PAPER

# Barometric pressure correction to gamma-ray observations and its energy dependence



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# Barometric pressure correction to gamma-ray observations and its energy dependence

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**Abstract.** Cosmic rays (CRs) have been studied extensively in the last century to understand the processes in the universe as well as in the solar system. In today's satellite era, although many observations are made from space, CR observations from the ground are still viewed as a significant tool. These observations, however, mainly detect the secondary cosmic rays (SCRs) produced via nuclear spallation processes during the interactions of the primary CR with the atmospheric nuclei. Neutron, muon, and gamma are the major components of SCRs detected on the ground. It is well known that atmospheric pressure plays a vital role in the SCR flux observed on the ground. Barometric pressure correction is standard practice for neutron monitor (NM) data. For gamma-rays, however, being massless, their pressure dependence is not intuitive. Nevertheless, the pressure affects the particles such as $e^{\pm}$, $\mu^{\pm}$, which produce gamma rays in the cascade. Subsequently, the indirect pressure dependence of the gamma-ray flux can be anticipated.

We examine this aspect in detail by studying the gamma-ray counts detected by the NaI (Tl) detector. The present study confirms that there is no correlation between the atmospheric pressure and the total counts covering the entire energy range (150 keV–10 MeV) recorded by the NaI detector. However, the scenario differs when the fluxes of different energies are investigated separately. The gamma rays of energy below ∼3 MeV are primarily due to the radioactivity originating from the ground, whereas gamma rays above 3 MeV are mainly produced in the CR cascade. It is observed that the counts of energy above 3 MeV are well anti-correlated with the atmospheric pressure. The barometric coefficient obtained here matches well with that reported by the previous studies which used anti-coincidence methods. This may indicate that the role of directly detected muons and electrons by the NaI (Tl) in the observed pressure dependence is non-significant. It is demonstrated that applying the barometric correction formula to NaI (Tl) data successfully removes the pressure dependence in the flux above 3 MeV. Therefore, we suggest that the particle flux data above 3 MeV measured by NaI (Tl) detector needs to be corrected for the local atmospheric pressure variations.

**Keywords:** gamma ray detectors, gamma ray experiments, cosmic ray experiments

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## Contents



## 1 Introduction

Cosmic rays (CRs) interacting with the atmosphere produce various particles known as secondary cosmic rays (SCRs). SCRs are primarily composed of pions, kaons, muons, neutrons, protons, electrons, positrons, gamma-rays, neutrinos, and many short-lived strange particles. Among these, neutron, proton, $\pi^+$, $\pi^0$, $\pi^-$ are generated first. Neutral pions decay into photons, and charged pions decay into muons, which can later produce photons. These reactions result in the abundance of photons, neutrons, and muons on the ground. Mostly, the neutron is used as a probe to study primary CRs (solar, galactic, or extragalactic origin), sun-earth connection, etc. Neutron monitors (NMs) have been used to collect neutron data for more than seven decades. The meteorological effects on neutron flux due to pressure, temperature, humidity, wind, snow, atmospheric electric field have been studied extensively [1–7]. The most prominent effect is due to the atmospheric pressure, which has been reported since the 1920s [8–12]. Earlier, it was interpreted as the effect due to absorption of CR by the atmosphere. Later, Dorman (1972) discussed the complex nature of the barometric effect as a result of absorption, decay, and generation of SCRs [1].

The barometric effect is corrected using a standard formula given by eq. (1.1).

$$N = N_0 \exp[-b(p - p_0)], \tag{1.1}$$

where the corrected counts ($N$) are calculated based on observation of variation in counts with pressure; $p$ is the atmospheric pressure, $N_0$ and $p_0$ are the reference values (usually, the average values) of counting rate and atmospheric pressure, respectively, over the specified time period. Eq. (1.1) can be used for the calculation of the barometric coefficient, $b$ using experimental observations by linear regression of $N$ and $p$ measurements for a specific period.

The intuitive explanation for the barometric effect is as follows: when the barometric pressure increases, essentially the overhead matter in the atmospheric column increases, as a result of which SCRs have to go through more interactions with other particles, thus attenuating the SCR flux on the ground. Thus, the barometric effect is different for different particle species of SCRs, depending on their mass and how they interact with other matter, i.e., $b$ is different for different types of particles detected at the same location and time. The



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value of $b$ for a specific type of particle depends on many other factors such as latitude (geomagnetic rigidity), altitude, and time of observation. The method to define the barometric coefficient of the different components of SCRs has been studied by many researchers in the past [1, 11]. During the last 60 years, the factors responsible for the change in $b$ have been investigated using the data from networks of the neutron as well as muon detectors. It is found to have 11-year solar cycle dependence [5, 6]. The absolute value of $b$ for neutrons is more than that for muons. The absolute value of $b$ for the same type of secondary particle changes with the energy of those particles. Also, absolute $b$ is greater for high altitudes than lower altitude locations (e.g., muon flux measured at a mountain-top will be more than that at the sea level) [13]. Thus, we can say that the barometric pressure effects on neutron and muon components of SCR have been studied comprehensively in the past.

To obtain useful data from NMs, correcting the NM data for the effect of barometric pressure is regarded as one of the most important corrections of raw data [14]. Raw data from a neutron detector is corrected for pressure using eq. (1.1) [1, 11]. Calculating $b$ for an NM station has become much easier because of an online tool developed by the Athens Cosmic ray team, as described by Paschalis et al. (2013), which uses the data available on NMDB [15].

Apart from the global network of NMs, there are some other set-ups dedicated to SCR detection and study. One of such set-ups is at Mt. Aragats (40.47°N, 44.17°E) at an altitude of 3200 m, where they have several detectors of various types, such as a solar neutron telescope, neutron monitor, and muon monitor. In their SEVAN set-up, multiple plastic scintillators are arranged in such a manner that coincidence from three layers can be used to separate out three different types of particles [16, 17]. They have studied the barometric effect of neutrons and muons in many energy ranges using their set-ups [13]. On the other hand, the studies discussing the barometric pressure effect on the photon component are scarce. Being massless, photons are not expected instinctively to undergo a barometric effect. Unlike neutron and muon, for which SCR is the only major source, photons originate from different sources. In addition to the SCRs, terrestrial radioactivity is also a major contributor to photon production. Terrestrial radioactivity produces photons up to 2.8 MeV, while SCR can produce photons of energies ranging from 100 keV to tens of MeV. Therefore, understanding the barometric effect can be complex. To our knowledge, only a couple of papers have attempted to study the role of pressure in gamma-ray flux exclusively [18, 19]. They reported an observation showing an anticorrelation of photon intensity with atmospheric pressure.

Chin & Standil (1968) evaluated $b$ for different energy ranges, and they found the energy dependence of $b$ in the range 3.8–183 MeV [19], namely an increase in $b$ with energy. It should be noted that their observations were made at a location with the geomagnetic cutoff rigidity, $R_c \approx 0.85$ GV (49.9°N, 97.2°W) and an elevation of 236 m a.s.l. Their set-up consisted of a NaI detector of size 9.5″ diameter and 8″ length (volume 238.76 inch$^3$ (606.45 cm$^3$)), which was completely surrounded by an efficient scintillating plastic anti-coincidence shield. Their paper has reported the barometric effect for energies above 3.8 MeV and has not discussed the effect below 3.8 MeV. In fact, NaI (Tl) is considered very effective for gamma-ray spectroscopy up to 3 MeV; therefore, it is important to examine the pressure aspect on energies below 3 MeV as well.

Arakelyan et al. (2014) describes a set-up at Aragats Space Environmental Center (ASEC), Mt. Aragats, which contains five NaI (Tl) detectors, each of size $5 \times 5 \times 12''$ and a plastic scintillator used for anti-coincidence. Data from this set-up have been used mainly to study thunderstorm ground enhancement (TGE) events. Karapetyan (2013) has described the barometric coefficients of these five NaI (Tl) detectors varying from -0.323%/mbar to -0.391%/mbar [20, 21].



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In these previous studies of the barometric effect on gamma-rays, they have performed statistically sound quantitative analysis. However, they do not provide a thorough scientific explanation of why the seemingly counterintuitive barometric effect is observed in gamma-ray counts as well as its physical mechanism. Here, along with quantitative analysis of our data, we provide the qualitative approach necessary to understand the barometric effect on gamma-rays of energies between 150 keV and ∼10 MeV, collected using NaI (Tl) of size $4 \times 4 \times 16''$ (volume of 256 inch$^3$ (650.24 cm$^3$)) located near the equator ($R_c \approx 17.4$ GV).

## 2 Data

### 2.1 Experimental set-up

The data used in the present analysis are obtained from a NaI (Tl) detector located at Equatorial Geophysical Research Laboratory (EGRL), Tirunelveli (30 m a.s.l.; Geographic Coordinates: 8.71°N, 77.76°E). The detector is placed inside a temperature-controlled cabin constructed six feet above the ground. The detector is surrounded by the lead shielding that covers the bottom and all four sides but not the top. The top of the cabin is covered by plywood. Digital pulse processing for pulse height analysis (DPP-PHA) is implemented to record an energy histogram each minute. The spectrum is calibrated using standard sources ($^{60}$Co and $^{137}$Cs) and distinct background radioactivity peaks such as $^{40}$K, $^{208}$Tl, $^{214}$Bi. The details of the experimental set-up are described in Vichare et al. (2018) [22]. It is very important to note the differences in our set-up from the set-ups in previous studies, namely in detector specifications, shielding, geographic and geomagnetic locations. The choice of NaI (Tl) is deliberate because the scintillators with a low atomic number are generally preferred for electron spectroscopy, whereas the opposite is the criterion desired for gamma-ray spectroscopy. Among others, NaI (Tl) is best suited for gamma-ray spectroscopy, as it has very high efficiency for gamma-rays. Previous studies have employed the anti-coincidence technique to remove electron-muon events while studying the barometric effect. Here, only one type of detector, i.e., NaI (Tl), is used to collect SCR data, and no additional plastic scintillators are used for anti-coincidence. This may be viewed as not in accordance with the standard methods; however, it may be justified as NaI(Tl) has a very high efficiency for detecting gamma rays compared to other particles, and more details are discussed in section 4 [20].

The uncertainty in a single measurement ($x$) is best estimated by taking the square root of the measurement, i.e., $\sigma = \sqrt{x}$. Assuming Gaussian distribution (for large x), there is 68% probability that the range $x \pm \sigma$ will contain the true value of $x$; whereas, $x \pm 1.64\sigma$ and $x \pm 2.58\sigma$ have 90% and 99% probability, respectively [23]. The data obtained from this set-up have been used successfully to study the diurnal variation in gamma rays and the response during a cyclone event [24, 25]. The atmospheric pressure data used in the present analysis is obtained from an in-house automatic weather station (AWS) at EGRL.

## 3 Gamma-rays and pressure variations

### 3.1 Total gamma-ray counts

The dependence of the *total* gamma-ray counts collected by the above set-up on the barometric pressure is examined in figure 1. Here, we have also presented the neutron data obtained from an NM station — PSNM (Thailand) which has similar latitude and rigidity as Tirunelveli. We have randomly selected NM data from 1 to 31 January 2018. For NaI (Tl),



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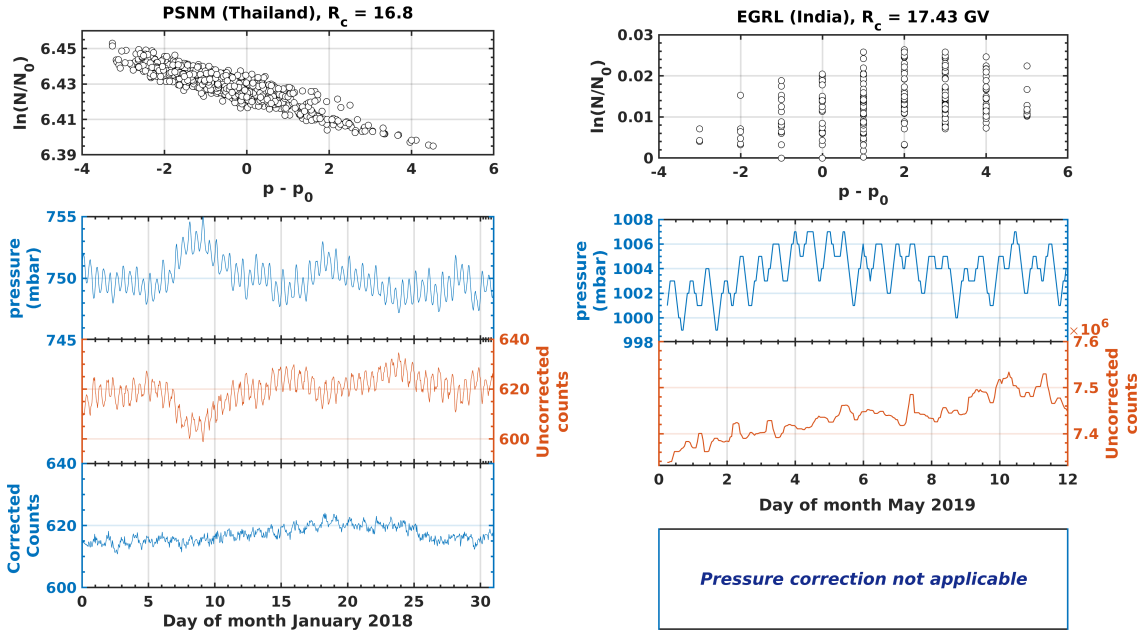


**Figure 1**. Barometric pressure correction for NM data (Thailand station) and NaI (Tl) data.

data from 1 to 12 May 2019 is presented. The x-axis denotes time in days. The significance of these observations can be determined by calculating the measurement error, as discussed in section 2. Here, values of single measurements vary in the range $7.34 - 7.54 \times 10^6$, which gives $\sigma$ in the range 2709–2745 using $\sigma = \sqrt{x}$. For $x = 7.44 \times 10^6$, $\sqrt{x} = 2727.6$, and thus the 90% uncertainty can be estimated as $x \pm 1.64\sigma$, i.e., $7.44 \times 10^6 \pm 4473$. This gives a total interval of less than 1% of the counts in which the true mean value lies with a 90% probability. This demonstrates that the measurements are statistically significant. The top panels show the graphs of $\ln(N/N_0)$ vs $p - p_0$. For NM, $p_0$ is the reference pressure value obtained from http://www.nmdb.eu/station_information/, which is a long-term average value. Similarly, for NaI data, $p_0$ is reference pressure taken as an average at Tirunelveli. $N_0$ is a base reference value of counts, which is taken as the minimum value of counts in the data. The plots on the left represent the NM data from PSNM, Thailand, while the plots on the right show gamma-ray data from NaI (Tl) located at EGRL, Tirunelveli. The second panels from the top show the barometric pressure recorded at the observation site. Third and bottom-most panels show uncorrected and corrected counts, respectively. It can be observed that the pressure and uncorrected counts of NM data are anti-correlated with each other over a long period (∼10 days) and also on a diurnal scale. The uncorrected counts of NM data show anti-correlation with the semi-diurnal variations of the atmospheric pressure. On the other hand, no such dependence is observed in uncorrected counts from NaI (Tl) detector.

For PSNM, the scatter plot of $\ln(N/N_0)$ vs $p - p_0$ is linear, and the slope of a linear fit is taken as $b$. Whereas for EGRL, the plot is totally scattered, indicating a lack of dependence, and no sensible linear fitting is possible. Thus, it is evident from figure 1 that the total counts collected by NaI (Tl) do not show any dependence on the atmospheric pressure, which is supported by the scatter plot depicted in the top panel. It should be noted that these are the total counts detected by the NaI (Tl) detector integrated over all the energies. However, considering various sources of gamma rays (terrestrial radioactivity is the major



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source for gamma rays up to 2.8 MeV, while SCR is the dominant source above 3 MeV), it would be interesting to conduct a similar analysis for different energies, which is presented in the next subsection.

### 3.2 Gamma-ray counts of different energies

The analysis for different energies of gamma flux during May 2019 is presented in figure 2 ((a) 0.3–2.7 MeV; (b) 3–5 MeV; (c) 5–7 MeV; (d) 7–10 MeV). The top panels in each subfigure show the graph of $\ln(N/N_0)$ on the y-axis and (p-$p_0$) in millibar (mbar) on the x-axis. As mentioned earlier, $N_0$ and $p_0$ are the reference values of counts and atmospheric pressure, respectively. The middle panel shows the atmospheric pressure (mbar) and the uncorrected counts from NaI (Tl) detector within the specified energy range with measurement error (grey shaded area denoting $\pm\sigma$). The bottom panel shows the corrected counts wherever applicable, i.e., whenever a good linear fit with a negative slope is obtained, the correction is applied using the barometric correction formula (eq. (1.1)). The goodness of the fit is determined using the statistical parameters displayed in table 1. It can be observed from the scatter plots that the scatter is more for the lower energy band (0.3–2.7 MeV) than the other energy bands. Among the rest of the energies, 3–5 MeV and 5–7 MeV have less scatter, and it is possible to fit a linear trend with a negative slope. For the 7–10 MeV energy range as well, it is possible to fit a line with a negative slope. The slopes of the linear fits in the scatter plots represent $b$ values and are shown in table 1. It can be noticed from table 1 that the $b$ value is negative above 3 MeV and small but positive for the energy range of 0.3–2.7 MeV. The $b$ value computed for all energies, as shown in figure 1 is also a small positive value. The plots of pressure and uncorrected counts above 3 MeV seem to be anti-correlated on semi-diurnal as well as long time scales. However, for the energy range 0.3–2.7 MeV, such a relationship is not clearly seen. The parameters such as Pearson correlation coefficient (CC), $R^2$, SSE, and RMSE enlisted in table 1 describe the statistical significance of the linear fits and hence that of $b$ values. The CC values for the parameters displayed in the scatter plots are, in general, good above 3 MeV. CC values are $\sim -0.6$ for energies between 3–7 MeV and dropped to -0.294 for the 7–10 MeV range, though it is statistically significant ($p < 0.01$). However, the CC for 0.3–2.7 MeV energy range is very small (0.125), indicating poor relation, and with $p > 0.01$, it is not statistically significant as well. CCs of all energy ranges above 3 MeV have a 99% confidence level (shown in bold in table 1). The SSE and RMSE values are small in general. It can be observed that for the energies above 3 MeV, the absolute value of $b$ increases with energy from 0.3 to 0.5, and the mean value of absolute $b$ for 3–10 MeV is $\sim$0.39. Further, based on the statistical significance of CC, we decided whether to apply the pressure correction or not. This information is shown in the last row of table 1.

To confirm the results obtained above, we carried out a similar analysis for two more data sets, viz., six days from June 2019 and five days from July 2019. The important observation in the present work is about the pressure dependence of gamma rays that varies with the energy of the gamma. The results from all these three data sets are plotted together in figure 3. Figure 3(a) shows the variation of obtained barometric coefficient with energy. The mean $b$ values in each energy range, along with standard deviation ($\sigma_s$), are depicted in figure 3(b). The error bars correspond to $\pm\sigma_s$ around the mean value $\bar{b}$ representing the dispersion relative to the mean.

$$\sigma_s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(b_i - \bar{b})^2}, \tag{3.1}$$



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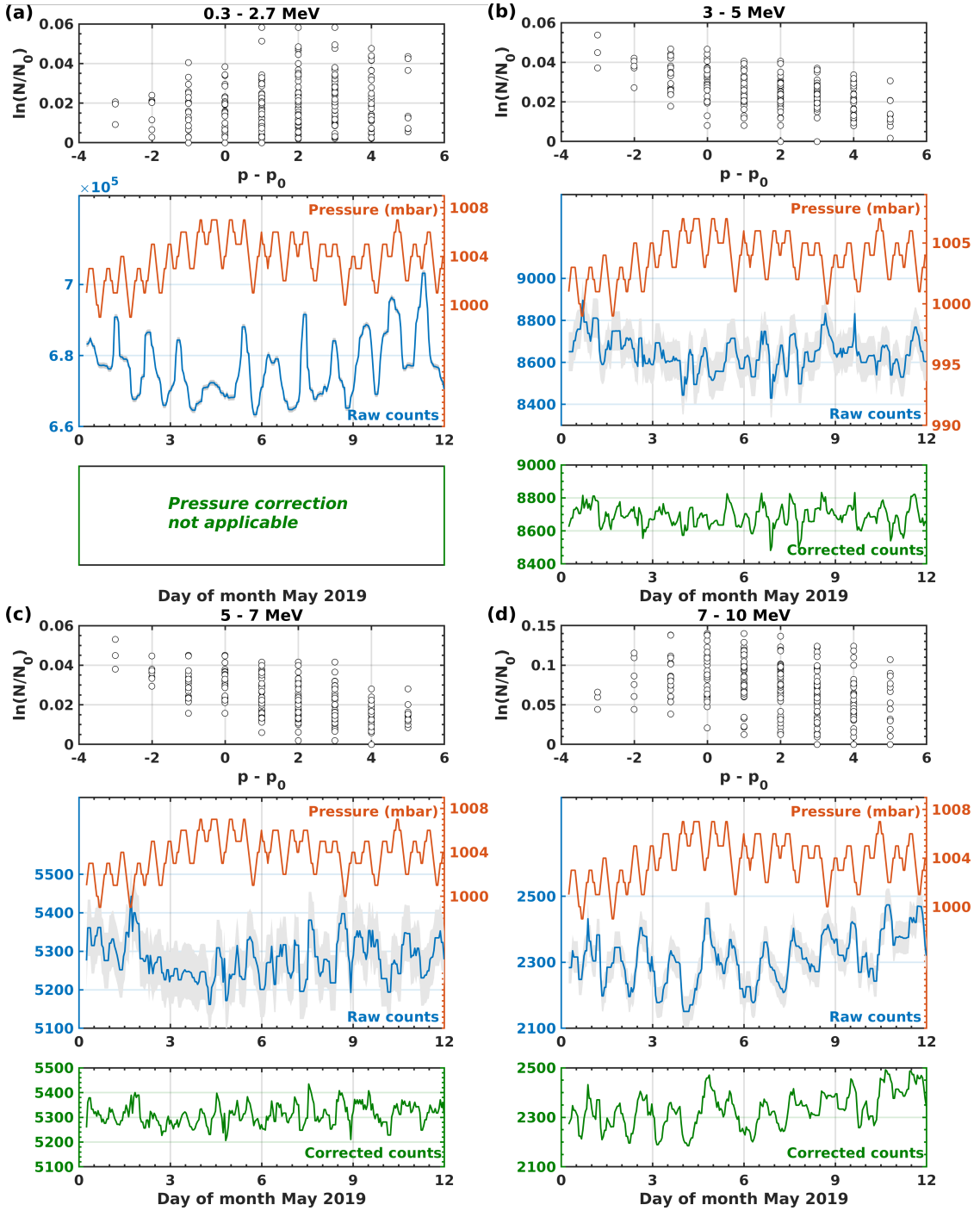


**Figure 2**. Barometric dependence of $\gamma$-ray counts of different energies during May 2019 (a) 0.3–2.7 MeV; (b) 3–5 MeV; (c) 5–7 MeV; (d) 7–10 MeV. Measurement errors ($\pm\sigma$) in NaI (Tl) data are denoted by the shaded area.

where $b_i$ is the $i^{\text{th}}$ data point of total $N$ data points. The significance of obtained $b$ value is indicated by averaged CC values which are displayed by bar plots in figure 3(b). It can be observed that for the 0.3–2.7 MeV energy range, the $b$ values are very small, and the



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| Parameter | All energies | 0.3–2.7 MeV | 3–5 MeV | 5–7 MeV | 7–10 MeV |
|---|---|---|---|---|---|
| $b$ (%/mbar) | 0.09174 | 0.08694 | -0.3044 | -0.3304 | -0.5237 |
| $R^2$,[1] | 0.08507 | 0.01559 | 0.3646 | 0.3614 | 0.08649 |
| CC[2] | 0.2917 | 0.1248 | **-0.6038** | **-0.6012** | **-0.2941** |
| SSE[3] | 0.00835 | 0.0440 | 0.0149 | 0.0178 | 0.267 |
| RMSE[4] | 0.00547 | 0.0126 | 0.00731 | 0.00799 | 0.0309 |
| Correction | NA | NA | Yes | Yes | Yes |

[1] $R^2$ indicates the success of the fit in explaining the variation of the data as it is the square of the correlation between the response values and the predicted response values.

[2] CC is the Pearson correlation coefficient.

[3] SSE is 'sum of squares due to error', which measures the total deviation of the response values from the fit to the response values. It is also called the summed square of residuals. A value closer to 0 indicates that the fit will be more useful for prediction.

[4] RMSE is 'root mean squared error' or the standard error of the regression.

**Table 1**. Goodness-of-fit statistics for $\gamma$-ray counts of different energies (May 2019).

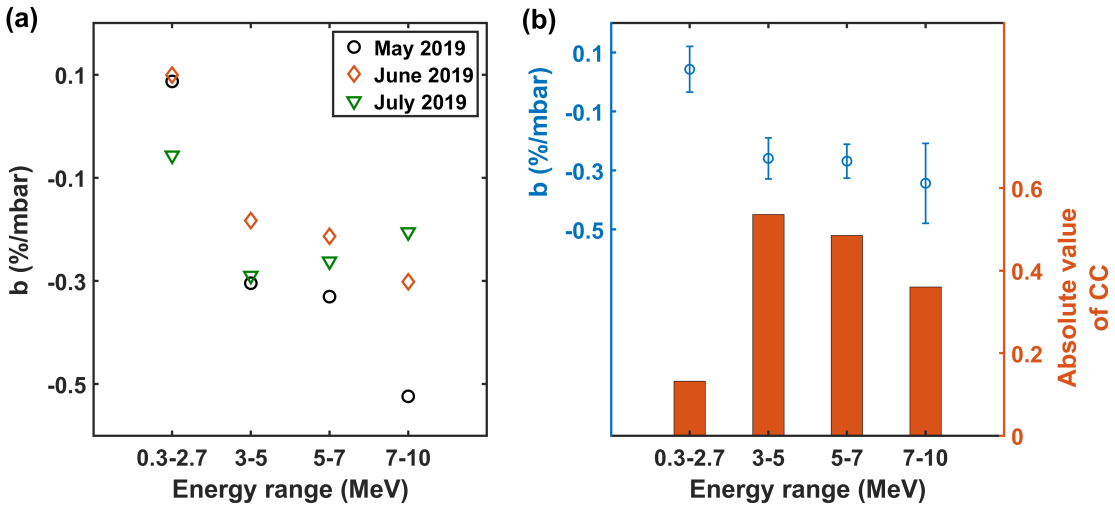


**Figure 3**. Summary and statistics of data from May, June, and July 2019.

average CC is also very small (0.13). This indicates that there is no pressure dependence for the energy range between 0.3–2.7 MeV. For 3–5 MeV and 5–7 MeV energy ranges, the mean $b$ is ∼-0.26 and -0.27, respectively, with mean CC greater than ∼0.5, implying significant pressure dependence. For 7–10 MeV, mean $b$ is -0.34 with mean CC of 0.36. Larger error bars in this higher energy band can be due to lower counts in this energy range. Thus, it is clear from figure 3 which is based on the data collected during different periods, that there is no pressure dependence for the energy range 0.3–2.7 MeV, while clear dependence exists for the gamma of energies greater than 3 MeV and the value of $b$ increases with the energy above 3 MeV.



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## 4 Discussion

The main objective of the present study is to investigate the pressure dependence of SCR data collected by NaI (Tl) scintillation detector and, unlike previous studies, try to explain why the counterintuitive barometric effect is observed in gamma-rays. Apart from gamma rays, NaI (Tl) can also detect other particles such as electrons, muons, neutrons. Any scintillation material generally responds to neutrons to some extent. Also, when electrons are incident on the detector crystal, some may be detected directly, and some of the secondary bremsstrahlung photons generated along the path of the electron may be detected. Thus, NaI (Tl) detector is not entirely opaque to particles other than gamma, and an undesirable background is unavoidably present in gamma-ray measurements [23]. Earlier researchers used the anti-coincidence method to exclude muon-electron events from getting detected by NaI (Tl) crystal [20, 26]. Nevertheless, the use of anti-coincidence does not assure the sole detection of gamma — it would still contain the contributions from neutrons. The present study has not implemented the anti-coincidence method, and as a result, our NaI (Tl) detector data might be a mix of gamma, electrons, positrons, muons, and neutrons. Therefore, it is important to discuss the contributions of other particles in the spectrum obtained from the NaI detector. There have been different studies on the efficiency of NaI (Tl) crystal to detect neutrons [20, 27, 28], and they concur that it is very low for lower energy neutrons ($< 10$ MeV). As pointed out by Arakelyan et al. (2014) [20], the ratio of efficiencies of a NaI (Tl) detector to detect gamma and neutrons varies from 5:1 to 8:1 in the energy range 3 MeV–10 MeV. This means that when a NaI (Tl) detects 50 to 80% of the incident gamma photons, it also detects 10% of the incident neutrons. Similarly, it might be having some efficiency to detect other particles like muons and electrons. However, as per EXPACS simulations, which compute the flux of various components of SCR [29, 30], a total flux of gamma photons equals 2.67E-01 $\mathrm{cm^{-2}\,s^{-1}}$ in the energy range of 113 keV–11.3 MeV. Similarly, for neutrons, it is 9.61E-03 $\mathrm{cm^{-2}\,s^{-1}}$ and 3.14E-05 $\mathrm{cm^{-2}\,s^{-1}}$ for muons ($\mu^{\pm}$). For electrons and positrons together, it is 1.04E-02 $\mathrm{cm^{-2}\,s^{-1}}$. Thus, with respect to gamma, the neutrons and $e^{\pm}$ have fluxes of 3.66% and 3.95%, respectively, while muons have a very little abundance of 0.012% in this energy range. Therefore, we may rule out the role of muons affecting our observations significantly. We cannot yet ignore the contribution of neutrons, electrons, and positrons (∼7.61% flux as compared to gamma) completely, despite the lower efficiency of NaI (Tl) to detect these particles. We have to keep in mind that the pressure effect on neutrons is well studied, and in the given set-up, we cannot separate them from gamma. Positrons will not be registered even if they enter the detector, as they will get annihilated soon. Thus, in principle, we may have a contribution from neutron and electron in the counts measured by the NaI (Tl) detector. However, this is going to be small, as demonstrated by the theoretical estimation of fluxes of different particles present in the surrounding of the detector. Even if the models underestimate the fluxes to some extent, the pressure correction is applicable to other particles as well. Although $b$ will be different if different particle populations are considered independently, as the detector is at a fixed location, the relative ratios of these particles will not change significantly over time. Ultimately, we will be calculating the effective barometric coefficient, not solely but mainly influenced by the gamma population. This approach can be useful to small-scale set-ups of NaI (Tl) detectors when they can correct their data for pressure without the additional infrastructure required for the anti-coincidence method.



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The present study finds the correlation between the atmospheric pressure and the *total* gamma-ray counts above 3 MeV, whereas if the gamma-rays collected from all energies are considered, no such correlation is observed. Besides the SCR, gamma rays observed on the ground originate from other sources as well, such as terrestrial radioactivity, thunderstorms. Therefore, understanding gamma-ray dependence on atmospheric pressure is complex. The gamma particles with energies up to 2.7 MeV have a major contribution from the terrestrial radioactivity coming from the ground. While gamma as the SCR component produced in the CR cascade has a broad energy range from few keV to tens of MeV. Datar et al. (2019) have reported the presence of a diurnal variation in the gamma-ray counts with energy less than 2.7 MeV, which they attributed to the transport of radon in the air emanating from the ground to the atmospheric boundary layer [24]. Therefore, the gamma radiation of energy $< 2.7$ MeV originating from the ground do not pass through the overhead atmosphere and will not be affected by atmospheric pressure variations. Thus, our observation of the lack of pressure dependence of gamma flux in the energy range of 0.3–2.7 MeV is justified. That might be the reason for excluding this energy range in the study by Chin and Standil (1968). Furthermore, as these energies have the highest counts associated with them in the energy histogram, it dominates the dependence relation when the total counts are considered (as seen in figure 1). Therefore, the total counts do not show the pressure dependence. It is evident from figure 2, figure 3 and table 1 that the barometric pressure dependence exists for gamma rays above 3 MeV. Chin and Standil (1968) have done very extensive work to study the pressure dependence of gamma rays. They focused on the gamma rays with energies ranging from 3.8 MeV to 183 MeV — dividing into 16 energy bands. Whereas our set-up has a detection range of up to 10 MeV, and we have divided 3–10 MeV energy range further into three bands. We have found that the absolute value of $b$ increases with energy. This observation is in accordance with Chin and Standil (1968) results. The averaged absolute value of $b$ for 3–10 MeV is found to be $\sim$0.4; whereas Chin and Standil (1968) reported it as $\sim$0.5 for 3.8–13.2 MeV energy band. Thus, when we consider the differences in the location of the stations (geographic latitude and altitude) and period of study, present estimates of $b$ are in good agreement with that reported by Chin and Standil (1968). Also, note that, unlike the present work, Chin and Standil (1968) have used the anti-coincidence method to eliminate the contribution of muons and electrons. So, it is quite interesting to note that the results obtained based on two different datasets and techniques match qualitatively and quantitatively.

Thus, we report here the pressure dependence of particle flux with energy $> 3$ MeV detected by NaI(Tl). However, gamma, i.e., photon being massless, is not expected to get affected by the atmospheric pressure variations. Therefore, the question is why the pressure dependence is observed in the present analysis for gamma with energy $> 3$ MeV? Even though a thorough observational and statistical study of pressure effect on gamma-rays by Chin and Standil (1968) was performed five decades ago, the theoretical understanding of the physics behind these observations is lacking. In this paper, we attempt to address the important question of *why* pressure dependence is observed in gamma-ray data contrary to intuition on a theoretical basis. A possible explanation could be due to the pressure dependence of the particles that generate photons. Photons are produced in the air shower during various interactions at different altitudes. Neutrons, $\pi^+$, $\pi^-$, $\pi^0$ are produced in the interactions of primary CRs with the atmospheric nuclei. $\pi^0$ directly produce photons, but charged pions decay into muons, which can produce photons after travelling some distance in the air. Thus, photons being *tertiary* or *quaternary* particles in this chain, their flux on the ground



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is a mixture of all those produced by different generation processes. Another possibility is that these particles other than gamma, such as neutron, electron, and muon that are being detected by the NaI (Tl) detector, contribute to the observed pressure effect directly as they are not massless and are directly affected by the pressure variations. This makes the dependence of counts detected by NaI (Tl) on the barometric pressure not so straightforward, and maybe it is the reason why we do not see a not very good value of CC (∼-0.6). Note that in the case of neutrons and muons, the CC values with atmospheric pressure are $> 0.9$ [13]. The barometric coefficient found through the present work is around -0.4%/mbar for 3–10 MeV, which is of the same order as those reported by Chin & Standil (1968) (-0.5%/mbar), and also by Karapetyan (2013) (-0.32 – -0.39%/mbar). As $b$ changes with rigidity, altitude, among other things, exact matching of this value with that of from another experimental site and set-up is not to be expected. However, if $b$ for the same type of particle is being compared, it is reasonable to expect it of the same order with slightly different values. The present result is interesting as it matches with the previous studies in spite of lacking the anti-coincidence.

## 5 Conclusion

Although the previous studies have calculated barometric coefficients for gamma-rays with neat experiments, they have not explained why the apparently counterintuitive effect is present. Gamma rays, being massless, are not expected to be affected by pressure variations. Present work gives a possible physical mechanism of the barometric effect on the gamma-rays for the first time to the authors' knowledge.

Atmospheric pressure affects the particles that have mass, such as $e^{\pm}$, $\mu^{\pm}$, which produce gamma rays in the cascade of SCRs. Thus, the indirect pressure dependence of the gamma-ray flux is observed in gamma rays of energies above 3 MeV, along with a possible contribution from the direct detection of particles such as neutrons that are affected by pressure. Interestingly, the value of $b$ obtained here matches well with that reported by the previous studies, which used anti-coincidence methods. This may indicate that the role of directly detected muons and electrons is non-significant. Naturally, gamma rays of energies below 2.7 MeV do not show such pressure dependence as it is dominated by the terrestrial radioactivity. The present work thus suggests that the gamma-ray data collected on the ground for energies above 3 MeV need to be corrected for atmospheric pressure. Even a simple set-up consisting of a single NaI (Tl) detector without employing the anti-coincidence method can correct their data for atmospheric pressure. Furthermore, the present study has been carried out at a location where the maximum pressure variation is only ∼7–8 mbar on an average, and yet we observe the pressure dependence in the gamma data. Thus, for the locations with stronger pressure variations, it is very important to consider the pressure corrections.

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**Author contributions statement.** All authors participated in designing the experiment. GD carried out the data analysis. GD and GV analysed the results and finalised the manuscript.

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