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The Effect of Atmospheric pressure and temperature on the cosmic rays detected by KAAU muon detector

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The variability of cosmic ray (CR) fluctuations is a crucial aspect of various applications, including space weather research, atmospheric chemistry, and climate change studies. Meteorological factors, particularly atmospheric pressure and temperature, significantly influence the rate of CR detected on the ground. In this study, the effects of these factors on detected CR were investigated using data obtained from a single-channel muon detector at King Abdulaziz University (KAAU) in Jeddah, Saudi Arabia (Rc = ~14.8 GV). The results showed that atmospheric pressure and temperature are generally inversely correlated with the muon rate, although there were instances where an increase in the air temperature resulted in an increase in the number of detected CR muons. Further investigation is needed to explain such anomalies, which may involve other meteorological variables and site-specific considerations. These findings emphasize the significance of considering local meteorological variations when studying CR fluctuations.

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1. Introduction

Galactic cosmic rays (CRs) are high-energy particles that originate from extraterrestrial sources and play a crucial role in various scientific fields, including space weather, atmospheric chemistry, and climate change. To accurately study CRs and their variations, it is necessary to remove the contribution of atmospheric effects on the secondary CRs. Secondary CRs are produced when primary CRs interact with atmospheric particles, and the most critical factor affecting CR muons and neutrons is atmospheric pressure, while atmospheric temperature specifically affects cosmic ray muons[1-3].

Despite the potential advantages of theoretical calculations, empirical approaches are more commonly used due to their ease of use. Empirical corrections involve using statistical methods to relate observed cosmic ray data to atmospheric variables, such as pressure and temperature. While these corrections may not be as accurate as theoretical calculations, they can still provide valuable insights into the impact of atmospheric effects on cosmic rays. However, standard statistical procedures may not account for unusual atmospheric events or consider the interrelationship between atmospheric variables, which can affect the correlations under investigation [4-7]. This study aims to explore the impact of atmospheric pressure and air temperature on cosmic ray (CR) muons using six years of accumulated observations from the muon detector at King Abdulaziz University (KAAU), which is a high rigidity site [8]. The utilization of data from high rigidity sites such as KAAU offers significant potential to gain insights into the variations of atmospheric conditions on CRs that have not garnered much attention in previous literature.

2. Instrumentation and Methods

Cosmic ray data from the King Abdulaziz University (KAAU) muon detector for the period 2007-2012 were utilized for the purpose of this study. The detector is a 1 m^2 plastic scintillator viewed by a photomultiplier tube (PMT) and contained in a light-tight box. The PMT signals are pre-amplified, amplified, and digitized by an Analogue to Digital Converter (ADC) [9]. The detector has been in operation since July 2007, 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.

The rate of the cosmic ray muons due to changes in a meteorological variable x, can be determined experimentally by:

$$\frac{I_i - I_0}{I_0} = \sigma(x_i - x_0) \qquad (1)$$

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 muon rates and that variable.

The barometric coefficient (α) was calculated by fitting the experimental data of cosmic rays (CRs) and atmospheric pressure for each month using equation (1). The obtained pressure coefficient was then used to eliminate the effect of atmospheric pressure from the measured data. The pressure-corrected muon data were then analyzed for correlation with air temperature, and the temperature correction factor was determined. In this case, the Ii in equation (1) represents the pressure-corrected CR data, and the temperature coefficient is β, which was used to remove the effect of temperature from the muon rates [5-9]. Correlations with a p-value greater than or equal to 0.05 were considered non-significant and excluded from consideration. The monthly coefficients were used for further analysis of seasonal, monthly, and annual fluctuations.Table 1 summarizes the results of the correlation analyses, showing the seasonal, annual, and total variations of the coefficients obtained for each atmospheric variable. Table 2 presents the same information as Table 1, but with coefficients obtained for each month of the year during the study period.

Table 1, Mean, Maximum, and Minimum values of α (barometric coefficient) and β (temperature coefficient) result from correlation between the monthly mean CR muons and atmospheric pressure and air temperature, respectively during the study period .

	Barometric coefficient (α) [%/hPa]			Temperature coefficient (β) [%/ºC]		
	Mean	Min.	Max.	Mean	Min.	Max.
All	-0.2±0.11	-0.66	-0.03	-0.004±0.1	-0.1	0.11
Winter	-0.18±0.07	-0.3	-0.03	-0.03±0.04	-0.10	0.04
Spring	-0.17±0.08	-0.36	-0.08	0.02±0.05	-0.06	0.09
Summer	-0.22±0.15	-0.66	-0.05	0.001±0.06	-0.1	0.11
Fall	-0.21±0.13	-0.49	-0.03	-0.01±0.05	-0.1	0.09

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

	Barometric coefficient (α) [%/hPa]			Temperature coefficient (β) [%/ºC]		
	Mean	Min.	Max.	Mean	Min.	Max.
January	-0.17±0.11	-0.30	-0.03	-0.02±0.05	-0.09	0.04
February	-0.17±0.05	-0.27	-0.12	-0.02±0.04	-0.06	0.03
March	-0.15±0.05	-0.24	-0.11	0.02±0.04	-0.02	0.06
April	-0.18±0.11	-0.36	-0.08	0.07±0.03	0.05	0.09
May	-0.18±0.09	-0.35	-0.12	0.03±0.08	-0.08	0.07
June	-0.17±0.11	-0.36	-0.09	0.02±0.07	-0.07	0.11
July	-0.19±0.08	-0.30	-0.11	-0.01±0.06	-0.08	0.05
August	-0.29±0.21	-0.66	-0.05	-0.01±0.06	-0.09	0.07
September	-0.19±0.12	-0.39	-0.10	-0.01±0.05	-0.05	0.06
October	-0.28±0.15	-0.49	-0.09	0.01±0.07	-0.06	0.09
November	-0.19±0.12	-0.39	-0.03	-0.03±0.05	-0.10	0.04
December	-0.18±0.06	-0.28	-0.11	-0.06±0.03	-0.09	-0.03

3. Results and Discussion

3.1 Pressure Effect

Figure 1 is an example visualizes the relationship between the hourly values of the atmospheric pressure and the CR muons recorded during November 2007. The results of the barometric coefficient (α) analysis (Table 1) indicate a negative correlation between atmospheric pressure and CR muons. The mean value of α for all the data was found to be -0.2±0.11%/hPa and ranges between -0.66 and -0.03 %/hPa.

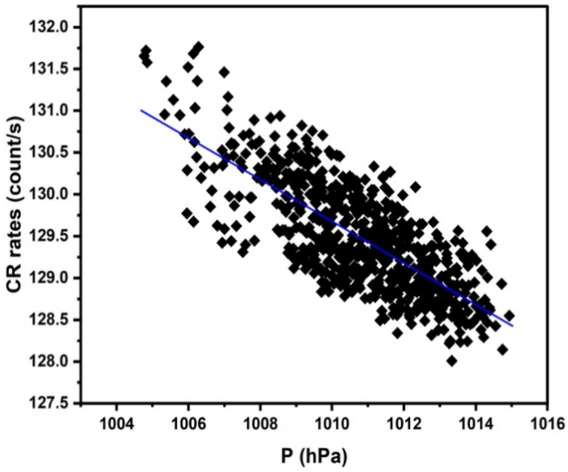

Figure 1. Scatter plot of the hourly values of atmospheric pressure and cosmic ray rates recorded by KAAU muon detector during November 2007. The straight dashed line is the best linear fit to the data.

The seasonal variations in the barometric coefficient also suggest that the influence of atmospheric pressure on the CR muon rate may vary depending on the season.

The highest value of α was found in summer (-0.22±0.15 %/hPa) and fall (-0.21±0.13 %/hPa), while the lowest value was found in spring (-0.17±0.08 %/hPa) and winter (-0.18±0.07 %/hPa). These results suggest that atmospheric pressure has a stronger influence on the CR muon rate in summer and fall compared to spring and winter.

The results presented here are in agreement with previous studies that have shown a consistent negative correlation between atmospheric pressure and cosmic ray muon intensity [e.g., 2-12].

For instance, Dmitrieva et al. [10] reported a barometric coefficient of 0.18 %/hPa for the URAGAN muon hodoscope. 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 [2]. De Mendonca et al. [4] utilized data 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. Moreover, Maghrabi et al. [9] 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 m2 detector. Wang and Lee [12] found for observations at Hong Kong (Rc =16.3 GV) by two muon cubical telescopes that α=-0.085 %/hPa [12].

Table (2) presents the results of the correlation analyses, showing the variations of the barometric coefficients obtained for each month. The mean values of the barometric coefficient (α) range from -0.15 to -0.29 %/hPa, indicating a consistent negative effect of atmospheric pressure on CR muon intensity across all months of the year. The strongest negative effect of atmospheric pressure is observed in August and October, where the mean values of the barometric coefficient are -0.29 %/hPa and -0.28 %/hPa, respectively. The weakest negative effect of atmospheric pressure is observed in March, where the mean value of the barometric coefficient is -0.15 %/hPa. The table also shows that the range of the barometric coefficient varies across different months of the year, with minimum values ranging from -0.66 to -0.03 %/hPa and maximum values ranging from -0.05 to -0.49. These variations suggest that the effect of atmospheric pressure on cosmic ray muon intensity is not constant throughout the year and must be considered when interpreting cosmic ray data.

Figure 2 shows the impact of different atmospheric pressure coefficients on the cosmic ray data. The graph compares the raw CR data with two different pressure-corrected datasets for the month of December 2007: one using the mean value of 0.2 %/hPa, and another using a correction factor of -0.6 %/hPa (the minimum value).

The figure highlights that all of the corrected data using the correct atmospheric pressure coefficient follow the pattern of the raw data, indicating that the correction process is effective in removing the effect of atmospheric pressure on the CR data. However, when an incorrect correction factor is used, such as -0.6 %/hPa, the differences between the raw and corrected data become more noticeable, with maximum values reaching about ~3%. This finding underscores the importance of using the appropriate correction factor when studying cosmic rays, particularly when studying cosmic ray modulation.

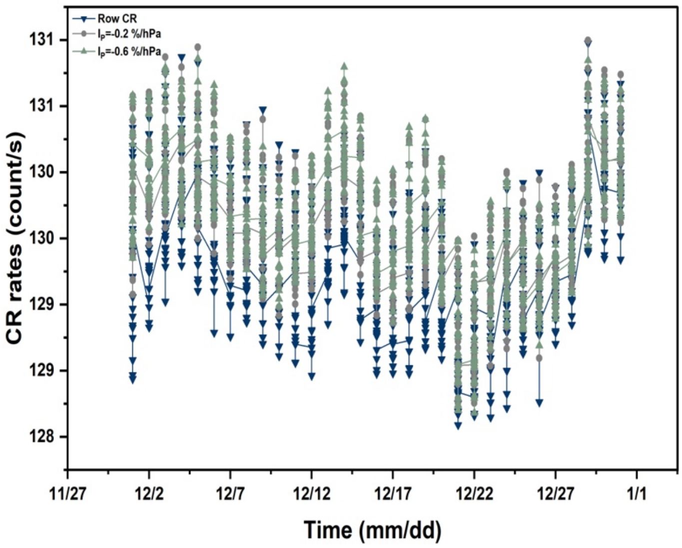

Figure 2. Time series of the hourly raw muon rate with pressure corrected rate using correction factor of -0.2 %/hPa (I_p = -0.2) and -0.6 %/hPa (I_p =-0.6) during December 2007.

3.2 Temperature Effect

Figure 3.a and 3.b provide visualizations of the relationship between air temperature and CR muons recorded during April and September 2010, respectively. In Figure 3.a, a negative relationship is observed between CR muon rate and air temperature, with the rate of CR muons decreasing as temperature increases. This is due to the inverse relationship between atmospheric density and temperature, where increasing temperature leads to a reduction in atmospheric density. As a result, muons produced at higher altitudes have to travel a longer distance to reach the detector, leading to a higher probability of decay and a lower CR muon rate. In contrast, Figure 3.b shows a positive relationship between CR muon rate and air temperature, which is contrary to previously established experimental results. The reason for this discrepancy is unclear, but possible explanations include high cutoff rigidity, unusual meteorological, environmental, or atmospheric changes, or the occurrence of temperature inversions.

Table 1 summarizes the results of the regression analysis between pressure-corrected CR muons and air temperature data for different time categories. For the entire study period, the mean value of the temperature coefficient (β) was found to be -0.004±0.1 %/°C, with a minimum and maximum value of -0.1 %/°C and 0.11 %/°C, respectively. These results suggest that the overall effect of temperature on CR muons at this site is small and not as significant as atmospheric pressure.

The mean value of the temperature coefficient (β) in summer was 0.001±0.06 %/°C, with a maximum of

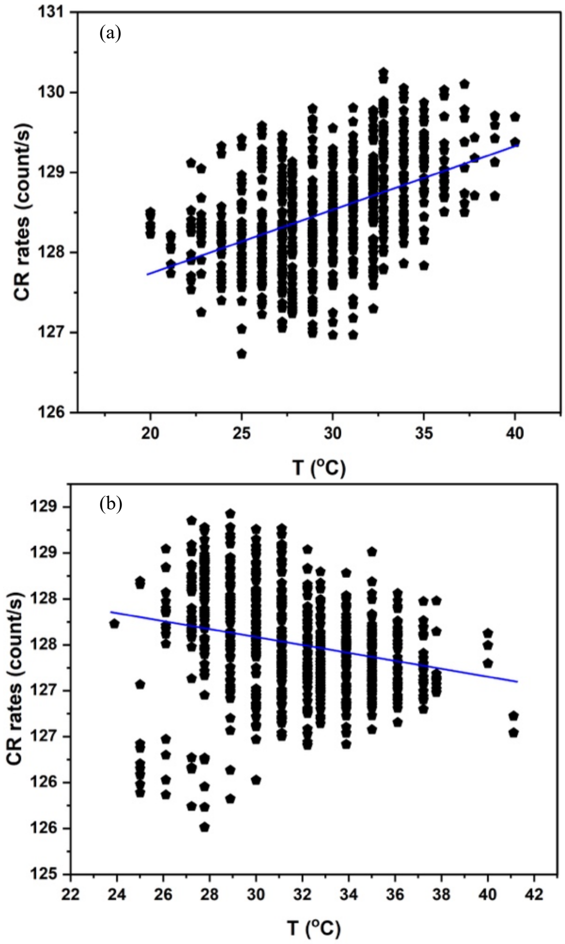

Figure 3. Scatter plot between the hourly values of air temperature and the pressure corrected muon count rate for (a) April and (b) September 2010.

0.11 %/°C and a minimum of -0.01 %/°C. In contrast, the minimum mean values of the temperature coefficient (β) were observed in winter and fall, with mean coefficients of -0.03±0.04 %/°C and -0.01±0.05 %/°C, respectively. The temperature coefficient calculated for this site is somewhat smaller than those reported at other locations, which may be due to the high rigidity of the KAAU detector's location. However, the mean value of the temperature coefficient found in this work is comparable to those previously obtained. For instance, Maghrabi et al. [11] correlated air temperature with CR muons detected by the KACST detector located in Riyadh and found a temperature coefficient of -0.053±0.0027 %/°C.

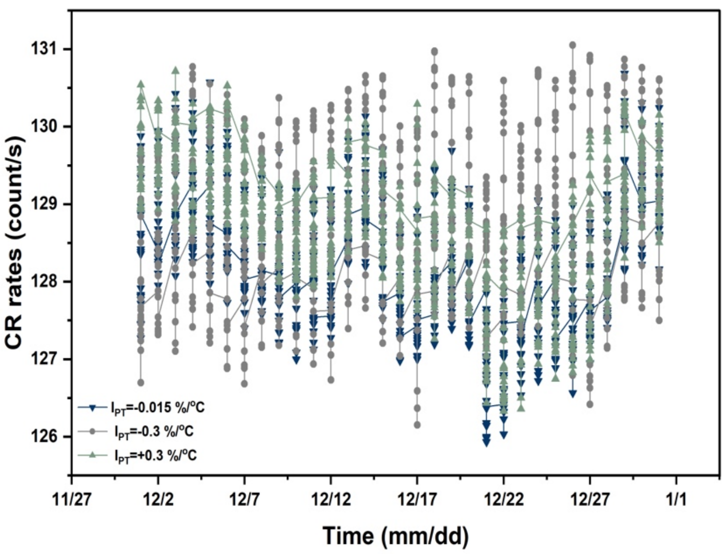

Figure 4. Time series of hourly pressure-temperature corrected muon rate using -0.015 %/°C correction factor (I_{PT} =-0.015), +0.3 %/°C (I_{PT} =+0.3) and -0.3 %/°C (I_{PT} =-0.3) for December 2007.The mean value of α = -0.21 %/hPa was used as correction coefficient.

Table 2 presents the results of the correlation analyses, showing the variations of the temperature coefficients (β) obtained for each month. The mean values of the temperature coefficient (β) range from -0.06 to 0.03 %/°C. The weakest effect of air temperature is observed in October, where the mean value of the temperature coefficient is -0.28 %/°C. The range of the temperature coefficient (β) varies across different months of the year, with minimum values ranging from -0.10 to -0.03 %/°C and maximum values ranging from 0.03 to 0.09 %/°C. These variations suggest that the effect of air temperature on cosmic ray muon intensity is not constant throughout the year and must be considered when interpreting cosmic ray data.

Figure 4 shows the effect of the air temperature on cosmic ray data using the temperature-corrected (I_T) with a mean value of 0.015 %/°C, the temperature-corrected (I_T) with a mean value of +0.3 %/°C, and the 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.

4. Conclusion

The study aimed to investigate the influence of atmospheric pressure and air temperature on cosmic ray muons using data obtained from the KAUU muon detector between 2007 and 2012. The results revealed an anti-correlation between pressure and temperature with muon rates, with small coefficients obtained for temperature that were slightly different from those reported by other investigators. The findings suggest that atmospheric pressure is a more significant factor in interpreting cosmic ray data than air temperature. However, the effect of air temperature should not be disregarded, particularly during periods where the temperature coefficient is relatively high. The observation of a positive correlation between air temperature and cosmic ray muon intensity in some periods highlights the complexity of the factors that influence cosmic ray muon intensity and emphasizes the need to consider multiple factors when interpreting cosmic ray data.

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