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Study of Atmospheric Temperature at Different Altitudes using Muon Angular Distribution at Sea Level

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A new method of continuous monitoring of changes of vertical temperature profile at altitudes from ground level up to stratosphere by the means of muon intensity measurements in a wide range of zenith angles was been developed and tested. Comparison of continuous sequences of derived values of temperature variations (for 2 hour intervals) with direct weather-balloon measurements (performed every 12 hours) demonstrates a good agreement at 9 levels of altitude ranging from 900 to 100 mb (with 100 mb step).

1. Introduction

It is well known that the cosmic ray flux at ground level depends on meteorological conditions and is related to changes in temperature T, and in atmospheric pressure P. The technique of monitoring of the atmospheric temperature at different altitudes was suggested more than 30 years ago [1]. The qualitative assessment of the change of the temperature at three different altitudes was obtained with the help of three different installations [2]. The measurement of variations of muon flux angular distribution for a wide range of zenith angles may be used to monitor the temperatures up to the stratosphere altitude by means of a large aperture setup [3]. These variations are described by:

$$\delta N(h_0,\theta) / N(h_0,\theta) = \int_0^{h_0} W_T(\Delta\varepsilon, h, h_0, \theta)\delta T(h)dh \,, \qquad (1)$$

where: $W_T(\Delta\varepsilon,h,h_0,\theta)$ is the differential temperature coefficient, dependent on the altitude of an atmospheric layer h, zenith angle θ along a trajectory of particles, level of observation h_0 and the energy threshold $\Delta\varepsilon$ for muon registration. Considering that the function W_T is known a priori the values T (h) can be found from the solution of (1). This technique still remained not implemented, up to the present time.

2. Methods

The study is carried out by means of the hodoscope TEMP [4] with active area of 9 m^2 that continuously measures an angular distribution of intensity of muons $N(\theta,\varphi)$ for a wide range of zenith and azimuthal angles: $0 \le \theta \le 60^0$ and $0 \le \varphi \le 360^0$ with accuracy of $1\text{-}2^0$. A level of observation is h_0 = 1030 g/cm^2 under the 2 m w.e. filter; a threshold energy of registration $\Delta\varepsilon \approx 400$ MeV. For these conditions, the calculated values of $W_T(\Delta\varepsilon,h,h_0,\theta)$ are available [3]. Further on they will be marked as $W_T(h,\theta)$. For obtaining the solution of the problem the atmosphere is conditionally separated into geopotential layers by width Δh=100 mb, in which the estimation of variations ΔT is carried out. The expression (1) for different angles is then reduced to a system of linear algebraic equations, where the integration is substituted by summation on different atmospheric layers with Δh width:

$$\begin{cases} \Delta N(\theta_1)/N(\theta_1) - \beta_p \Delta P = W_T(h_1,\theta_1)\Delta T(h_1)\Delta h_1 + \ldots + W_T(h_m,\theta_1)\Delta T(h_m)\Delta h_m \\ \ldots \\ \Delta N(\theta_n)/N(\theta_n) - \beta_p \Delta P = W_T(h_1,\theta_n)\Delta T(h_1)\Delta h_1 + \ldots + W_T(h_m,\theta_n)\Delta T(h_m)\Delta h_m \end{cases} \quad (2)$$

The index m corresponds to a separate atmospheric layer and n to an interval of zenith angles. The integral barometric effect correction on the average ($\beta_P\Delta P$, where β_P = - 0.15 % mb^{-1}) is included in (2). The values ΔP were measured every minute with 0.05 mb accuracy. The experimental data were grouped together in angles so that the event rate N(θ) had approximately equal values in all intervals, which provides identical statistical accuracy of results. For increase of accuracy the muon distribution data are summed in 2 hour period. Values N(θ) are obtained by summing of distribution N(θ,φ) over an angle φ within the limits of 360^0, because of the absence of azimuth dependence of muon angular distribution at high energy [4].

3. Discussion

In the experiment, the one-minute matrix arrays of muon angular distribution of intensity $N_{ik}(t)$ are registered, where each pair of indexes *ik* corresponds to values of angles (θ,φ) [4]. The angular size of individual cell is 2^0x2^0. Therefore, information N (θ) for each interval $\Delta\theta = \theta_{n+1} - \theta_n$ is obtained from a ring of the matrix data N_{ik}. In Figure 1, the segment of a matrix and the position of one of such rings are shown. It is clear that practically all cells located within the boundaries of the ring contribute to it only partially. In this case, the number of muons from a boundary cell for a given ring is proportional to the fraction of the cell area that is included in this ring.

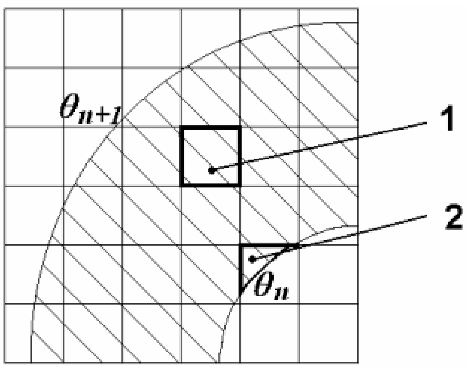

Figure 1. The scheme for the calculation of muon intensity for different cells of a matrix. Shaded area shows a segment of a ring with set of cells for an interval of angles $\theta_{n+1} - \theta_n$. 1 - internal cell of the ring (the intensity is taken into account completely), 2 - boundary cell (the intensity is proportional to a shaded part of the area of the cell).

In total, nine atmospheric layers, which means the altitudes h = 900, 800, …100 mb, were considered. Width of all angular intervals, except for the first one, equals to 3^0. The separate intervals of zenith angles Δθ, their average values <θ> and reference 2-hour statistics of muons N(θ) are listed in Table 1.

The solution of a set of equations (2) for 9 atmospheric layers (n=9) and 10 angular intervals (m=10) is found by means of the least squares method.

Figure 2 shows a variation of atmosphere temperature ΔT (h) at two stratosphere altitudes (100 and 200 mb) for a 2-week period of continuous measurements. At that time, the Earth magnetic field was quiet enough and it was not required to take into account the magnetosphere corrections for the muon intensity.

Table 1. Parameters from Direct Measurements

Number n	$\Delta\theta$, degree	$\langle\theta\rangle$, degree	$N(\theta)$
1	0 – 7	3,5	104580
2	9 – 11	10	89460
3	14 – 16	15	116200
4	19 – 21	20	133530
5	24 – 26	25	141900
6	29 – 31	30	137280
7	34 – 36	35	119480
8	39 – 41	40	103250
9	44 – 46	45	78130
10	49 – 51	50	53520

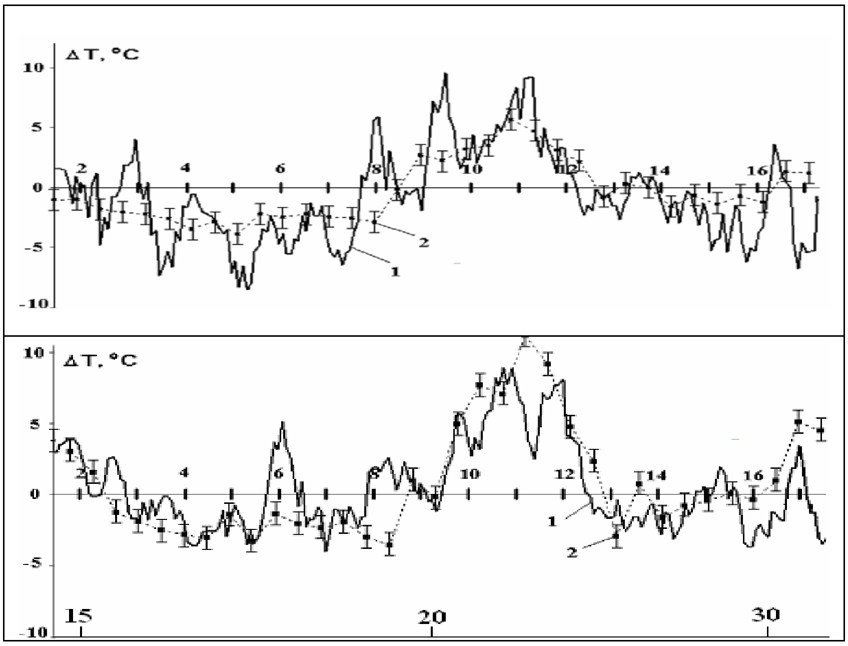

Figure 2. Variations of the temperature at 100 (upper panel) and 200 (lower panel) mb geopotential levels of stratosphere. Solid line (1) are data obtained from variations of the angular distribution of muons for 2-hour intervals and using a rounded data windowing method. Dotted line (2) represents direct measurements of temperature. X-axis - calendar time (days) from May 15 till May 31, 1998. Y-axis - change of temperature.

The direct measurements of the temperature with the help of weather balloons were regularly conducted (at 00:00 and 12:00 UT) by the Rosgidromet CAO for Moscow region. In Figure 3, the variations of temperature measured using both methods, for the same time interval relating to troposphere levels of 600 and 800 mb are shown.

The comparison of variation of the temperature at all other altitudes (300, 400, 500, 700 and 900 mb) gives a similar agreement with direct measurements. At atmosphere depth of 800 and 900 mb the difference between the results increases.

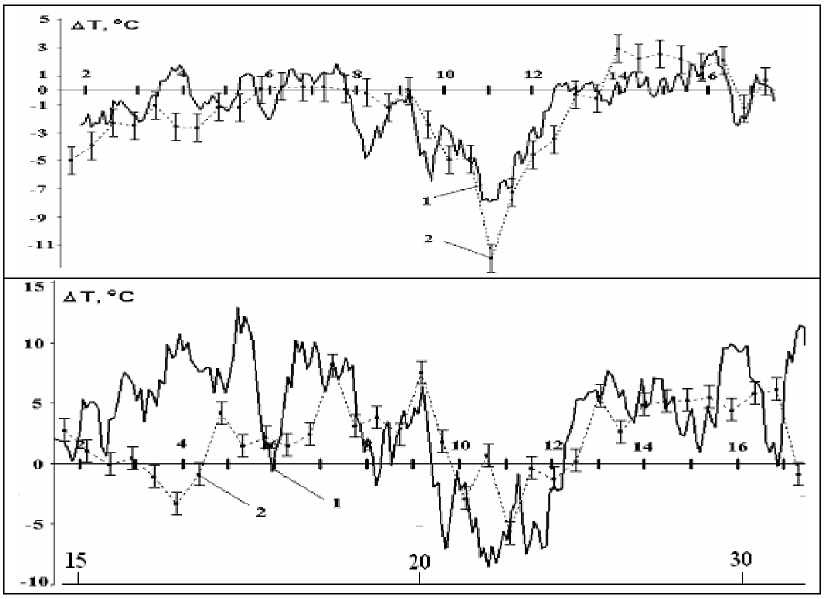

Figure 3. Variations of temperature at two levels of the troposphere: 600 (upper) and 800 (lower) mb. (1) - data obtained from variations of the angular distribution of muons, (2) - direct measurements of temperature. X-axis - calendar time from May 15 till May 31, 1998. Y-axis - temperature change.

The method was checked for different seasons of 1998 (for two-week long intervals at quiet magnetosphere). During data processing, the intensity of muons was not corrected for modulation of the flux of primary cosmic rays. A similar agreement of the reconstructed temperature profiles with direct measurements was found.

4. Conclusions

For the first time it has been shown in practice that precise measurements of differential angular distribution of muons in a wide range of zenith angles allow to carry out the continuous monitoring of the vertical profile of temperature of atmosphere up to stratosphere altitudes.

5. Acknowledgements

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