International Journal of Astronomy and Astrophysics, 2023, 13, 236-258
https://www.scirp.org/journal/ijaa
ISSN Online: 2161-4725
ISSN Print: 2161-4717

The Role of Atmospheric Pressure, Temperature, and Humidity on Cosmic Ray Muons at a Low Latitude Station

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How to cite this paper: Maghrabi, A.H., Alzahrani, S.A. and Alruhaili, A.S. (2023) The Role of Atmospheric Pressure, Temperature, and Humidity on Cosmic Ray Muons at a Low Latitude Station. *International Journal of Astronomy and Astrophysics*, **13**, 236-258.
https://doi.org/10.4236/ijaa.2023.133014

Received: July 22, 2023
Accepted: September 11, 2023
Published: September 14, 2023

Abstract

This study aimed to investigate the relationship between atmospheric conditions and cosmic ray (CR) muons using daily and monthly CR data collected by the KAAU muon detector in Jeddah, Saudi Arabia between 2007 and 2012. Specifically, the study examined the effects of atmospheric pressure, air temperature, and relative humidity on CR muons at different time scales (annual, seasonal, and monthly). The results of the analysis revealed that atmospheric pressure and air temperature had a negative impact on CR muons, while relative humidity had a positive impact. Although air temperature and relative humidity had small mean values across all time scales, their coefficients varied significantly from month to month and season to season. In addition, the study conducted multivariable correlation analyses for each day, which showed that pressure coefficients had consistently negative mean values, while the temperature and humidity coefficients had varying effects, ranging from positive to negative values. The reasons for the variations in the coefficients are not yet fully understood, but the study proposed several possible terrestrial and extraterrestrial explanations. These findings provide important insights into the complex interactions between the Earth's atmosphere and cosmic rays, which can contribute to a better understanding of the potential impacts of cosmic rays on the Earth's climate and environment.

Keywords

Cosmic Rays, Jeddah, Atmospheric Effect, High Rigidity, Muons

1. Introduction

Galactic cosmic rays (CRs) are high-energy particles that originate from extraterrestrial sources and travel close to the speed of light. When a CR particle collides with a molecule in the Earth's atmosphere, it creates a cascade of secondary particles that diffuse laterally. The study of cosmic rays is essential in various scientific fields, including climate change, atmospheric chemistry, and human health [1]-[9]. However, to study CRs and their variations accurately, the contribution of the atmospheric effects on the secondary cosmic rays must be removed. Atmospheric pressure is the most crucial factor that affects CR muons and neutrons, while atmospheric temperature specifically affects cosmic ray muons. Correcting for atmospheric temperature is complicated and involves several methods. Different correction methods can yield different results, leading to significant implications for the interpretation of cosmic ray data [10]-[15].

To obtain the atmospheric effect on the CR flux, experimentally correlating the measured CR secondary particles with atmospheric variables over a specific period is typical. Corrections are then applied to the CR data to remove the effect of the atmospheric variable [3] [15]. However, standard statistical procedures often do not account for unusual atmospheric events like heat waves, dust storms, and pressure systems, which may affect the pattern of the considered atmospheric variable during the study period. Additionally, the interrelationship between atmospheric variables is often not considered, which may affect the correlations under investigation [16] [17] [18].

Different correction factors can lead to significant differences in the observed cosmic ray flux, with variations of up to 15% for pressure corrections, up to 10% for temperature corrections, and up to 5% for RH corrections [15]. These findings highlight the importance of carefully considering the choice of correction factor when analyzing cosmic ray data. The choice of correction method should be based on a careful evaluation of the available data, taking into account the potential sources of systematic error and variability of terrestrial and extraterrestrial conditions [19].

The main objective of this study is to investigate the effect of atmospheric pressure, temperature, and relative humidity on CR muons using six years of accumulated observations recorded by King Abdulaziz University (KAAU) muon detector.

It, also, aims to provide new insights into the variability of atmospheric conditions on CRs at high rigidity site, which have not been extensively studied in the literature.

2. Instrumentation and Methods

Cosmic ray muon data used in the study were obtained from the King Abdulaziz University (KAAU) detector for the period 2007-2012. The detector is a 1 m^2 plastic scintillator contained in a light-tight box and viewed by a photomultiplier tube (PMT). The signals from the PMT are pre-amplified, amplified, and digitized by an Analogue to Digital Converter (ADC). The detector was installed in the fourth building of KAAU's Faculty of Science main building in July 2007 and has been in operation since then, with some periods of downtime for calibration procedures, relocations, and power failure. Days with missing data exceeding 20% were removed from consideration. Detailed descriptions of the detector and calibration procedures can be found elsewhere [20].

The relationship between changes in a meteorological variable x and the intensity of CR muons can be experimentally determined using the Equation (1):

$$\frac{I_i - I_0}{I_0} = \sigma\left(x_i - x_0\right) \tag{1}$$

where I_0 is the mean muon intensity, x_0 is the mean value of the x variable during the considered time period, and σ is the coefficient of the corresponding variable, which is obtained from the fit between the measured CR rates and that variable [3].

To investigate the effects of atmospheric pressure, air temperature, and relative humidity on CR muon intensity, Equations (2)-(4) were used:

$$\frac{I - I_0}{I_0} = \alpha\left(P - P_o\right) \tag{2}$$

$$\frac{I_P - I_0}{I_0} = \beta\left(T - T_o\right) \tag{3}$$

$$\frac{I_{PT} - I_0}{I_0} = \delta\left(\mathrm{RH} - \mathrm{RH}_o\right) \tag{4}$$

The coefficients obtained from these equations are referred to as daily-based coefficients, with P_o, T_o, and RH_o representing the mean values of the three atmospheric parameters for the given day. I_P, and I_{PT} are the pressure corrected, and temperature and pressure corrected mean muon intensities. Additionally, monthly-based coefficients were obtained from hourly data for each month, with P_o, T_o, and RH_o representing the mean values of the three atmospheric parameters for the given month.

To investigate the combined effect of all three variables, multivariable correlation analyses were conducted using Equation (5):

$$\frac{I - I_0}{I_0} = \alpha\left(P - P_o\right) + \beta\left(T - T_o\right) + \delta\left(\mathrm{RH} - \mathrm{RH}_o\right) \tag{5}$$

where the coefficients (α, β, and δ) were calculated for each day. Statistical indicators, including the correlation coefficient, standard deviation, and p-values of the tests, were obtained for each correlation. Correlations with a p-value greater than or equal to 0.05 were considered non-significant and excluded from consideration. Daily and monthly values of the calculated coefficients were taken into account for further analysis, including seasonal, monthly, and annual fluctuations.

Table 1 summarizes the results of the single variable correlation analyses, showing the seasonal, annual, and total variations of the coefficients obtained for each atmospheric variable. These coefficients represent the sensitivity of cosmic ray muon intensity to changes in atmospheric pressure, air temperature, and

Table 1. Mean, Maximum, and Minimum values of α, β, and δ result from single variable correlation for the considered times. It summarizes the daily-based and monthly-based coefficients α, β, and δ, which represent the sensitivity of cosmic ray muon intensity to changes in atmospheric pressure, air temperature, and relative humidity, respectively.

		Barometric coefficient (α)				Temperature coefficient (β)				Relative humidity coefficient (δ)			
		N	Mean	Min.	Max.	N	Mean	Min.	Max.	N	Mean	Min.	Max.
ALL	Daily	1483	−0.24 ± 0.18	−0.99	0.85	1034	−0.02 ± 0.13	−0.69	0.4	846	0.08 ± 2.91	−11.16	15.77
	Monthly	66	−0.2 ± 0.11	−0.66	−0.03	51	−0.004 ± 0.1	−0.1	0.11	45	−0.014 ± 1.3	−2.33	3.2
Winter	Daily	420	−0.22 ± 0.12	−0.74	0.32	250	−0.06 ± 0.12	−0.36	0.34	188	0.63 ± 2.73	−7.39	6.35
	Monthly	17	−0.18 ± 0.07	−0.3	−0.03	14	−0.03 ± 0.04	−0.10	0.04	11	0.45 ± 1.35	−2.29	3.20
Spring	Daily	365	−0.23 ± 0.19	−0.92	0.66	269	0.04 ± 0.12	−0.40	0.33	233	−0.26 ± 2.72	−9.24	5.56
	Monthly	16	−0.17 ± 0.08	−0.36	−0.08	9	0.02 ± 0.05	−0.06	0.09	12	0.10 ± 1.12	−1.67	1.27
Summer	Daily	307	−0.26 ± 0.24	−0.99	0.58	267	0.00 ± 0.14	−0.41	0.40	197	−1.03 ± 2.76	−11.16	10.79
	Monthly	16	−0.22 ± 0.15	−0.66	−0.05	14	0.00 ± 0.06	−0.1	0.11	11	−0.75 ± 1.12	−2.26	1.78
Fall	Daily	391	−0.24 ± 0.21	−0.97	0.85	248	−0.04 ± 0.15	−0.69	0.25	228	0.78 ± 3.00	−6.57	15.77
	Monthly	17	−0.21 ± 0.13	−0.49	−0.03	14	−0.01 ± 0.05	−0.1	0.09	11	0.14 ± 1.42	−2.33	2.38
Annual	2007	229	−0.2 ± 0.15	−0.62	0.56	144	−0.02 ± 0.12	−0.37	0.34	109	−0.26 ± 2.14	−6.57	6.42
	2008	259	−0.28 ± 0.22	−0.97	0.4	197	−0.04 ± 0.14	−0.41	0.40	150	1.69 ± 2.52	−5.69	7.70
	2009	284	−0.24 ± 0.1	−0.57	0.09	194	−0.01 ± 0.11	−0.36	0.17	183	−0.42 ± 2.57	−8.96	7.15
	2010	277	−0.22 ± 0.1	−0.62	0.38	220	0.01 ± 0.11	−0.33	0.33	159	0.69 ± 2.04	−4.34	3.78
	2011	222	−0.21 ± 1.81	−0.97	0.85	152	−0.04 ± 0.15	−0.69	0.34	154	−1.29 ± 2.8	−5.36	15.77
	2012	212	−0.28 ± 0.17	−0.99	0.72	127	0.02 ± 0.17	−0.52	0.34	91	0.08 ± 4.54	−11.16	10.79

relative humidity, respectively. Table 2 presents the same information as Table 1, but with coefficients obtained for each month of the year during the study period.

3. Results and Discussion

3.1. Pressure Effect

From 1982 days during the considered period, 1483 days about ~75% of the total data showed significant correlations between CR and pressure, with 65 days ~4.4% presented positive barometric coefficients. The average barometric coefficient (α) was −0.24 ± 0.18%/hPa, the maximum is 0.85%/hPa, and the minimum is −0.99%/hPa. On the other hand, the average α value, based on monthly data, has a mean of −0.2 ± 0.11%/hPa, with a range between −0.66%/hPa and −0.03%/hPa. This suggests that using monthly data masks the positive effects of pressure.

The mean atmospheric pressure correction values obtained in this study are consistent with those reported in previous studies using muon detectors. For instance, Dmitrieva *et al.* (2013) reported a barometric coefficient of 0.18%/hPa for the URAGAN muon hodoscope [21]. The Adelaide (Rc = 3 GV) muon telescope, which is similar to the detector used in this study, had an obtained barometric coefficient of 0.13%/hPa [11]. De Mendonca *et al.* (2016) utilized data

Table 2. Same as **Table 1** but results were obtained for each month of the year.

		Barometric coefficient (α)				Temperature coefficient (β)				Relative humidity coefficient (δ)			
		N	Mean	Min.	Max.	N	Mean	Min.	Max.	N	Mean	Min.	Max.
Jan	Daily	140	−0.21 ± 0.08	−0.50	−0.08	83	−0.06 ± 0.14	−0.36	0.34	55	0.94 ± 2.7	−7.39	6.35
	Monthly	5	−0.17 ± 0.11	−0.30	−0.03	6	−0.02 ± 0.05	−0.09	0.04	3	−0.31 ± 1.75	−2.29	1.03
Feb	Daily	122	−0.19 ± 0.13	−0.64	0.32	83	−0.01 ± 0.11	−0.19	0.31	78	0.66 ± 2.54	−5.32	5.56
	Monthly	6	−0.17 ± 0.05	−0.27	−0.12	4	−0.02 ± 0.04	−0.06	0.03	3	0.34 ± 1.20	−1.04	1.10
March	Daily	137	−0.23 ± 0.13	−0.60	0.13	87	0.02 ± 0.12	−0.30	0.33	87	0.05 ± 2.61	−8.96	5.37
	Monthly	5	−0.15 ± 0.05	−0.24	−0.11	3	0.02 ± 0.04	−0.02	0.06	6	−0.26 ± 1.19	−1.67	1.00
Apr	Daily	107	−0.24 ± 0.17	−0.69	0.40	74	0.07 ± 0.10	−0.40	0.29	61	0.22 ± 2.66	−9.24	4.96
	Monthly	5	−0.18 ± 0.11	−0.36	−0.08	2	0.07 ± 0.03	0.05	0.09	3	0.56 ± 1.05	−0.64	1.27
May	Daily	121	−0.23 ± 0.27	−0.92	0.66	108	0.03 ± 0.13	−0.35	0.33	85	−0.92 ± 2.78	−7.13	5.90
	Monthly	6	−0.18 ± 0.09	−0.35	−0.12	4	0.03 ± 0.08	−0.08	0.07	3	−0.80 ± 2.23	−2.26	1.78
June	Daily	94	−0.31 ± 0.26	−0.99	0.58	102	0.03 ± 0.14	−0.24	0.40	79	−1.09 ± 3.15	−9.37	10.79
	Monthly	6	−0.17 ± 0.11	−0.36	−0.09	5	0.02 ± 0.07	−0.07	0.11	5	−0.79 ± 0.77	−1.37	0.51
July	Daily	92	−0.26 ± 0.18	−0.89	0.29	73	−0.01 ± 0.13	−0.33	0.26	63	−1.11 ± 2.2	−4.34	5.48
	Monthly	4	−0.19 ± 0.08	−0.30	−0.11	3	−0.01 ± 0.06	−0.08	0.05	3	−0.63 ± 0.25	−0.90	−0.41
Aug	Daily	121	−0.22 ± 0.17	−0.78	0.38	92	−0.05 ± 0.12	−0.41	0.33	55	−0.31 ± 3.36	−11.16	7.15
	Monthly	6	−0.29 ± 0.21	−0.66	−0.05	6	−0.01 ± 0.06	−0.09	0.07	6	0.19 ± 1.60	−1.32	2.38
Sep	Daily	116	−0.25 ± 0.25	−0.97	0.56	98	−0.02 ± 0.14	−0.52	0.24	74	0.07 ± 2.82	−4.98	7.82
	Monthly	6	−0.19 ± 0.12	−0.39	−0.10	6	−0.01 ± 0.05	−0.05	0.06	3	−0.36 ± 1.71	−2.33	0.68
Oct	Daily	131	−0.22 ± 0.22	−0.92	0.85	79	−0.03 ± 0.17	−0.69	0.25	70	0.58 ± 3.13	−5.05	15.77
	Monthly	5	−0.28 ± 0.15	−0.49	−0.09	3	0.01 ± 0.07	−0.06	0.09	2	0.71 ± 0.32	0.49	0.94
Nov	Daily	144	−0.25 ± 0.15	−0.89	0.46	71	−0.06 ± 0.12	−0.31	0.19	84	1.58 ± 2.18	−6.57	8.06
	Monthly	6	−0.19 ± 0.12	−0.39	−0.03	5	−0.03 ± 0.05	−0.10	0.04	5	0.94 ± 0.78	−1.04	3.20
Dec	Daily	158	−0.24 ± 0.12	−0.74	0.22	96	−0.09 ± 0.11	−0.33	0.25	55	0.31 ± 2.83	−5.11	6.33
	Monthly	6	−0.18 ± 0.06	−0.28	−0.11	4	−0.06 ± 0.03	−0.09	−0.03	3	0.38 ± 0.33	0.28	0.53

from the Global Muon Detector Network (GMDN) to investigate the atmospheric effects on CR muons and found that the barometric coefficient ranges from 0.17%/hPa to 0.12%/hPa [18]. Moreover, Maghrabi *et al.* (2017) utilized data from the MWPC and KACST muon detector to investigate the effect of atmospheric pressure on the CR muons detected at Riyadh, Saudi Arabia. They found a correction value of 0.135%/hPa for the MWPC and a value of 0.180%/hPa for the one m^2 detector [22]. Wang and Lee (1967) found for observations at Hong Kong (Rc =16.3 GV) by two muon cubical telescopes that $\alpha = -0.085$%/hPa [23]. These results indicate that atmospheric pressure is a significant factor affecting cosmic ray flux and that the barometric coefficient varies depending on the location, altitude, and sensitivity of the detector used.

Figure 1 illustrates the time series of daily barometric pressure coefficient (α)

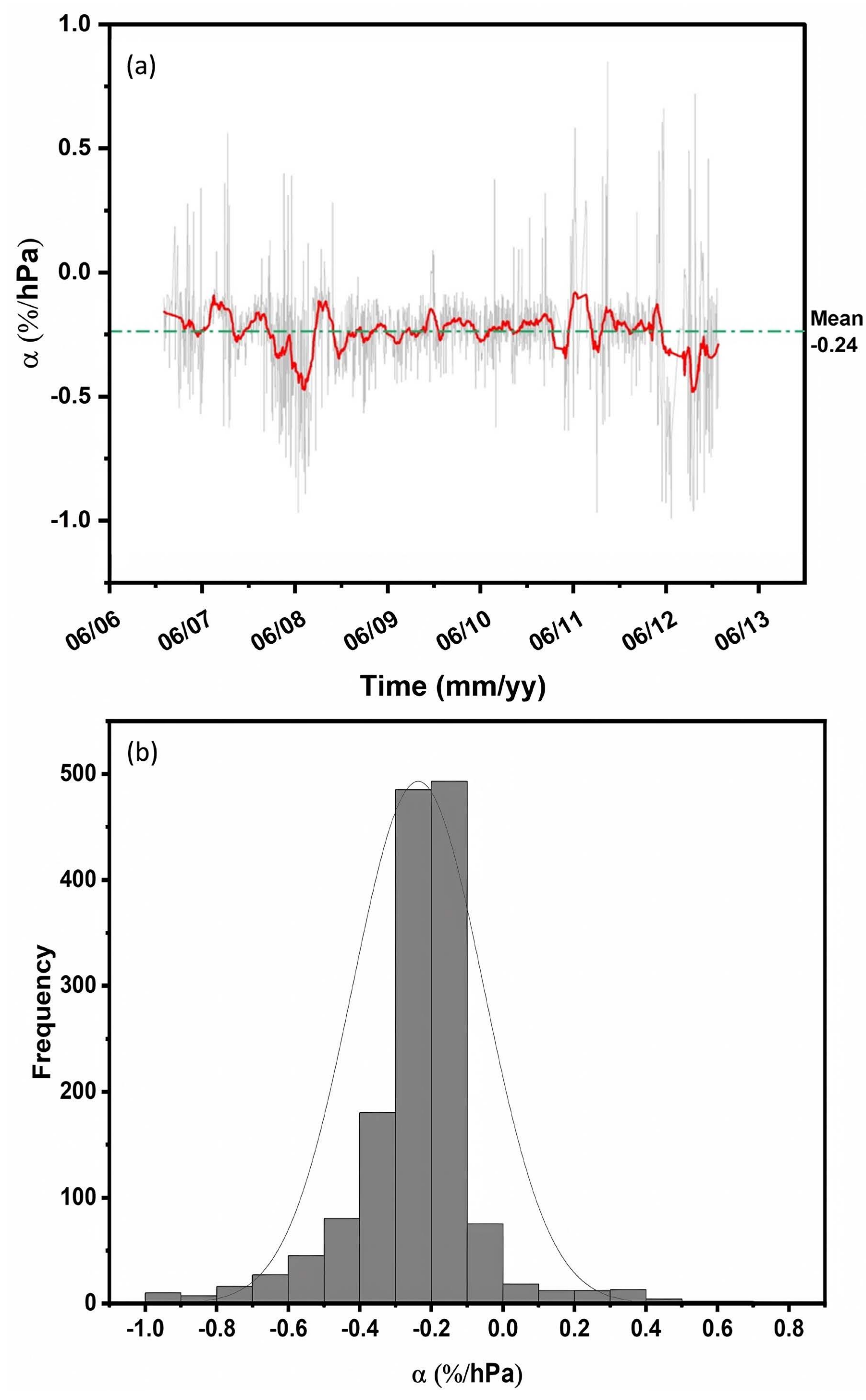

Figure 1. (a) Time series of daily barometric pressure coefficient (α) values and (b) the distribution of the daily values of α values, during the study period.

values and the distribution of the daily values of α during the study period. Figure 1(a) shows the variation of α over time, indicating a consistently negative mean value, which suggests a negative effect of atmospheric pressure on cosmic ray muons. Figure 1(b) shows the distribution of daily α values, which reveals a wide range of values and a peak around −0.21%/hPa. The distribution of daily of the pressure coefficients indicates that on some days, atmospheric pressure has a positive effect on CR.

The analysis of the daily barometric pressure coefficient (α) values highlights the variability of the atmospheric pressure effect on CR muons from day to day and emphasizes the importance of correcting for atmospheric pressure when analyzing CR data. The data show that there were approximately 478 days with a pressure coefficient of −0.42%/hPa (−1 standard deviation), while about 52% of the total data showed a pressure coefficient of −0.06%/hPa (+1 standard deviation). The number of days with these pressure coefficients differed significantly from season to season, with winter having the highest number of days with a pressure coefficient of −0.42%/hPa (250 days) and summer having the lowest number (146 days). These findings suggest that pressure coefficients are highly variable during seasons and may be influenced by other meteorological factors.

The mean values for the four seasons based on monthly values are slightly larger than those determined using hourly values. The range of α values is limited to small and negative values, whereas for those using daily means, these ranges are different in each season and cover a wider range.

Table 2 shows the variations of the barometric coefficient over the course of the year, broken down by month. Obviously, there is significant variability in the mean α values based on daily and monthly data for each month. The mean α values based on daily data ranged from −0.31 ± 0.26%/hPa in June to −0.19 ± 0.13%/hPa in February, while the mean values based on monthly data ranged from −0.29 ± 0.21%/hPa in August to −0.15 ± 0.05%/hPa in March. Furthermore, the range of α values for each month was also quite wide. For example, in January, the range of mean α values based on daily data was −0.50 to −0.08%/hPa, while the range based on monthly data was −0.30 to −0.03%/hPa. The minimum α value of −0.99%/hPa was reached in June, followed by −0.97%/hPa in September, and −0.92%/hPa in May and October. On the other hand, the daily values had maximum values of 0.85 and 0.66%/hPa for October and May, respectively. Likewise, the minimum α value for the monthly data for August is −0.66%/hPa, while the minimum values for the rest of the months range from −0.24 to −0.49%/hPa.

The smaller range of values for monthly data suggests that it can provide a more stable estimate of the barometric coefficient over longer periods of time. These variations in the mean and range of α values suggest that the effect of atmospheric pressure on CR muon flux can vary significantly even within a single month.

Figure 2 shows the distribution of α with significantly positive values for each season. There are approximately 66 days with positive α values, which indicates that on some days, the effect of pressure on CR was opposite, and/or the influence of other factors might have influenced their relationship. However, it is difficult to estimate exactly what causes these fluctuations. Fall has the highest number of days with positive α values (23 days), followed by spring with 19 days, summer and winter with 13 days, and 10 days, respectively.

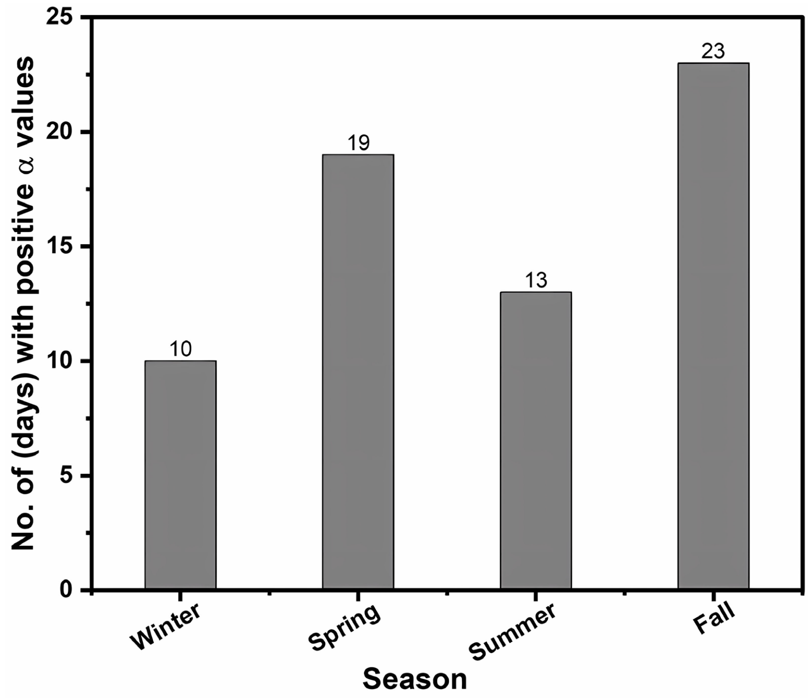

Figure 2. The distribution of *α* with significantly positive values for each season.

Figure 3 shows the effect of using different atmospheric pressure coefficients on cosmic ray data. The figure plots the raw cosmic ray data and different pressure-corrected datasets, one using the mean value of 0.2%/hPa, the other using a correction factor of +0.13%/hPa (the maximum) and the last one using a correction factor of −0.6%/hPa (the minimum), for the month of March 2007. The figure shows that all the corrected data follow the pattern of the raw data, but not using the appropriate correction factor can lead to significant differences between the raw and corrected data. Using the mean value of 0.2%/hPa, the differences between the raw and corrected data were mainly below 1% with a maximum difference of about 0.82%. However, using a correction factor of +0.13%/hPa, the differences between the raw and corrected data were lower, with maximum values reaching about 0.43%. On the other hand, when a correction factor of −0.6%/hPa used the differences between the raw and corrected data were much more noticeable, with the maximum values reaching about ~3%. This finding highlights the importance of using the appropriate correction factor when studying cosmic rays, especially for studying cosmic ray modulation.

The last six rows of Table 2 display the annual average *α* values for the number of days and months considered in each year. The mean *α* values ranged from −0.2%/hPa in 2007 to −0.28%/hPa in 2008 and 2012. In 2009, 2010, and 2011, the values were −0.24 ± 0.1%/hPa, −0.22 ± 0.1%/hPa, and −0.21 ± 0.81%/hPa, respectively. The broadest range of barometric coefficients was between −0.99 and 0.72%/hPa in 2012, followed by −0.97 and 0.85%/hPa in 2011, while values in 2009 were between −0.57 and 0.09%/hPa, and in 2010 between −0.62 and 0.38%/hPa.

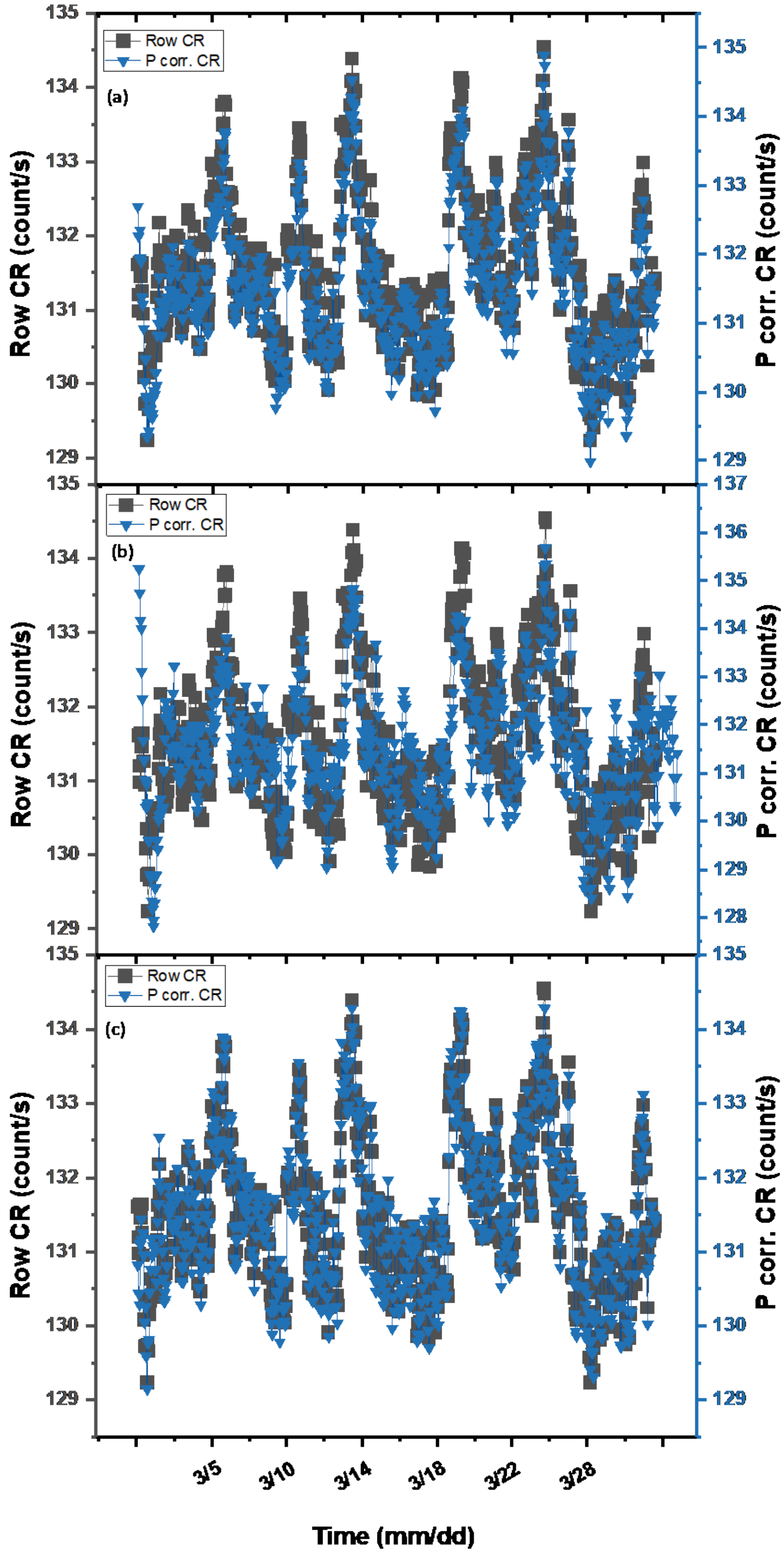

Figure 3. Time series of the hourly raw muon rate with pressure corrected rate using correction factor of (a) −0.2%/hPa ($I = -0.2$), (b) +0.13%/hPa ($I = +0.13$) and (c) −0.6%/hPa ($I = -0.6$) during March 2007.

3.2. Temperature Effect

The results of the regression analysis between pressure-corrected (I_p) CR muons and air temperature using daily and monthly data for different time categories are summarized in the middle of Table 1. Out of the 1980 days available for temperature analysis, 1034 days (52%) showed a significant correlation between CR muons and air temperature, with about 459 (44%) indicating a positive temperature effect on CR muons. The average temperature coefficient (β) did not exceed 0.1%/˚C for all time categories, although there were some days and months with a high temperature coefficient. The time series of daily significant values of the temperature coefficients are displayed in Figure 4(a) whereas their distributions are shown in Figure 4(b).

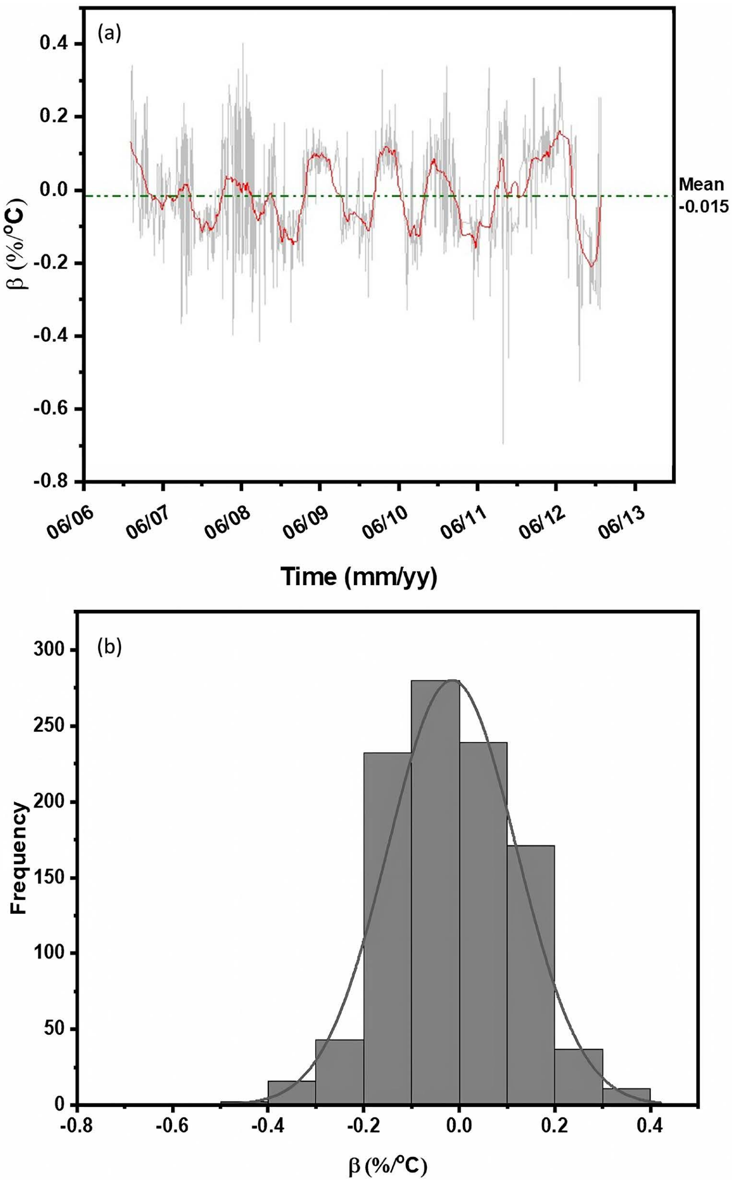

Figure 4. (a) Time series of daily β values, and (b) the distribution of the daily values of the β during the study period.

The temperature coefficient (β), using daily data, is ranging from −0.69 to 0.4%/˚C with a mean of −0.02 ± 0.13%/˚C. For the monthly data, the mean value of β is −0.004 ± 0.1%/˚C, with a maximum value of 0.11%/˚C and a minimum value of −0.1%/˚C. About 98% of the data falls between 0.2 and −0.2%/˚C.

The mean value of the temperature coefficient found in this work is comparable with those previously obtained. For instance, Maghrabi *et al.* (2016) correlated the air temperature with CR muons detected by KACST detector and found a temperature coefficient of −0.053 ± 0.0027%/˚C [24]. De Mendonca *et al.*, (2016) correlated the pressure corrected data for the GMDN and air temperature and found that the temperature coefficients for Nagoya roughly twice the value as for SMS (−0.171%/˚C and −0.088%/˚C respectively), whereas the temperature coefficients for Hobart and Kuwait were −0.128%/˚C and −0.155%/˚C respectively [18].

The analysis of daily and monthly data reveals that the range of β values differs across seasons (**Table 1**). Daily β values ranges in spring from −0.4 to 0.33%/˚C, while spring monthly data yields values between −0.06 and 0.09%/˚C. During summer, the daily and monthly values fall between −0.41 to 0.40%/˚C and −0.1 to 0.11%/˚C, respectively. In winter, both daily and monthly averages of β were negative. The daily average β was −0.06 ± 0.12%/˚C, ranging from −0.36 to 0.34%/˚C, while the monthly data had an average β of −0.03 ± 0.04%/˚C, with a maximum of 0.04%/˚C and a minimum of −0.10%/˚C. During fall, the daily average β was negatively correlated, with an average of −0.04%/˚C ± 0.15, a maximum of 0.25%/˚C, and a minimum of −0.69%/˚C, while the monthly average of β was −0.01 ± 0.05%/˚C, varying between −0.1%/˚C and 0.09%/˚C.

Figure 5 displays the distribution of positive β values. Out of the four seasons,

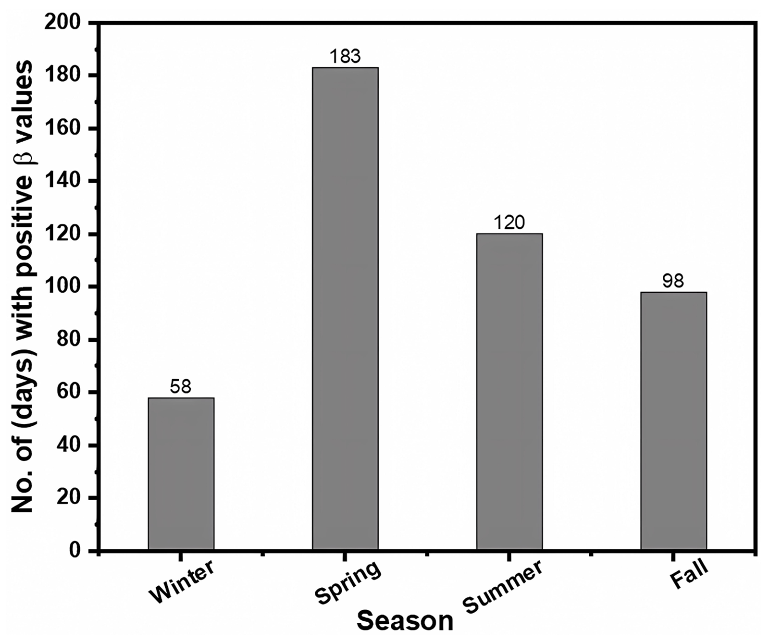

Figure 5. The distribution of temperature coefficient β, with significantly positive values for each season.

spring had the highest number of positive temperature effects on CR muons with 183 days, followed by 120 days in summer, 98 days in autumn, and 58 days in winter.

Figure 6 shows the effect of the air temperature on cosmic ray data using (a)

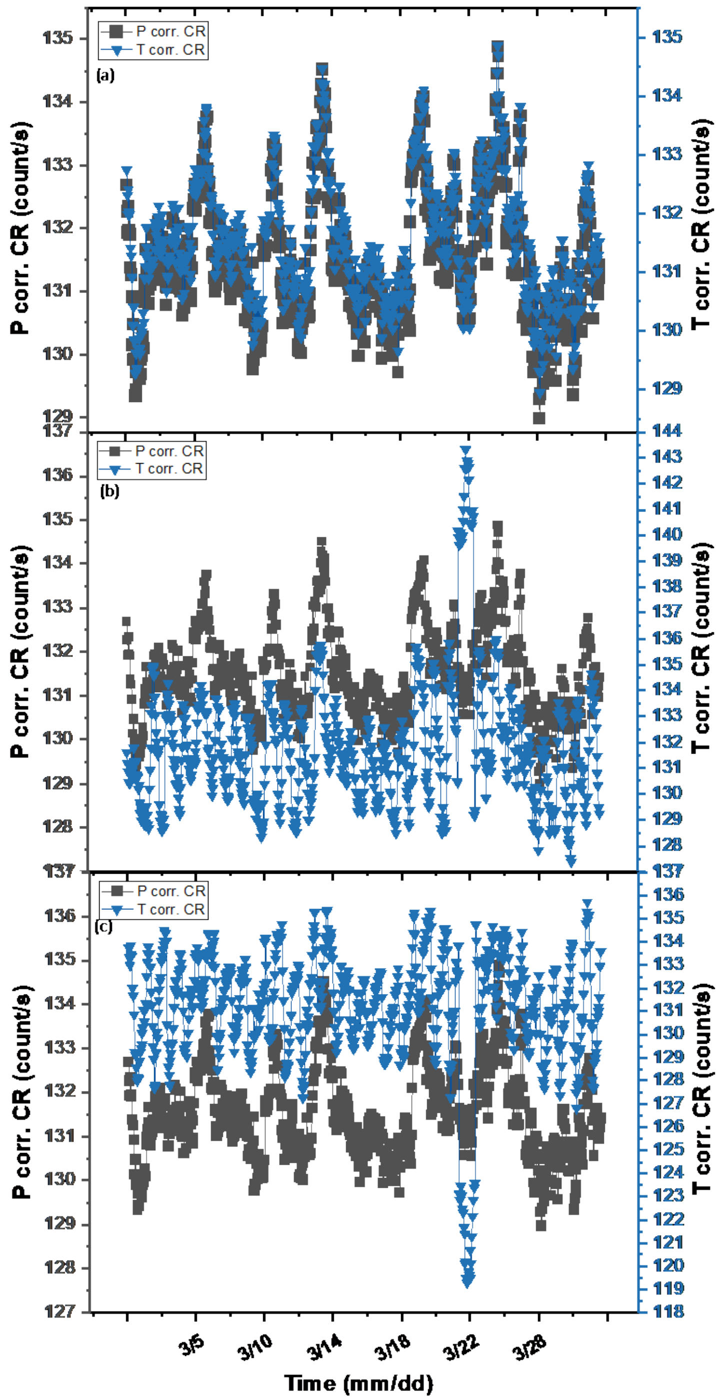

Figure 6. Time series of hourly pressure-temperature corrected muon rate using (a) −0.015%/˚C correction factor (I_T = −0.015), (b) +0.3%/˚C (I_T = +0.3) and (c) −0.3%/˚C (I_T = −0.3) for March 2007. The mean value of α = −0.21%/hPa was used as correction coefficient for the pressure effect.

temperature-corrected (I_T) with a mean value of 0.015%/˚C, (b) temperature-corrected (I_T) with a mean value of +0.3%/˚C, and (c) temperature-corrected (I_T) with a mean value of −0.3%/˚C.

By using the mean value of β = −0.015%/˚C it can be seen that the temperature-corrected data are very close to the pressure-corrected data, with differences between the two values not exceeding 0.1% in most cases. On the other hand, using the correction coefficients of β = +0.3%/˚C and β = −0.3%/˚C the maximum difference reached ~9% and ~3% respectively, indicating that the temperature can have substantial effect the cosmic ray rate at this latitude.

Table 2 displays the mean monthly values of β based on daily and monthly regressions. The mean β values for all months typically do not exceed 0.1%/˚C based on daily and monthly data, but the temperature effect varies from positive to negative in different months. Positive mean β values were observed for daily and monthly data from March to June, with an increase in CR muons corresponding to increasing temperatures. However, the monthly and daily data for July, August, November, December, January, and February showed negative β means. October is the only month that showed a mean negative β with daily data and a positive β with monthly data. The minimum β value ranged from −0.69 to −0.02%/˚C, with the highest value of 0.69%/˚C in October, followed by −0.52%/˚C in September and −0.4%/˚C in April. On the other hand, the maximum β values for all months except December ranged from −0.40%/˚C (April) to 0.04%/˚C (January). The β value for December had a maximum value of −0.03%/˚C and a minimum value of −0.09%/˚C.

The yearly variations of the temperature coefficients are displayed in Table 1. With the exception of 2010 and 2012, which showed a positive effect of temperature on CR muons, the mean values of β for the other years were negative. The mean β values for 2007, 2008, 2009, and 2011 were −0.02 ± 0.12%/˚C, −0.04 ± 0.14%/˚C, −0.01 ± 0.11%/˚C, and −0.04 ± 0.15%/˚C, respectively.

The findings presented in this section suggest that, in general, temperature has a negative effect on CR muons. However, the effect of temperature on CR muons varies greatly by season, month, and year. The standard deviations of the temperature coefficients indicate that there is a degree of variability in the data, which could be attributed to meteorological factors or instrumental uncertainties [25] [26] [27] [28]. These results provide valuable insights into the intricate relationship between the Earth's atmosphere and cosmic rays, underscoring the need for precise and comprehensive data analysis to enhance our understanding of this relationship.

3.3. Humidity Effect

In order to study the effect of relative humidity on CR muons, pressure and temperature-corrected CR muons data were correlated with relative humidity (RH). Out of the 1981 days, approximately 847 (42.7%) showed a significant correlation between RH and CR, with about 460 days (~54% of these significant days) indicating positive humidity coefficients. This means that RH at that particular location can increase the number of CR muons at a given time and do the opposite on another date. The time series of daily significant values of the humidity coefficients are displayed in Figure 7(a) whereas their distributions are shown in Figure 7(b).

The results of correlations between RH and pressure-temperature CR muons for several time categories are presented in Table 1. The mean value of the RH

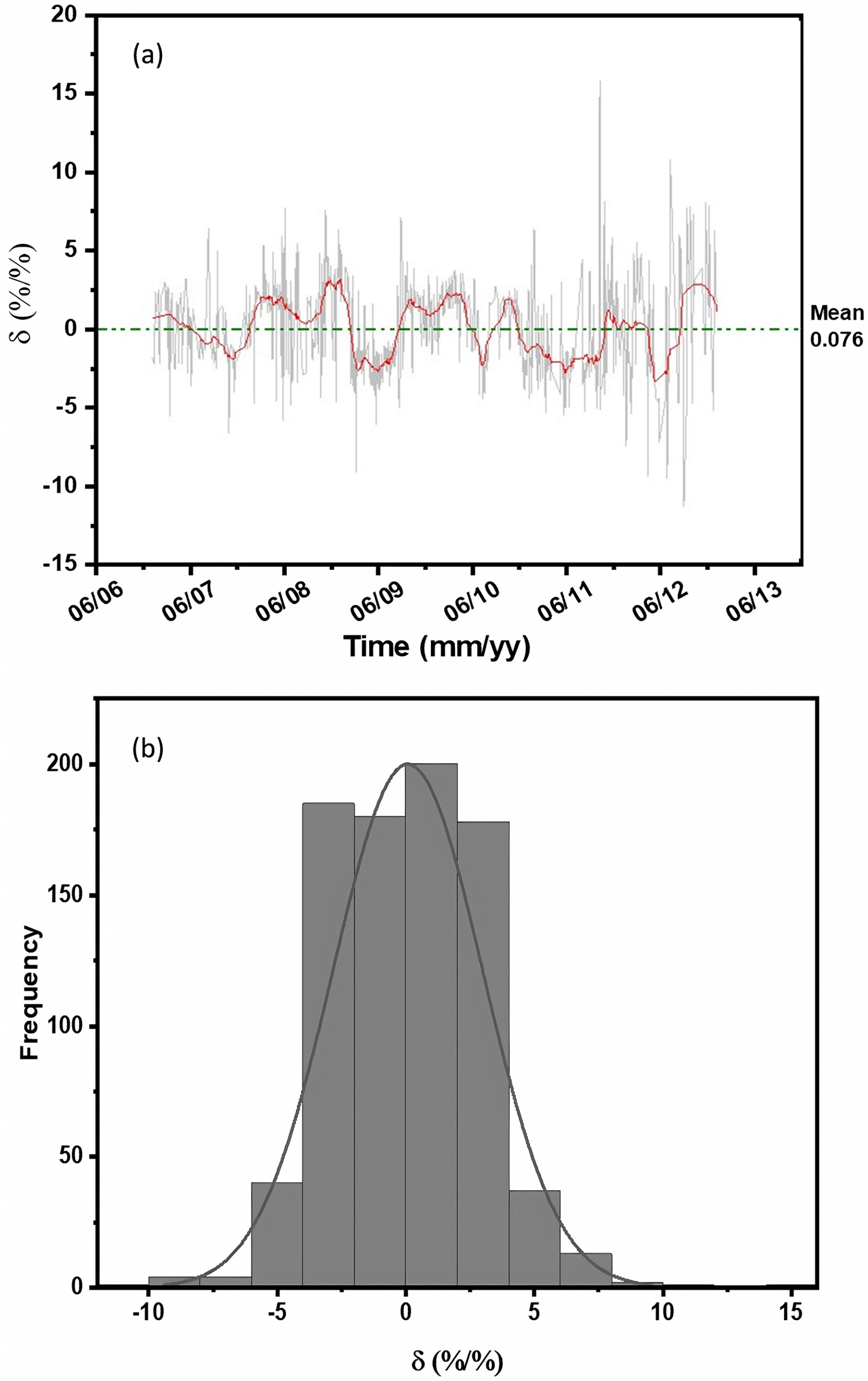

Figure 7. (a) Time series of the daily values of the relative humidity coefficients (δ) and (b) their distributions during the study period.

coefficient δ based on daily data was 0.08 ± 2.91%/% with a maximum of 15.7% and a minimum of −11.16%/%. Approximately 75% of the data falls between −2.5 and 2.5%/%, indicating a relatively narrow range of variation. Using monthly data, the average of the δ values was −0.014 ± 1.3%/%, with a range between −2.33 and 3.2%/%.

The average value of δ for the 188 days data in winter was 0.63 ± 2.73%/%, with a maximum value of 6.35%/% and a minimum value of −7.39%/%. However, using 11 data points with monthly values gives an average of 0.45 ± 1.35%/%, ranging from −2.29 to 3.20%/%. The mean spring δ using daily and monthly data was −0.26 ± 2.72 and 0.10 ± 1.12%/%, respectively. The maximum δ value based on the daily correlation was 5.56%/%, and the minimum was −9.24%/%. For monthly data, δ ranged from 1.27 to −1.67 counts /%. Summer was the only season where relative humidity had a negative effect on CR, with a mean value of −1.03 ± 2.76%/% based on 197 days of data. The maximum δ value was 10.79%/%, and the minimum was −11.16%/%. The average δ value based on summer monthly data was −0.75 ± 1.12%/%, with a range between 1.78 and −2.26%/%. In fall, using 228 days, the δ coefficient was 0.78 ± 3.00%/%, with a range between 15.77 and −6.57%/%. This accounted for the largest range of all considered times. Using monthly data, the δ mean was 0.14%/%, but the standard deviation was smaller at 1.42%/% compared to 3.00%/% using the daily value. Using monthly data, the maximum δ was 2.38%/% and the minimum was −2.33%/%.

Figure 8 illustrates the distribution of days showing the negative and positive effects of RH on CR muons for each season.

With exception of spring, clearly seen that the seasons with high positive δ values have fewer negative values. For instance, during winter, there were 116 days with positive δ values and 72 days with negative values. Additionally about 140 days, fall exhibited the most positive δ values, while 88 days showed a negative

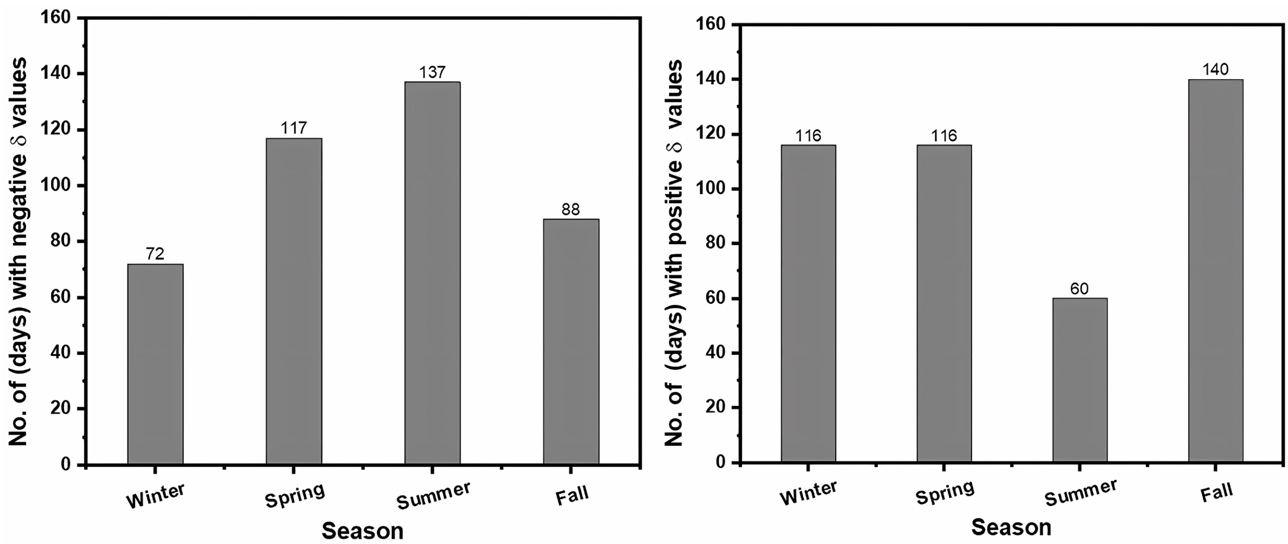

Figure 8. The distribution of days with the negative and positive δ values for each season.

effect of RH on CR muons. Conversely, summer showed the smallest delta values, with 60 days for positive values and 137 days for negative values. The number of positive and negative scores in spring was almost the same.

Based on the annual value of δ, it fluctuated greatly every year. The mean values of δ for 2007, 2009, and 2011 were −0.26 ± 2.14%/%, −0.42 ± 2.57%/%, and −1.29 ± 2.8%/%, respectively, indicating that RH had negative effects on CR muons during those years. The range of δ values in 2007 and 2009 was close, while the range in 2011 was wider. The δ values for the remaining years showed positive values, with 1.69 ± 2.52%/% in 2008, 0.69 ± 2.04%/% in 2010, and 0.08 ± 4.54%/% in 2012. The range of δ values was smaller in 2010 (between −4.34 and 3.78%/%) and wider in 2008 (between −5.69 and 7.70%/%).

Table 2 displays the mean values of humidity coefficients (δ) using daily and monthly data for each month, along with their maximum and minimum values. It can be observed that the effect of humidity on CR muons differs in magnitude and sign from month to another. The δ mean values using monthly data for October, November, December, and February were positive, ranging between 1.58 and ~0.31 ± 2.83%/%. On the other hand, the daily and monthly data values for May, June, and July showed a negative impact on CR muons. For the remaining months, the δ mean values differed between datasets. In January-March, the δ values based on daily data showed the opposite trend compared to the months when monthly data were used. The August δ mean value based on daily data was −0.31 ± 3.36%/%, while it was 0.19 ± 1.6%/% based on monthly data. It is clear that the standard deviations for all the mean values are large, which may be due to the variability of atmospheric conditions during certain months or days within the same month. The monthly maximum and minimum values fluctuate significantly. For example, the minimum and maximum δ values for August were −11.15 and 7.15%/%, respectively. The maximum δ range for daily data was between 15.77 and 5.37%/%, while for monthly data, it was less than 2.5%/%. On the other hand, the minimum values for the daily data were between −11.16 and −4.4%/%, while the minimum values for the monthly data were below −2.5%/%.

Figure 9 visualize the effect of the relative humidity on cosmic ray data using (a) humidity-corrected (I_{RH}) with a mean value of 0.05%/%, (b) humidity-corrected (I_{RH}) with a mean value of −5.37%/%, and (c) humidity-corrected (I_{RH}) with a mean value of 8.96%/%. Clearly seen that the effect of RH on cosmic ray data small when the 0.05%/% being used, with RH-corrected data being close to the pressure –temperature corrected data and the differences not exceeding 0.04% in most cases. However, using inappropriate correction factors for RH can lead to larger differences. For example, using a correction factor of δ = +5.37 and/or δ = −8.96 can result in differences up to 3% and ~5%, respectively. This indicates that the appropriate correction factor needs to be carefully considered when studying cosmic rays [3] [15].

3.4. Multivariable Correlation Analysis

Multivariable correlation analysis was conducted between CR muons and the

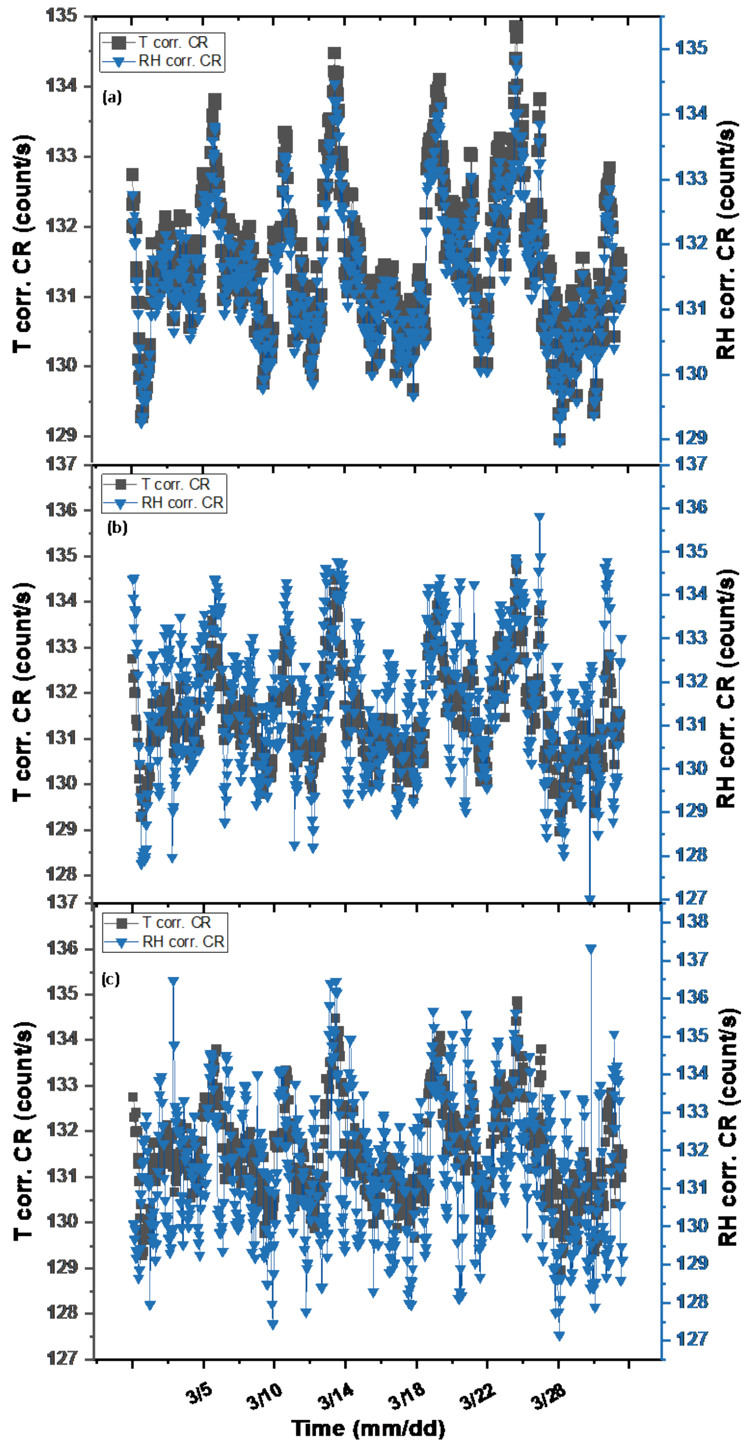

Figure 9. Time series of hourly humidity corrected muon rate using (a) +0.07%/% correction factor (I_{RH} = 0.07), (b) +5.37%/% (I_{RH} = −5.37) and (c) +8.96%/% (I_{RH} = +8.96) for March 2007. The mean values of α = −0.21%/hPa and β = −0.015%/˚C were used as correction coefficient for the pressure and temperature effects, respectively.

three considered variables (air pressure, temperature, and relative humidity) for each day. Significant results were considered, and annual, seasonal, yearly, and monthly values were calculated and presented in Table 3.

Table 3. Mean, Maximum, and Minimum values of *α*, *β*, and *δ* result from multivariable correlations between the daily values of the considered metrological variables and CR muons during the considered times.

			Barometric coefficient (*α*)			Temperature coefficient (*β*)			Relative humidity coefficient (*δ*)		
		N	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Seasons	ALL	1074	−0.33 ± 0.28	−2.06	1.65	−0.01 ± 0.17	−1.67	1.21	0.13 ± 4.05	−29.70	40.48
	Winter	324	−0.30 ± 0.16	−1.14	0.67	−0.03 ± 0.13	−0.74	0.35	0.1 ± 3.2	−16.68	13.59
	Spring	245	−0.32 ± 0.35	−1.14	1.65	−0.015 ± 0.18	−0.96	0.73	0.15 ± 3.96	−15.50	15.64
	Summer	211	−0.4 ± 0.3	−1.42	1.10	0.0014 ± 0.18	−1.10	0.54	−0.1 ± 3.85	−20.40	14.02
	Fall	294	−0.33 ± 0.30	−2.06	0.98	0.0006 ± 0.21	−1.67	1.21	0.33 ± 4.9	−29.70	40.48
Annual	2007	183	−0.28 ± 0.2	−0.97	0.86	0.01 ± 0.1	−0.43	0.31	0.50 ± 2.6	−10.94	8.54
	2008	197	−0.39 ± 0.3	−1.42	0.61	0.002 ± 0.17	−0.81	0.64	0.91 ± 4.14	−14.76	13.59
	2009	211	−0.34 ± 0.15	−0.88	0.01	−0.003 ± 0.13	−0.39	0.35	0.05 ± 2.81	−9.45	9.00
	2010	176	−0.32 ± 0.17	−0.81	0.40	−0.01 ± 0.13	−0.40	0.31	−0.44 ± 2.65	−10.18	8.75
	2011	158	−0.26 ± 0.25	−0.83	0.98	−0.02 ± 0.18	−0.44	1.21	0.12 ± 3.75	−10.02	26.04
	2012	149	−0.39 ± 0.53	−2.06	1.65	−0.02 ± 0.32	−1.67	1.20	−0.57 ± 7.18	−29.70	40.48
Monthly	Jan	104	−0.28 ± 0.17	−1.06	0.67	−0.034 ± 0.12	−0.44	0.35	0.026 ± 3.08	−7.12	13.6
	Feb	98	−0.30 ± 0.17	−0.82	0.40	−0.04 ± 0.14	−0.50	0.35	−0.4 ± 3.15	−14.76	7.54
	March	96	−0.35 ± 0.2	−0.88	0.52	−0.013 ± 0.18	−0.96	0.64	0.17 ± 3.78	−15.50	11.32
	April	71	−0.31 ± 0.32	−1.11	1.04	0.02 ± 0.16	−0.41	0.52	−0.32 ± 3.69	−11.37	8.98
	May	78	−0.28 ± 0.5	−1.14	1.65	0.05 ± 0.2	−0.52	0.73	0.59 ± 4.39	−15.07	15.64
	June	63	−0.5 ± 0.37	−1.42	0.47	0.01 ± 0.21	−0.81	0.43	0.31 ± 4.34	−11.69	14.02
	July	65	−0.41 ± 0.23	−1.16	−0.16	0.001 ± 0.12	−0.31	0.30	−0.15 ± 2.93	−7.23	8.75
	Aug	83	−0.31 ± 0.28	−1.18	1.10	−0.002 ± 0.2	−1.10	0.54	−0.34 ± 4.11	−20.40	12.17
	Sep	79	−0.34 ± 0.37	−1.36	0.86	−0.001 ± 0.3	−1.67	1.20	0.28 ± 6.99	−29.70	40.48
	Oct	100	−0.33 ± 0.37	−2.06	0.98	−0.001 ± 0.21	−0.51	1.21	−0.03 ± 4.62	−15.83	26.04
	Nov	115	−0.33 ± 0.17	−0.89	0.12	0.003 ± 0.14	−0.38	0.36	0.69 ± 3.43	−13.86	10.03
	Dec	122	−0.31 ± 0.15	−1.14	−0.12	−0.023 ± 0.13	−0.74	0.35	0.45 ± 3.36	−16.68	8.65

A total of 1074 days showed significant correlations between CR muons and all three variables. The average value of the air pressure coefficient was −0.33 ± 0.28%/hPa, with a minimum value of −2.06%/hPa and a maximum value of 1.66%/hPa. The temperature coefficient had an average of −0.01 ± 0.17%/˚C and ranged from −1.67 to 1.21%/˚C. The mean value of the positive coefficient of humidity was found to be 0.13 ± 4.05%/%, with a wide range between −29.70 and 40.5%/% which evident in (**Figure 10**).

The seasonal analysis revealed some interesting results. In winter and spring, there is a negative temperature effect and a positive humidity effect, while the average value of atmospheric pressure is −0.3%/hPa. The standard deviations of all three variables are higher in spring than in the other three seasons. In summer, the average value of pressure coefficient is the highest, which is 0.4 ± 0.3%/hPa, and small positive temperature coefficients appear in summer and autumn.

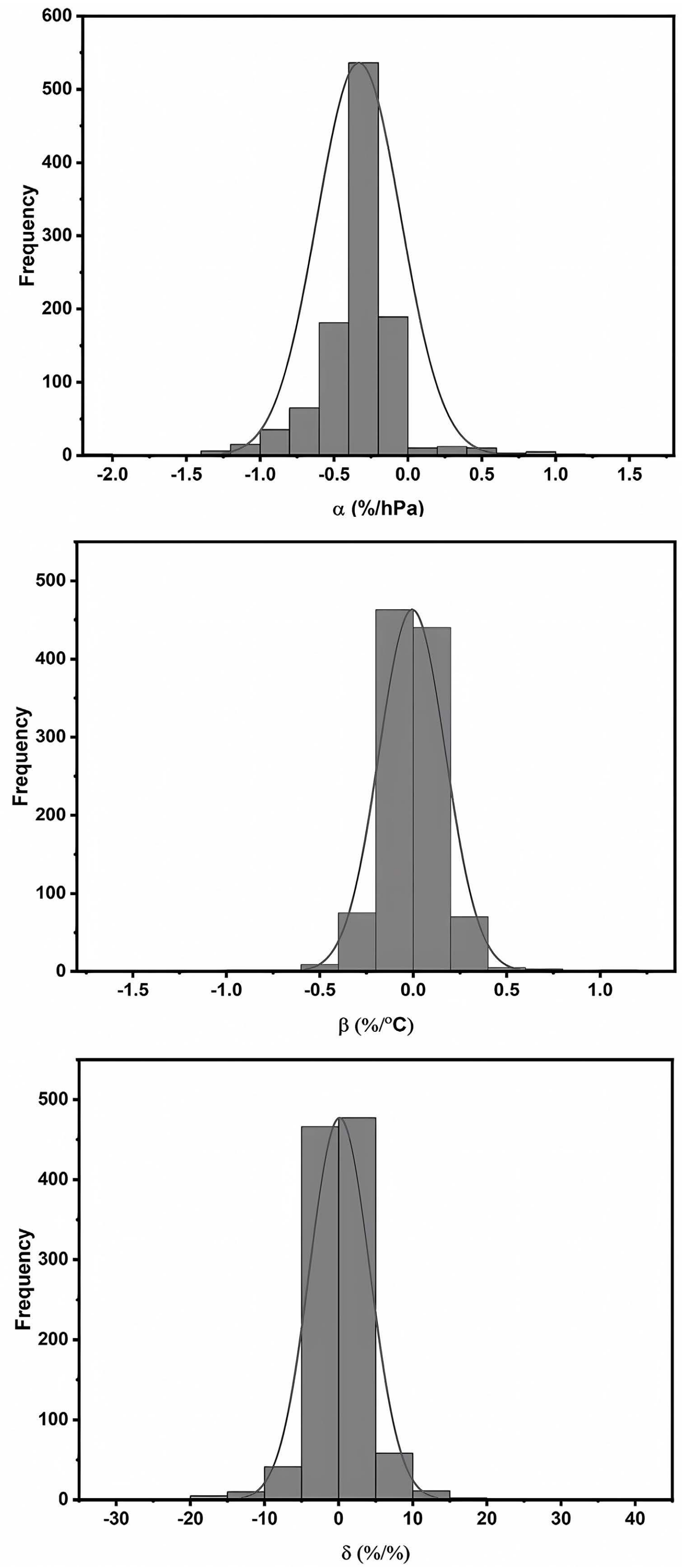

Figure 10. The distribution of the daily values α, β, and δ result from multivariable correlations.

Interestingly, the humidity coefficient in autumn is positive with an average of 0.33 ± 4.9%/% and a range between −29.7%/% and 40.48%/%. This suggests that in summer, both pressure and relative humidity have a negative effect on CR, while temperature has a negligible effect. On the other hand, RH in fall is correlated with CR and inversely correlated with barometric pressure.

It is worth noting that on some days, these results are not valid as they are determined from the calculated maximum and minimum values of the coefficients. For example, the minimum and maximum temperature coefficients range from −1.10 to 0.5%/˚C in summer and −1.67 to 1.21%/˚C in fall.

The average pressure coefficient in 2008 gradually decreased from −0.39 ± 1.5 to −0.29 ± 0.25%/hPa in 2011, and then jumped to −0.39 ± 0.53%/hPa. In 2007 and 2008, both temperature and humidity coefficients were moderately positive. Although the temperature coefficient (mean value) showed smaller values, the humidity coefficient in 2007 was 0.50 ± 2.6%/%, and the highest value obtained was 0.91 ± 4.14%/%.

The results of the multivariable coefficients for each month indicate negative values of the atmospheric pressure with a maximum of −0.5 ± 0.3%/hPa in June, followed by −0.41 ± 0.23%/hPa in July. The mean temperature and humidity coefficients in May, June, and November show positive effects on CR muons. In February, August, and October, the daily mean atmospheric variables presented negative effects on the CR muons. In January, March, September, and December, the mean β values showed a negative temperature effect and a positive relative humidity effect on CR muons. In April and July, the temperature showed a positive effect, while the RH averages showed a negative effect. The average maximum and minimum δ values for May are 0.59 ± 4.39%/%, 15.64%/%, and −15.07%/%, respectively. The results of the multivariable correlations between the three atmospheric variables and CR muons provide essential information for understanding the complex relationship between atmospheric variables and cosmic rays, which has significant implications for various scientific fields [3].

4. Conclusions

The study utilized data from the KAAU muon detector in Jeddah, Saudi Arabia, collected between 2002 and 2012, to investigate the relationship between atmospheric pressure, air temperature, relative humidity, and cosmic ray muon observations. Both single variable correlations and multivariable analyses were performed.

The results consistently showed that atmospheric pressure had a negative impact on cosmic ray muons in most cases, with relatively small to moderate variability in the barometric coefficients. Air temperature exhibited a weak negative effect on cosmic ray muons, but with significant variations observed from month to month and season to season. Relative humidity had a small mean positive effect on cosmic ray muons in daily analyses, but with large variability across different months and seasons.

Multivariable analyses indicated consistently negative mean values for the atmospheric pressure coefficients, while temperature and humidity coefficients generally had small mean values but exhibited substantial variability in their effects. The wide range of coefficients for all three variables suggested that certain factors may dominate at specific times compared to others.

Possible explanations for the variability in the coefficients were identified, including the interrelationships among the variables themselves, their associations with other meteorological factors, atmospheric water content, vertical wind distribution, air density, variations in upper air temperatures, extreme atmospheric events, extraterrestrial factors, site-specific characteristics, seasonal variations, and the solar cycle.

In conclusion, this study provides valuable insights into the effects of atmospheric pressure, air temperature, and relative humidity on cosmic ray observations. It highlights the importance of considering these factors when analyzing cosmic ray data. Further research is needed to explore the proposed explanations and gain a deeper understanding of the underlying mechanisms driving the variability in atmospheric coefficients and their impact on cosmic ray muon observations. This knowledge can contribute to improved accuracy in cosmic ray measurements and a better understanding of the interactions between cosmic rays and the Earth's atmosphere.

Acknowledgements

We would like to thank King Abdulaziz University (KAAU) for supporting this work.

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

The authors have no relevant financial or non-financial interests to disclose.

The data used in this work are belonging to KAAU and the availability of the data requires their permission.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used Grammarly in order to improve the language and readability of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and took full responsibility for the content of the publication.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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