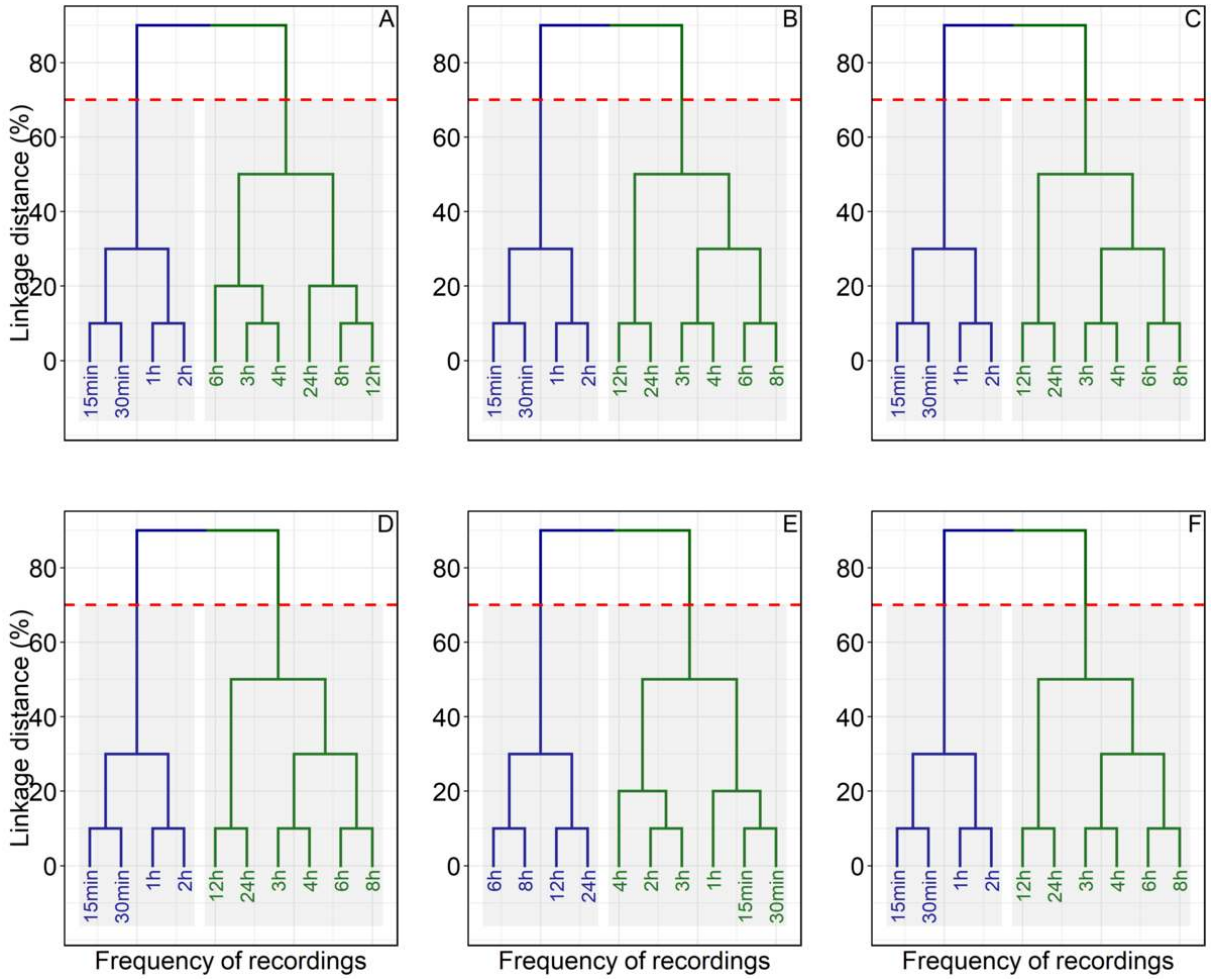
Figure 5 - Cluster analysis of the different frequencies of recording air temperature (°C) in the climate classifications Aw (A), Cfa (B) and Cwa (C), and relative humidity (%) in the climate classifications Aw (D), Cfa (E) and Cwa (F), from the date of foundation of the meteorological stations until the year 2022. Group I (blue) and Group II (green).



Source: Prepared by the authors (2024).

Regarding relative humidity (Figures 5D, 5E, 5F) and incident global solar radiation (Figures 6A, 6B, 6C), the pattern was consistent across all climate classifications, with a minimum data collection interval of 2 hours for these variables, regardless of the climate type. For wind speed, similar behavior was observed in the Aw (Figure 6D) and Cwa (Figure 6F) climates, where the minimum recording frequency was 2 hours. Conversely, in the Cfa climate (Figure 6E), the original frequency fell within intervals of up to 4 hours, which represents the recommended minimum interval for data collection.

Figure 6 - Cluster analysis of the different recording frequencies of incident global radiation (W m^{-2}) in the climate classifications Aw (A), Cfa (B) and Cwa (C), and of wind speed (m s^{-1}) in the climate classifications Aw (D), Cfa (E) and Cwa (F), from the date of foundation of the meteorological stations until the year 2022. Group I (blue) and Group II (green).



Source: Prepared by the authors (2024).

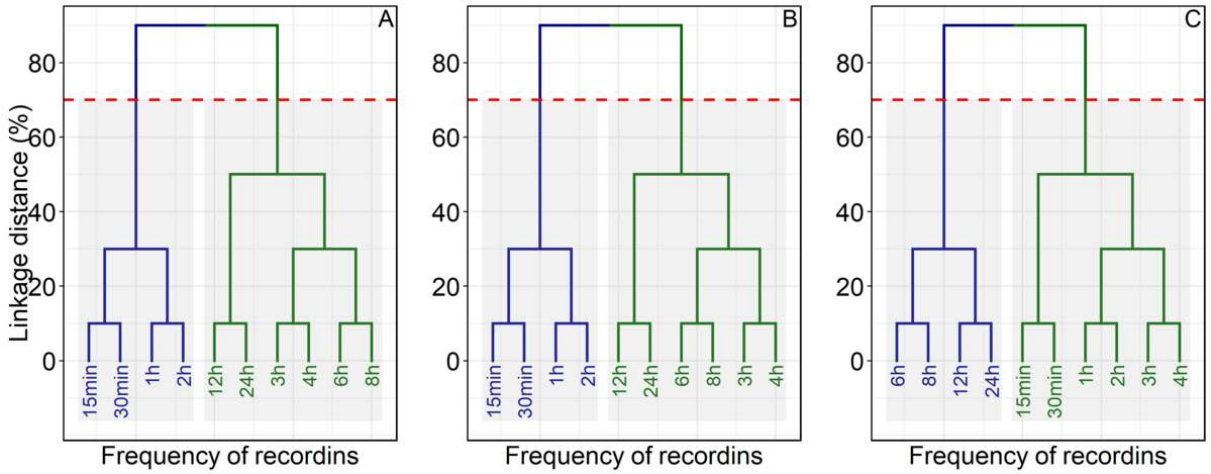
The use of inadequate temporal sampling frequency of data is one of the main sources of error, although it is rarely cited in the literature, especially due to the high variability of meteorological data in a short period of time (Hupet; Vanclooster, 2001). Lower frequencies, with few observations throughout the day or only one daily reading, are not recommended (Engers, 2023) and may compromise the representativeness of the data. The cluster analysis performed in this study showed that, when the meteorological elements were evaluated in isolation (air temperature, relative humidity, solar radiation, and wind speed), the most appropriate collection frequency was every 2 hours, with the exception of air temperature in the Cfa climate (6-hour intervals) and wind speed in the Cfa climate (4-hour intervals). This

periodicity ensures the accuracy in recording meteorological data and allows minimizing the dataset.

The relevance of these meteorological variables in estimating *ETo* is widely recognized. Periods of low relative humidity and high air temperature result in an increased vapor pressure deficit, culminating in a greater demand for water vapor from the atmosphere and contributing to increased evapotranspiration from agricultural crops (Oliveira; Silva; Oliveira, 2021). Solar radiation is considered the largest source of energy capable of transforming large quantities of water from the liquid state into water vapor (Allen *et al*., 1998). Meanwhile, high wind speeds promote the removal of the boundary air layer, resulting in less resistance to gas exchange, greater stomatal conductance, and leading to increased plant transpiration (Guimarães *et al*., 2017).

Considerando a *ETo*, nos tipos climáticos Aw (Figura 7A) e Cfa (Figura 7B), a frequência mínima de registros foi de 2 horas. Já para o clima Cwa (Figura 7C), o intervalo mínimo foi de 4 horas. A frequência mínima determinada para cada variável meteorológica não corresponde, necessariamente, à frequência mínima para a estimativa da ET_O, pois esta resulta da integração de diferentes elementos meteorológicos.

Figure 7 - Cluster analysis of the different frequencies of reference evapotranspiration recording (mm day^{-1}) in the climate classifications Aw (A), Cfa (B) and Cwa (C), from the date of foundation of the meteorological stations until the year 2022. Group I (blue) and Group II (green).



Source: Prepared by the authors (2024).

Cluster analysis was an efficient technique for determining the minimum frequency of meteorological variable records for calculating reference evapotranspiration, which is

essential for managing irrigation systems. There are few studies in the literature on this topic. The technique has already been used to determine the minimum frequency of observation of micrometeorological variables in canola cultivation. In this case, it was concluded that collections every 8 hours, i.e., only three readings throughout the day, would be sufficient. In addition to saving storage space, this technique also facilitates the handling and analysis of the data obtained, ensuring its accuracy (Engers, 2023).

This study demonstrated for the first time that the minimum frequency for recording meteorological variables obtained from weather stations, for the purpose of calculating reference evapotranspiration, is every 2 hours for climate classifications Aw and Cfa, and every 4 hours for Cwa. It became evident that a recording frequency every two hours can be recommended as a minimum and standard for all climatic regions and meteorological variables considered in this research. It is worth noting that this recording frequency provides an 87.5% reduction in the database compared to the original, since seven out of eight records would not need to be stored, generating memory savings and facilitating data management, in addition to guaranteeing the quality and accuracy of the generated data. These results are fundamental to the scientific field and can also serve as a basis to assist the business sector, especially those that provide irrigation management services to producers, based on meteorological conditions. It is also important to highlight that, for other study purposes that do not aim at estimating reference evapotranspiration, further research can be conducted to obtain precise answers.

4. CONSIDERAÇÕES FINAIS

The evaporative demand of the air is influenced by meteorological variables such as solar radiation, air temperature, relative humidity, and wind speed. The Cwa climate exhibits the highest average air temperature, whereas the Cfa climate shows the lowest average, along with greater thermal variability. Conversely, the Cfa climate records the highest average relative humidity, with lower variability. Solar radiation is highest in the Aw climate, while wind speed is highest in both the Cfa and Aw climates. Consequently, average reference evapotranspiration is also highest in the Aw climate. It is important to consider climatic diversity when determining the minimum recording frequency of meteorological variables for estimating reference evapotranspiration.

Cluster analysis proves to be an efficient approach for determining the minimum recording frequency of meteorological variables for calculating reference evapotranspiration (*ETo*). The study demonstrates that the minimum recording frequency for *ETo* calculation is a 2-hour interval for the Aw and Cfa climate classifications, and a 4-hour interval for the Cwa climate. Based on the results, adopting a two-hour recording interval across the different climatic regions and meteorological variables is recommended; this yields an 87.5% reduction in the volume of stored data compared to the original frequency. These findings are significant for the scientific community and can also serve as a basis to assist the business sector—particularly companies providing weather-based irrigation management services to producers.

A limitation of the study is that it was conducted using three weather stations representing different climate classifications, meaning it could not encompass the full climatic diversity of Brazil. Therefore, future research should be expanded to include regions with climate classifications not covered in this study. Furthermore, while the minimum data frequency for estimating reference evapotranspiration using the standard Penman-Monteith method was determined, it would also be important to identify the required frequency for applying alternative estimation methods.

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