Variations of the high energy muon flux and space-time structure of the temperature profile in the atmosphere

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Abstract. We present the investigation of the Correlation and Temperature Coefficients as a function of the altitude of the temperature measurements. The flux of high-energy muons (threshold energy 220 GeV) as a function of atmospheric temperature is measured using data from the Baksan Underground Scintillation Telescope (BUST). The minima of the Correlation and Temperature Coefficients as a function of the altitude correspond to atmosphere tropopause and maxima are related to troposphere and stratosphere. The magnitude of temperature variation corresponding to minimum is approximately a half of the magnitude corresponding to maxima. The values of the Correlation and Temperature Coefficients around of the minimum are approximately a half of the corresponding values around of the maxima. The approximate coincidence of the minimum and maxima in the Correlation and the Temperature coefficients leads to the conclusion that this is due to not the magnitude, but rather to the temporal behaviour of the temperature in the respective regions of the atmosphere.

1. Introduction

Studies of past years variations in the intensity of the registration of the various components of the secondary cosmic radiation led to the fact that meteorological corrections, whose introduction into the primary observational data allows us to find variations of cosmic rays of extra atmospheric origin. Meteorological effects on cosmic rays were possible to obtain some information about the state of the upper atmosphere and some of the characteristics of nuclear cascade in the atmosphere.

The continuous development of our knowledge with respect to nuclear interactions, and possibilities of computer technology makes it justified a new appeal to these problems in order to obtain more precise results.

As it is well known, very high energy cosmic rays interacting in the stratosphere, produce mesons in the primary hadronic interaction, these mesons or produce lower energy hadronic cascades, or decay into high energy muons which can be recorded deep underground detectors. The daily variations of the temperature of the troposphere are considerable, the temperature of the stratosphere usually changes on the timescale of seasons.

If the temperature of the stratosphere increases, the density decreases, leading to reducing the chance of meson interaction, resulting in a larger fraction decaying to produce muons, and to a higher muon rate observed deep underground. The majority of muons is produced in the decays of pions (decays of kaons must be considered for a more advanced muon flux description).

Interrelations between processes in the Earth’s atmosphere and variations in secondary cosmic rays have been studied for several decades now [1], and interest to this field of research are revived in recent years. The increased attention given to the state of the environment is one reason for this. The applied aspect of this group of problems is no less important, since cosmic ray detectors allow us to monitor of the state of the Earth’s atmosphere in real time. The relationship between processes in the Earth’s atmosphere and variations in cosmic ray intensity is now being studied at many experimental facilities. Such large underground detectors as MACRO [2], AMANDA [3], MINOS [4], and LVD [5] analyze seasonal variations in the flux of high-energy muons. Based on their data, it was found that the period of variation is equal to one year. In the northern hemisphere, the maximum and minimum of the
muon flux fall in July and January respectively, which is in agreement with theoretical predictions.

The temperature effect of high-energy muons was studied at the Baksan Underground Scintillation Telescope [6] as long ago as in 1980s, and some preliminary results were published in [7]. In [7], Temperature Coefficients and Correlation Coefficients were also presented for three different atmospheric depths.

In this work we present the results from studying the Correlation Coefficients (between the counting rate of muons (CRM) and the temperature) and the Temperature Coefficients dependency on the altitudes of the points of atmosphere (where the temperature has been measured), and on different muon arrival directions. The results for Correlation Coefficients are compared with the conclusions drawn in [7].

2. The BUST Counting Rate as a function of temperature at separate points in the atmosphere

Direct analysis of the scatter of points corresponding to the BUST counting rate versus temperature in the region of the city Mineralnye Vody shows that (as in [7]) Correlation Coefficients are different for different altitudes.

Preliminary investigation of correlations between the BUST counting rate and the temperature in the region of Mineralnye Vody revealed a nontrivial dependence of the Correlation Coefficients on the altitude where the temperature was measured. Figure 1 presents the Correlation Coefficients dependency on the altitude H. The altitude is plotted against the horizontal axis, while the vertical axis represents values of the corresponding Correlation Coefficients.

We can see that Correlation Coefficients vary non-monotonically as a function of altitude H; in particular, a well-pronounced minimum is observed in the region of 15–20 km. The numerical discrepancy between the values of the Correlation Coefficients of this work and [7] is apparently due to our analyzing correlations (as opposed to the procedure in [7]: for the data obtained over a five-month period and averaged over a day). We should nevertheless note that the tendency of the Correlation Coefficients to pass through a minimum with variation of the altitude is identical in this work and in [7].

3. Correlation and Temperature coefficients analysis at different altitude of points of the atmosphere and at different zenith angle and all azimuth ones

The BUST muon intensity depends on the threshold energy and the cosine of the zenith angle. The Correlation Coefficient and Temperature Coefficient dependency on the height of the atmosphere point for equal solid angles corresponding different directions has been investigated.

Solid angles correspond to intervals between six values of cosine of zenith angle $\theta$ according to formula:

$$\cos(\theta_j) = (6 - j) / 6,$$

where $j = 0,1,2,3,4,5,6$.

The Correlation Coefficients C and Temperature Coefficients $\alpha$ have been calculated as

$$C = \frac{\sum (T_i - T)(I_i - I)}{\left[ \sum (T_i - T)^2 \sum (I_i - I)^2 \right]^{1/2}}, \quad \alpha = \frac{\sum \Delta T_i (\Delta I_i / I)}{\sum \Delta T_i^2} (\% / K),$$

where $T_i$ are the values of the temperature of the a half of the day beginning, the values $I_i$ is one day, one hour, a half of the hour averaged quantity (see corresponding Figures), $T$ and $I$ are mean values for 2008 year.
The Correlation Coefficient dependency on the height of the atmosphere point, CRM data are one day averaged. Curve 1: integral CRM; curves 2-6: 
\( (6-j)/6 \leq \cos(\theta_j) \leq (6-j+1)/6; j=1,2,3,4,5. \)

Figures 1 and 2 show us the behavior of the Correlation and Temperature Coefficients as a function of the height of the atmosphere point for equal solid angles corresponding to different directions. As one can see, Correlation Coefficient dependency manifests a minimum (17.5 km) and maxima (12.5 and 25 km) for all directions.

The minimum of the Correlation and Temperature Coefficients as a function of the height corresponds to atmosphere tropopause and maxima are related to troposphere and stratosphere correspondingly (see Figures 1, 2).

4. Analysis of the dependence of the correlation and temperature coefficients on the height of the point of temperature measurement

Analyzed sine approximation of the temperature time series and the integral counting rate of muons (CRM) at BUST give a qualitative explanation of the non-trivial dependence of the coefficients of the height. Fitting function is of the form:

\[ y = y_0 + A \sin \left[ \frac{\pi(x-x_c)}{w} \right], \]

where \( x \) corresponds to number half a day, and \( y \) is appropriate value of the temperature or CRM, values of the fitting parameters \( y_0, A, x_c, w \) temperature time series corresponding to different heights (Mineralnye Vody city). The fit has been done for 2008. Sine approximation of temperature time series and the CRM gives a qualitative explanation of non-trivial dependence (see Figures 1,2) of the coefficients on the height.

A joint analysis of Correlation and Temperature Coefficients and the parameters of the sine fit (SF) dependence on the altitude manifest the coincidence of the features of the change of both (see Figures 3). The approximate coincidence of the minima and maxima of the Correlation and Temperature coefficients lead to the conclusion that this is not due to magnitude, but rather the nature of the temporal behaviour of temperature in the respective regions of the atmosphere, because the Correlation Coefficient does not change if the temperature and CRM will be multiplied by any value simultaneously. The difference in periods of temporal change in CRM and the tropopause temperature is the only reason for having a minimum (see Figure 3). At the moment, it can be argued, it is true as far as the extent to which SF adequately reflects the temporal behaviour of temperature at different
altitudes.

![Graph showing the relationship between temperature and CRM (horizontal line) as a function of altitude.](image)

**Figure 3.** A half of the period of the sine fit of the temperature and CRM (horizontal line) as a function of the altitude.

5. Conclusions
The behavior of the Correlation and Temperature Coefficients as a function of the atmosphere point altitude (where the temperature was measured) has been presented for different muons arrival directions to BUST (with equal solid angles). The minimum of the Correlation and Temperature Coefficients as a function of the height corresponds to atmosphere tropopause and maxima are related to troposphere and stratosphere correspondingly. If sine fit of the temperature time series and the integral counting rate of muons adequately reflects its space-time behaviour, the non-trivial of the Correlation and Temperature Coefficients dependence on the altitude is not due to magnitude, but rather the nature of the temporal behaviour of temperature in the respective regions of the atmosphere.

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