Temperature variations of high energy muon flux

V.B. Petkov, M.G. Kostyuk, R.V. Novoseltseva, Yu.F. Novoseltsev, L.V. Volkova, P.S. Striganov, M.M. Boliev

Institute for Nuclear Research, Russian Academy of Sciences, Moscow, 115409 Russia
e-mail: vpetkov@yandex.ru
DOI: 10.7529/ICRC2011/V11/0685

Abstract: 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 temperature was measured every 12 h by radiosonde at different levels of observations. The results from studying the Correlation Coefficient between the counting rate of muons and the temperature of the atmosphere at different altitudes are presented. The Correlation and Temperature Coefficients have been calculated and their dependency on the altitudes of the points (where the temperature has been measured) and on different of muon arrival direction are presented.

Keywords: muons, temperature, correlation.

INTRODUCTION

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 change on the timescale of seasons.

If the temperature of the stratosphere increase, 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 are produced in the decay 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 of 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 setups. 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 that work, it was shown that variations in the BUST counting rate of muons could be explained by variations in the temperature of the upper layers of the atmosphere. The Correlation Coefficient between the counting rate of muons and the effective temperature of the upper layers of the atmosphere, derived using the data from five months of observations, turned out to be 0.784. 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].

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 of Mineralnye Vody shows that (as in [7]) Correlation Coefficients are different for different altitudes. Figure 1 presents a typical scatter of points for the BUST muon counting rate versus the temperature at an altitude of 12500 m near Mineralnye Vody in 2008. The temperature data (in degrees centigrade along the abscissa axis) correspond to the beginning of a 12-hour period. The vertical axis represents the BUST counting rate of muons for the 15-min time intervals at which the temperature was measured. The value **K** = 0.442 was obtained for the Correlation Coefficient. The temperature data were taken from the website http://weather.uwyo.edu/upperair/sounding.

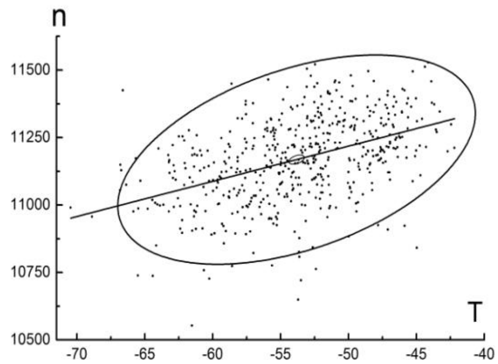

Fig. 1. BUST counting rate as a function of temperature at an altitude of 12000 m near the city of Mineralnye Vody.

ANALYZING THE CORRELATION BETWEEN THE BUST MUON COUNTING RATE AND THE TEMPERATURE AS A FUNCTION OF ALTITUDE

Preliminary investigation of correlations between the BUST counting rate and the temperature in the region of Mineeralnye Vody revealed a nontrivial dependence of the Correlation Coefficients on the altitude where the temperature was measured. Figure 2 presents the Correlation Coefficients **K** dependency. on the altitude **H**. The altitude is plotted against the horizontal axis, while the vertical axis represents values of the corresponding Correlation Coefficient.

We can see that correlation coefficient **K** change non-monotonically as a function of altitude **H**; in particular, a well-pronounced minimum is observed in the region of 15–20 km. The squares in Fig. 2 correspond to the Correlation Coefficients obtained in [7]. The numerical discrepancy between the values of the correlation coefficients 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 coefficient to go through a minimum with variation of the altitude is identical in this work and in [7], as can be seen in Fig. 2.

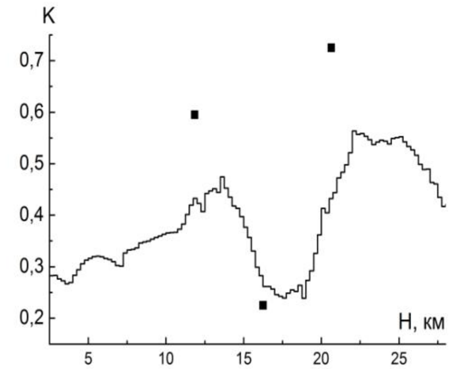

Fig. 2. Correlation coefficient versus the altitude of the atmospheric point where the temperature was measured near Mineralnye Vody. Squares represent the results in [7].

CORRELATION AND TEMPERATURE COEFCIENTS ANALISIS 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 intervals between six values of cosine of zenith angle θ 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 **α** have been calculated as

$$\frac{\Delta I}{I} = \alpha T,$$

where T is the temperature (K).

Correlation and Temperature Coefficients C and α can be calculated as

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

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 corresponding mean values for 2008 year.

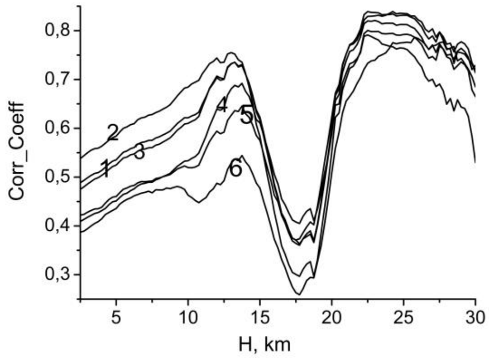

Fig. 3. The Correlation Coefficient dependency on the height of the atmosphere point, CRM data are one day averaged.
Curve 1: integral CRM;
curve 2-6: (6-j)/6≤cos(ɵ)≤(6-j+1)/6; j=1,2,3,4,5.

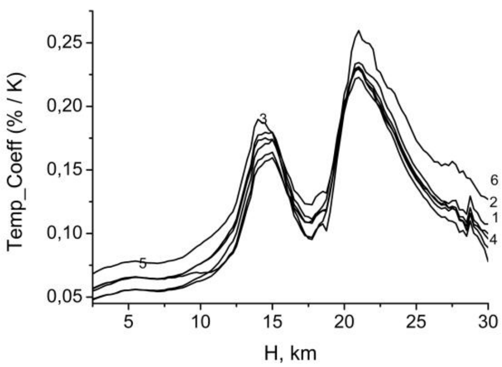

Fig. 4. The Temperature Coefficient dependency on the height of the atmosphere point, CRM data are one day averaged.
Curve 1: integral CRM;
curve 2-6: (6-j)/6≤cos(ɵ)≤(6-j+1)/6; j=1,2,3,4,5.

H =	12.5 km	17.5 km	25 km
$\sigma =$	5.428	3.045	5.583

Table 1.

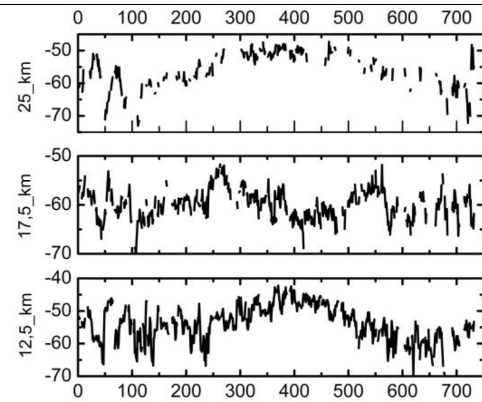

Fig. 5. Time variation of temperature (at heights being equal to 12.5, 17.5, 25.0 km correspondingly), horizontal axis represents a number of 12 hour interval of 2008 year.

Figures 3 and 4 shows us the behavior of the Correlation and Temperature Coefficients as a function of the height of the atmosphere point for equal solid angles corresponding 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. Figure 5 shows that this phenomenon may be related to the relatively small magnitude of temperature variation in time (the height being equal to 17.5 km, corresponding to the minimum of the Correlation Coefficient height dependency) against relatively significant magnitude corresponding the maxima (the heights being equal to 12.5 and 25 km correspondingly). Table 1 shows as the measure of the temperature time variation magnitude (in the terms of the Standard Deviation σ corresponding to the one year's (2008) temperature time series for different altitude) reproduce visually obtained qualitative picture from Fig. 5.

As one can see, the magnitude of temperature variation corresponding to minimum is approximately a half of the magnitude corresponding to maxima; it is remarkable that the values of the Correlation and Temperature Coefficients neighborhood of the minimum are approximately a half of the corresponding values neighborhood of the minima.

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 3 and 4).

CONCLUSIONS

Correlations between the rate of counting of high-energy muons on BUST and the temperature of the atmosphere in remote locations are investigated.

Correlations between the BUST integral (summed over all directions) counting rate of high-energy muons and temperature at distant points in the atmosphere were studied. There is qualitative agreement with the conclusions drawn in [7]. More complete investigation of variations in the muon flux and monitoring of the state of the atmosphere on the Earth's surface during unsteady atmospheric processes suggests an analysis of correlation effects and temperature coefficients for various arrival directions of particles at the observation level. The behavior of the Correlation and Temperature Coefficients as a function of the point height of the atmosphere (where the temperature was measured) have been presented for different of muons arrival directions to BUST (with equal solid angles). Minimum and maxima of the Correlation and Temperature Coefficients as a function of the height are related to the magnitude of the temperature variations for this altitude. The magnitude of the temperature variations corresponding to minimum is approximately a half of the magnitudes corresponding to maxima; it is remarkable that the values of the Correlation and Temperature Coefficients neighborhood of the minimum are approximately a half of the corresponding values neighborhood of the minima.

Irregularity in the behavior of the Correlation and Temperature Coefficients for altitudes above 30 km can be explained by the significant gaps in the temperature data for these heights**.**

Our results are of a preliminary nature, more complete research of variations in the muon flux assume certain theoretical model analysis. The Temperature Coefficients for cosmic ray muons were calculated in [8], in which the authors concluded that it was possible to reconstruct the temperature profile of the atmosphere at high altitudes, based on measurements of temperature coefficients of cosmic ray muons, if the ratio of the production of kaons and pions in nuclear interactions of nucleons with nuclei of air atoms were known. This quantity has so far been measured with sufficient accuracy in accelerator experiments, and the problem of reconstructing the temperature profile of the atmosphere could thus be solved if appropriate experimental data were available. Such data can be obtained using the complex of facilities of the Baksan Neutrino Observatory of the Institute for Nuclear Research. of the Russian Academy of Sciences.

ACKNOWLEDGMENTS

This work is partially supported by the Physics of Neutrinos and Neutrino Astrophysics program of the Presidium of the Russian Academy of Sciences; and by the Federal Targeted Program of Ministry of Science and Education of Russian Federation "Research and Development in Priority Fields for the Development of Russia's Science and Technology Complex for 2007—2013", contract no. 16.518.11.7072.

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