

Comparison between meteorological data from conventional and automatic weather stations in the state of Espírito Santo, Brazil

ABSTRACT

The meteorological elements are monitored by conventional and automatic weather stations, and in recent years conventional weather stations have been replaced by automatic stations. In order for this permanent replacement to take place, it is necessary that the exposure conditions of the sensors and the methodologies used to obtain meteorological data remain standardized. Therefore, the objective of this study was to carry out a comparative study between the meteorological data from conventional and automatic weather stations in two cities, São Mateus and Vitória, located in the state of Espírito Santo. Daily meteorological data series of maximum and minimum air temperatures, average relative humidity, wind speed, rainfall and atmospheric pressure were used simultaneously from 2007 to 2016. The data between the respective stations were compared by frequency histogram, linear regression analysis, coefficient of determination, Willmott index of agreement, bias (systematic error), root mean square error, confidence coefficient and Pearson correlation coefficient. Based on the results, the best data adjustments were found for maximum and minimum air temperature and atmospheric pressure. For the other meteorological elements, there was a need for adjustment coefficients to ensure that existing historical series continues to exist and, consequently, Conventional Weather Station being replaced.

Keywords: Climate, Sustainability, Agrometeorology, Sensors, Meteorological elements

1. INTRODUCTION

While analyzing the history of extreme climatic events in Brazil, it is notable that there is decay, especially in the last three decades [1]. This is mainly due to global warming, which has affected several regions of Brazil, such as the agriculture, causing enormous economic losses and leading people to migrate to urban areas.

In the state of Espírito Santo, the agricultural sector has great socioeconomic importance, occupying an area of 2.3 million hectares with annual gross revenues of R\$ 8.4 billion in 2014 [2]. However, this sector has suffered several losses since 2014, since high temperatures and below-normal rains have caused several damages to agricultural production, even in regions with high technology in irrigation systems. This is due to the high dependence of agricultural activities on meteorological elements, making it a determining factor for agriculture. Thus, the knowledge and availability of reliable meteorological data are fundamental to quantify the impacts on crop productivity, as well as assisting in monitoring and controlling irrigation, frost prediction and pest and disease control [3, 4].

In the past, a large part of the climatic variables were obtained exclusively by conventional weather stations, but nowadays they have been replaced by sensors or automatic weather stations, due to the advances in technology, mainly in automatic meteorological data [5]. This has allowed greater advances in meteorology, such as sampling capacity, usage in difficult-to-reach places, and a faster

way to monitor atmospheric conditions, which favors the application of agricultural practices with greater efficiency [6, 5]. Although automatic stations are calibrated based on a standard station, it is very important that there is a comparison of the meteorological elements, in order to verify if they maintain good accuracy while observing the data [7]. According to Ribeiro et al. [8], replacing a conventional weather station with an automatic one, is not a simple procedure. In order to replace a conventional weather station to an automatic one, there is a need for comparative studies between the two types, therefore it will guarantee the homogeneity of the data and reliable to replace conventional stations by automatic ones, since the automatic stations are subject to greater deterioration caused by physical damage [9, 5]. Several authors have found a good agreement between the meteorological elements, when comparing the data obtained by the two stations, such as Pereira et al. [4], Oliveira et al. [10] and Ribeiro et al. [8]. However, as reported by Strassburger et al. [5], it is necessary that the adjustment coefficients are calculated independently in each region in which they are installed. In Espírito Santo research on this subject is still developing, justifying the comparative study between the two weather stations. Therefore, the objective of this study was to carry out a comparative study between the meteorological data from conventional and automatic weather stations in the cities, São Mateus and Vitória, located in the state of Espírito Santo, in order to observe if there are errors that could compromise the permanent replacement of automatic stations by conventional ones.

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54 **2. MATERIAL AND METHODS / EXPERIMENTAL DETAILS / METHODOLOGY**

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The study was carried out with the data obtained from two automatic weather stations (AWS) and two conventional weather stations (CWS) in operation, that belong to the network stations of the National Institute of Meteorology [20], located in two cities of the state of Espírito Santo. The geographic location of the stations, the coordinates, and the data collection period are shown in Figure 1 and Table 1. In the both cities, the automatic and conventional weather stations are close, reaching a distance of 3022.891 meters between the stations in São Mateus and 5198.703 meters between the stations in Vitória, being able to exclude from the comparative analysis the possible influences of where they were installed.

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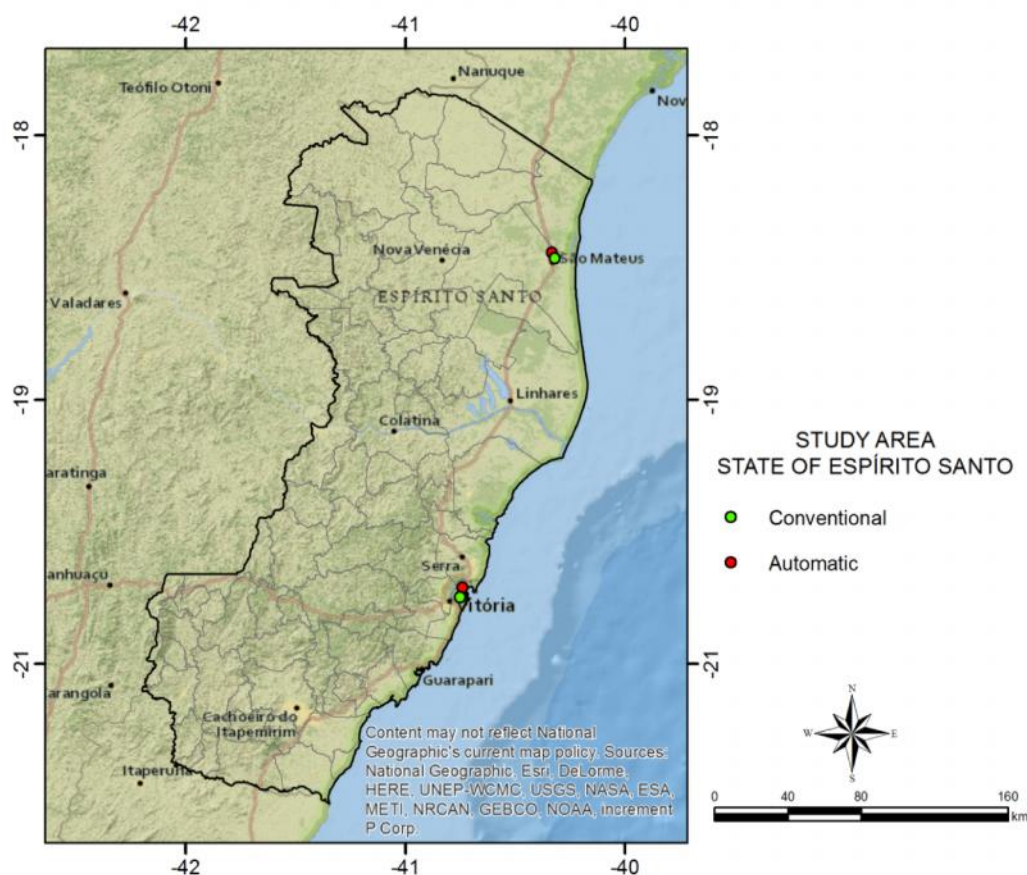


Figure 1. Map identifying the cities with the INMET automatic and conventional weather stations used in the study.

Table 1. Cities, identification of the stations, geographical coordinates and comparative analysis period of the meteorological data of the automatic and conventional stations of the state of Espírito Santo.

City	Station	Geographic Coordinates			Time (years)
	(ID) *	Lat (S)	Long (W)	Alt (m)	
São Mateus	A616	18°40'34"	39°51'50"	29.00	2007-2016
	83550	18°41'60"	39°51'00"	25.04	
Vitória	A612	20°16'15"	40°18'21"	9.00	2007-2016
	83648	20°19'00"	40°19'00"	36.20	

* Identification of the station in automatic stations network (upper line) and synoptic number of the conventional station (OMM) (bottom line).

The daily data obtained in the CWS were compared with the data obtained in the AWS referring to the maximum and minimum air temperature (°C), average relative humidity (%), rainfall (mm) and mean atmospheric pressure (hPa). The equipment used in the two stations, sensor elements, and their sensitivities and precision are presented in Table 2.

Table 2. The meteorological elements observed in the stations, as well as the sensor element, its sensitivity and manufacturer are presented in Table 2.

Station	Climate element	Sensor element	Sensibility	Maker
CWS	MaxT	Mercury	0.2°C	R Fuess
	MinT	Alcohol	0.2°C	R Fuess
	RH	Humanhair	5%	R Fuess
	Precipitation	Pluviometer	0.1 mm	R Fuess
	Atmospheric pressure	Mercury	0.1 hPa	R Fuess
AWS	MaxT	Thermistor	0.1 °C	Vaisala
	MinT	Thermistor	0.1 °C	Vaisala
	RH	Capacitor	3%	Vaisala
	Precipitation	Scale system	0.1 mm	Vaisala
	Atmospheric pressure	Capacitor	0.1 hPa	Vaisala

*MaxT: maximum air temperature; MinT: minimum air temperature; RH: relative humidity.

The collected data went through previous analysis for adequacy and to standardize the dates. This procedure standardized the dates in order to compare them. The days were removed when the data were not collected. Table 2 presents the comparison on the how they data were collected from CWS and AWS.

Table 3. Comparison of how the meteorological data were collected from the CWS and the AWS, according to INMET.

Meteorological Element	CWS	AWS
MaxT	Read 09:00 pm	>value of 24:00h
MinT	Read 9:00 am	<value of 24:00h
RHmed	$\frac{(RH^{09:00am} + RH^{max} + minU + 2 RH^{09:00pm})}{5}$	$\frac{\sum_{t=1}^{24} UR^t}{24}$
Pp n+1	Read 9:00 AM	Sum of the rain collected from 9:00am to 9:00 pm+1

$$\text{Patm} = \frac{(\text{Patm}_{9:00} + \text{Patm}_{3:00pm} + \text{Patm}_{9:00pm})}{3}$$

$$\frac{\sum \text{Patm}^*}{24}$$

*T: air temperature; RH: relative humidity; Pp: precipitation; Patm: atmospheric pressure of air; 9:00 AM; 3:00 pm and 9:00pm are the times of the data collection in conventional stations; * measurements taken every hour.*

For the comparison of the data from CWS and AWS, the linear regression analysis was done and the coefficient of determination (R^2), Willmott index of agreement (d) [11], and bias (systematic error), root mean square error (RMSE), the coefficient of confidence (c) [12] and the Pearson correlation coefficient in Table 3.

Table 4. Tests used to compare the estimates of the meteorological variables.

Statistical analysis	Equation
Pearson Correlation Coefficient	$r = \frac{\sum_{i=1}^n [(\hat{y}_i - \bar{x}_i)(y_i - \bar{y}_i)]}{\sqrt{\sum_{i=1}^n (\hat{y}_i - \bar{x}_i)^2 \sum_{i=1}^n (y_i - \bar{y}_i)^2}}$
Coefficient of Determination	$R^2 = r.r$
Willmott Index of Agreement	$d = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (\hat{y}_i - \bar{y}_i + y_i - \bar{y}_i)^2}$
Bias	$\text{Bias} = n_d^{-1} \sum_{i=1}^n (y_i - \hat{y}_i)$
Root Mean Square Error (%)	$\text{RMSE} = \sqrt{\frac{1}{n} \times \sum_{i=1}^n (\hat{y}_i - y_i)^2}$
Coefficient of confidence	$c = r * d$

In which, e represent respectively the meteorological variable in the CWS, AWS, and the means of the CWS and AWS, n is the number of observations nd is the number of data pairs.

The values of the index of performance or confidence (c) were classified according to the classification proposed by [12] (Table 4).

Table 5. Values of the coefficients of performance according to Camargo and Sentelhas [12].

Value of “c”	Performance
> 0.85	Great

0.76 a 0.85	Very good
0.66 a 0.75	Good
0.61 a 0.65	Medium
0.51 a 0.60	Tolerable
0.41 a 0.50	Bad
≤ 0.40	Terrible

The root mean square error (RMSE%) was calculated according to Loague and Green [13], being considered excellent when RMSE is less than 10%, good between 10 and 20%, acceptable between 20 and 30% and poor when higher than 30% [14]. Absolute frequency histograms were also performed in order to verify the distribution of the data between the stations.

3. RESULTS AND DISCUSSION

It is observed in Figure 2 the distribution of the maximum temperature data, in which, for the weather stations in Vitória (Figure 2 (A), (B)), it is observed that the highest frequency of the data occurred in 28-30 °C, with more than 800 days for both conventional and automatic weather stations. The CWS presented 78.8% of the data in 26-34 °C, while in this same range, the AWS presented 76.5%.

For the weather stations in São Mateus (Figure 2 (C), (D)), there was a higher frequency of data in the range of 28-30 °C, with more than 1000 observations in conventional and automatic weather stations, respectively. AWS presented a frequency of 87.2 and 56.8%, respectively, in the class range of 28-30 °C, thus showing a less homogeneous data distribution.

When the statistical values of the maximum air temperature (Table 6) were evaluated, the stations in Vitória presented a high value of the coefficient of determination, with $R^2 = 0.92$, a positive value for the Bias, indicating that the CWS overestimated the AWS by 0.48 °C. There was also a high correlation between the data, with a value of 0.96 and a RMSE error of 3.45 %, presenting low dispersion and being considered excellent.

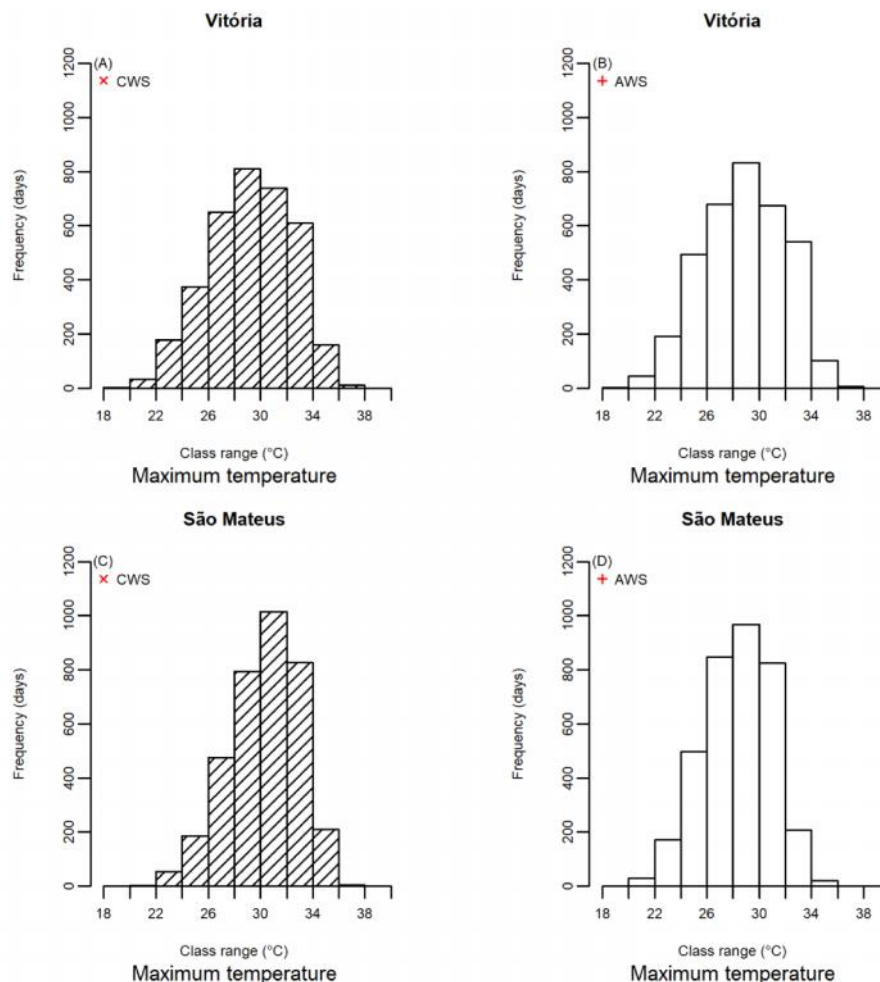


Figure 2. Absolute frequency histogram of maximum temperature data for conventional (CWS) and automatic (AWS) weather stations for the cities, Vitória (A, B) and São Mateus (C, D).

While evaluating the maximum temperature, a high index of agreement is observed among the weather stations in Vitoria, with $d=0.97$, together with an excellent index of performance. For the maximum air temperature, obtained by the stations in São Mateus (Table 6), it is noticed that although the coefficient of determination and index of agreement were below 0.90, there was a very good performance between the comparison of the stations with a correlation of 0.92, and good accuracy between the data, with RMSE below 8 %, and this difference can be explained by the different the sensors calibration. Several authors found positive results for this meteorological element, with a performance varying from good to optimal, for example, Carvalho [15] in Teresina, Piauí, Almeida and Hermenegildo in Areia, Paraíba [16] and Ribeiro, et al. [8] in Maranhão.

Table 6. Statistical indexes for the concordance analysis of the meteorological element maximum air temperature between the CWS and the AWS.

Cities	Maximum air temperature (°C)						
	R^2	d	Bias	RMSE (%)	r	c	Performance

Vitória	0.92	0.97	0.48	3.47	0.96	0.93	Good
São Mateus	0.84	0.84	1.99	7.46	0.92	0.77	Very Good

R^2 = coefficient of determination; r = Pearson's correlation; Bias = bias; RMSE = root mean square error; d = Willmott index of agreement and c = index of performance.

For the minimum air temperature (Figure 3), it is observed in the stations located in Vitória that between 18-26 °C there was an absolute frequency of 3368 days for the CWS (Figure 3 (A)), representing 94.4 % of the data, while in this same range, AWS showed 2826 days (Figure 3 (B)), that is, 79.2 % of the data. The greatest discrepancy between the data occurred between the class range of 24-26 °C, in which the AWS overestimated the CWS in 498 days. The stations located in São Mateus presented a homogeneous data distribution, and the CWS presented a frequency of 3086 days in the range of 18-26 °C (Figure 3 (C)), which represents 86.1%, while the AWS in this same class range presented a frequency of 3086 days (Figure 3 (D)), that is, 81.0% of the data.

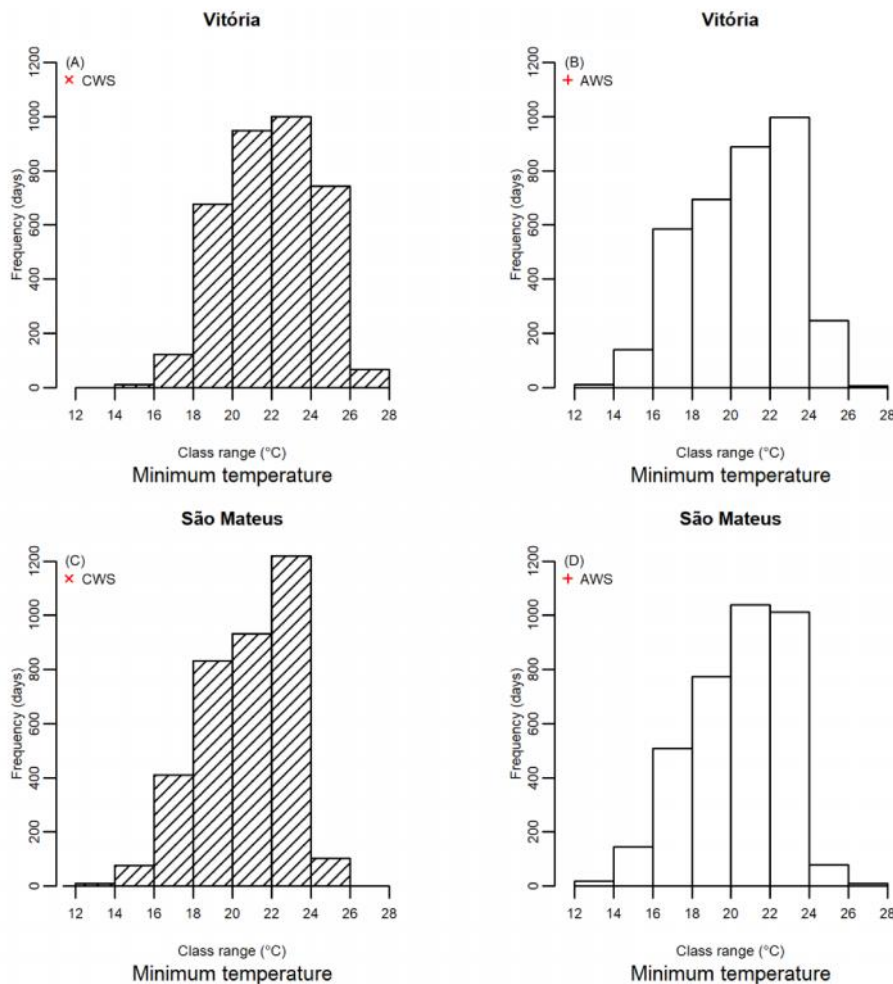


Figure 3. Absolute frequency histogram of minimum temperature data for conventional (CWS) and automatic (AWS) weather stations for the cities, Vitória (A, B) and São Mateus (C, D).

Vitória and São Mateus presented overestimated values for the CWS, as observed by the bias (Table 7). The temperatures that were overestimated in the conventional weather stations is also observed by Hermenegidio [16] in Areia, Paraíba, in which the authors state that this is due to the sensitive elements, and the same result was observed for this study.

A high correlation was observed for the minimum air temperature between the weather stations in Vitória, with a coefficient of determination $R^2 = 0.79$ and index of agreement of 0.87. Although the values of the coefficient of determination and the index of agreement for Vitória were below 0.90, the comparison of the stations obtained a very good performance and an error of 8.36 % for the RMSE.

It is also observed in Table 7 that the weather stations in São Mateus presented a high agreement between the data of minimum temperature, together with the RMSE below 5 %, that is, excellent, and with an optimum performance. The values found for the coefficient of determination and for the correlation were 0.85 and 0.92, respectively.

Table 7. Statistical indexes for the concordance analysis of the meteorological element minimum air temperature between the CWS and AWS.

Cities	Minimum air temperature (°C)						Performance
	R^2	d	Bias	RMSE (%)	r	c	
Vitória	0.79	0.87	1.41	8.36	0.89	0.77	Very Good
São Mateus	0.85	0.96	0.27	4.67	0.92	0.88	Good

R^2 = coefficient of determination; r = Pearson correlation; Bias = bias; RMSE = root mean square error; d =

Willmott index of agreement and c = index of performance.

According to Figure 4, the relative humidity presented a close distribution between the weather stations. It is observed in the weather stations located in Vitória that between the class range of 65-85 % there was an absolute frequency of 1993 days for the CWS (Figure 4 (A)), representing 84.7% of the data, whereas in this same range, AWS presented 2009 days (Figure 4 (B)), that is, 85.4 % of the data.

The CWS located in São Mateus presented a frequency of 2460 days in the class range of 65-85 % (Figure 4 (C)), which represents 81.9 %, while the AWS in that same class range presented a frequency of 2324 days (Figure 4 (D)), which represents 77.3 %. In spite of this proximity between the data distribution, it can be observed in Table 9 by the statistical indexes, that the R^2 values for Vitória and São Mateus presented values below of 0.70.

For relative humidity (table 8), a good agreement was observed in the weather stations located in Vitória, showing a correlation of 0.82 and good performance. Regarding the RMSE, a value of 5.51 % was observed, which can be classified as excellent, according to Jamieson et al. [14], and with underestimated values at -0.51 % when compared to the AWS.

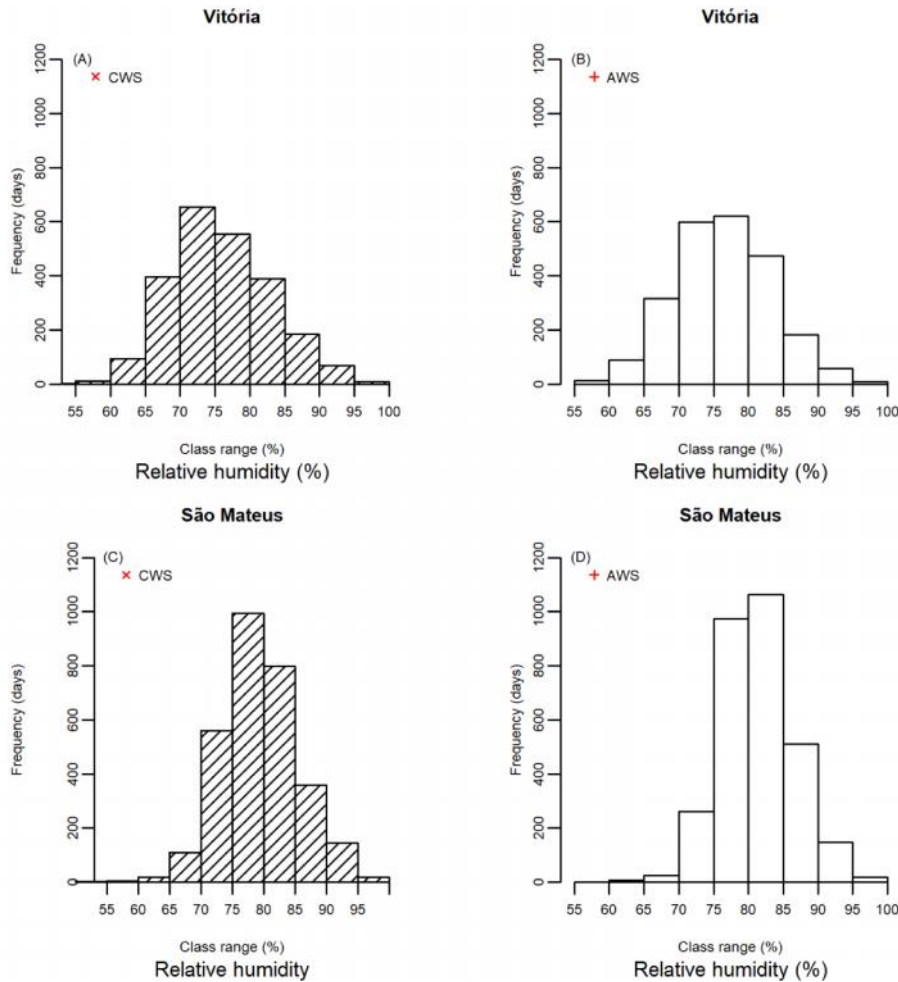


Figure 4. Absolute frequency histogram of the relative humidity data for the conventional (CWS) and automatic (AWS) weather stations for the cities, Vitória (A, B) and São Mateus (C, D).

Statistical indexes for the weather stations in São Mateus (Table 8) showed a behavior very close to the weather stations in Vitória for the relative humidity. A high agreement between the data was observed, with correlation values of 0.81, and with good performance. When the RMSE was evaluated, it had values below 5 %, that is, an error considered low, and with underestimated values for the CWS of -1.78 %. The differences observed between the CWS and AWS in Vitória and São Mateus may be due to the type of sensitive element of the instruments, which in the automatic weather station is a capacitor and in the conventional, a thermohygrograph.

Table 8. Statistical indexes for the analysis of the concordance of the meteorological element relative humidity between the CWS and AWS.

Cities	Relative humidity (%)						
	R^2	d	Bias	RMSE (%)	r	C	Performance

Vitória	0.68	0.90	-0.51	5.51	0.82	0.75	Good
São Mateus	0.66	0.87	-1.78	3.94	0.81	0.71	Good

R^2 = coefficient of determination; r = Pearsons correlation; $Bias$ = bias; $RMSE$ = root mean square error; d = Willmotts index of agreement and c = index of performance.

The atmospheric pressure data distribution is shown in Figure 5, in which there was an absolute frequency of 2697 days for the CWS (Figure 3 (A)) for the class range of 010-1020 hPa for the weather stations in Vitória (Figura 5 (A), (B)), representing 75.7 % of the data, whereas in this same range, AWS presented 2807 days (Figure 5 (B)), 78.8 % of the data. Although this class range presented close values, when the range with the highest frequency (1010-1015 hPa) was evaluated, a very large difference was observed, with AWS overestimating in this range when compared to CWS in 639 days.

For the weather stations in São Mateus (Figure 5 (C), (D)), there was a higher frequency in the range of 1010-1015 hPa, with more than 1600 observations in conventional and automatic weather stations, respectively. AWS showed a frequency of 75.1 and 76.7 %, respectively, in the class range of 1005-1010, thus showing a very homogeneous data distribution.

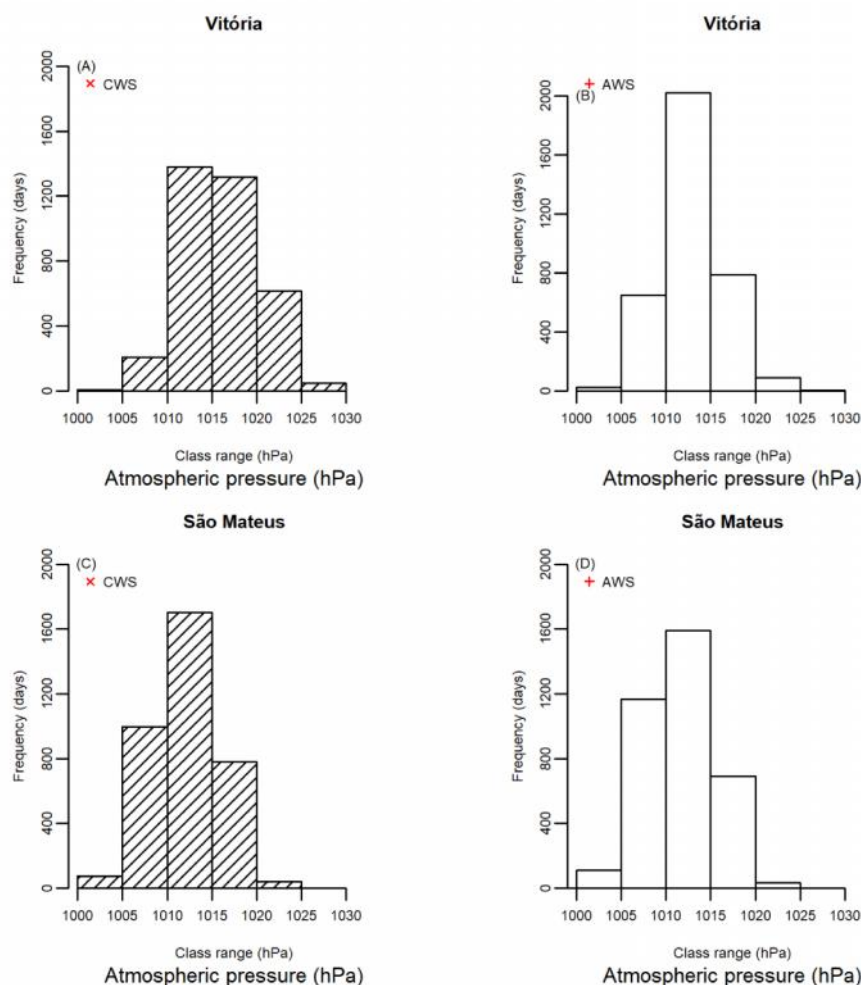


Figure 5. Absolute frequency histogram of atmospheric pressure data for conventional (CWS) and automatic weather stations (AWS) in Vitória (A, B) and São Mateus (C, D).

From the statistical indexes in Table 9, there are notable differences in the performance of the stations according to where they are located. The weather stations in Vitória had a low value in the coefficient of determination, with a value of $R^2 = 0.65$, with a positive value for the Bias, indicating that the CWS overestimated the AWS by 3.09 hPa. The index of agreement presented a value of 0.76 with correlation of 0.81, and index of performance classified as medium. This greater difference observed in the weather stations in Vitória may be due to the difference in the altitude between the two weather stations, resulting in lower values of atmospheric pressures in the AWS due to the higher air rarefaction caused by the higher altitude. In São Mateus, low dispersion of data is observed, with R^2 of 0.92 and index of agreement of 0.97. It is also observed overestimated in the conventional weather station of 0.45 hPa, and an error below 1 %. The overestimated observed in the conventional weather stations for the atmospheric pressure was also observed by Souza et al. [17], in Maringá, Paraná.

Table 9. Statistical indexes for the concordance analysis of the meteorological element atmospheric pressure between the CWS and the AWS.

Cities	Atmospheric pressure (hPa)						Performance
	R^2	d	Bias	RMSE (%)	r	c	
Vitória	0.65	0.76	3.09	0.38	0.81	0.61	Medium
São Mateus	0.92	0.97	0.45	0.12	0.96	0.93	Great

R^2 = coefficient of determination; r = Pearsons correlation; Bias = bias; RMSE = root mean square error; d = Willmotts index of agreement and c = index of performance.

The statistical coefficients for concordance analysis of the precipitation data between the two stations can be observed in Table 10. Both cities presented high errors and low dispersion of data. In Vitória an underestimation of the conventional weather stations is observed, whereas São Mateus presented overestimated values. The highest difference observed in the weather stations in Vitória and São Mateus is mainly due to the distance between the stations, being 5 and 3 km for Vitória and São Mateus respectively, which was also observed by Sanchez-Moreno et al. [18] in the Island of Santiago, Cape Verde, at nearby stations. According to Mellaart [19], rainfall presents high spatial variability even at relatively small distances (1 km), corroborating with the results found in this study.

Table 10. Statistical indexes for the concordance analysis of the meteorological element precipitation between the CWS and the AWS.

Cities	Precipitation (mm)						Performance
	R^2	d	Bias	RMSE (%)	r	C	
Vitória	0.51	0.84	-0.23	181.68	0.71	0.60	Tolerable
São Mateus	0.27	0.69	0.17	220.01	0.52	0.36	Terrible

R^2 = coefficient of determination; r = Pearsons correlation; Bias = bias; RMSE = root mean square error; d = Willmotts index of agreement and c = index of performance.

Low correlation and poor performance were observed in the weather stations in Vitória, with $c = 0.60$. While evaluating the weather stations in São Mateus, poor performance was observed, with an RMSE value of 220 %. The high RMSE values can be due to the outliers, which greatly increase the margin of error of this statistic.

4. CONCLUSION

The best data adjustments were found for maximum and minimum temperatures and atmospheric pressure, in which the atmospheric pressure is only for São Mateus.

The results were intermediate for the relative humidity, and bad for the atmospheric pressure and precipitation for the weather stations in Vitória, with greater differences between the CWS and AWS, due to the difference of the geographic position where the CWS and AWS are located.

Overestimations were observed in the conventional weather stations in all the variables, except for the relative humidity of the two cities and precipitation in Vitória.

The data analysis indicated the need for adjustment coefficients ensure that the existing historical series continues to exist and, consequently, to replace conventional weather station by the automatic weather station in São Mateus and Vitória.

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