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The atmospheric muon flux in correlation with temperature variations in the low stratosphere (50-200 mb)

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Abstract: The dependence of the muon flux from the atmospheric parameters (pressure and temperature) is a well known effect since long time ago, that is usually corrected for in cosmic ray measurements. We have correlated at EAS-TOP (LNGS) the muon flux detected by the EMD detector (29 stations, 10 m^2 each, $E_{\mu,thr} >$3 MeV) with the atmospheric temperature (up to few mb level) monitored by the radio-soundings of the Aeronautica Militare at Pratica di Mare (Rome). A significant effect has been observed when the muon flux is correlated with the atmospheric temperature in the region 50-200 mb, as expected, since this is the region where the mesons of first generation are produced. The effect becomes even larger when the variations of the cosmic ray primary flux are taken into account (Neutron Monitor, Rome). Then, the technique has been used to monitor strong temperature variations in the low stratosphere through the muon flux in two periods, showing that the temporal pattern of the temperature in the low stratosphere is reproduced with a $\sim 2\ ^\circ$C uncertainty. The main results of this analysis are presented.

Introduction

The muon flux at ground level follows a power law spectrum which is a result of different factors: the primary cosmic ray spectrum (the injection spectrum), the properties (life time and interaction length) of the parent mesons (π and k) whose decay originates the μ flux, and the life time of the μ component. While the variations on the primary cosmic rays are of solar (i.e. Forbush decreases, flares) or of extra-solar origin (i.e. sidereal anisotropies), the cascade in atmosphere of the meson and muon components depends on the atmospheric parameters. The atmospheric effects on the μ flux have been the object of different studies in the past, among others [1, 2, 3, 4] and they have been mathematically treated and summarized by Dorman in [5]. In particular, Dorman has parametrized the variation of the μ flux (C) related to the variation of atmospheric parameters with the following expression: $\frac{\delta C}{C} = k_p \delta h_0 + \int_0^{h_0} W_T(h) \delta T(h) dh$, where h_0 is the observation level, $k_p$is the barometric coefficient and $W_T(h)$ are the partial temperature coefficients that characterize the contribution of each atmospheric layer to the total temperature effect. While the barometric effect is always negative because high pressure at observation level implies a higher aborption of the μ component in air, the temperature coefficients W_T have a different sign depending on the $E_{\mu,thr}$ of the detector. Experiments with threshold energies in the MeV region [1] observe negative $W_T(h)$ coefficients because the effect is related to the surviving probability of the low energy muons from the production to the detection level. A warmer and, therefore, less dense atmosphere, implies a longer path to be crossed by the μ with a higher probability of decaying on flight. On the other hand, experiments with $E_{\mu,thr}$ in the GeV [2, 3] or TeV [4] region observe positive $W_T(h)$. In this case, the effect is related to the competitive processes of decay and interaction of the parent mesons π and k. In fact, a warmer, or in other words, a less dense atmosphere increases the relative decay over interaction probability of mesons. The so produced μ are almost insensitive to decay effects on flight because of the much longer life time compared to the MeV counterpart. Dorman's calculations show also that the most predominant $W_T(h)$ coefficients are those related to the 50-200 mb (50-200 g/cm^2) region, where μ are produced by the decay of the mesons of first generation.

We have verified the above interpretation by means of a very simple simulation in which protons assumed as primary cosmic rays have been cascaded through an isothermal atmosphere. The temperature has then being changed only in the upper layers ($h < 250g/cm^2$) and the μ flux at ground level has been studied for different muon energy thresholds. The results showed that the temperature coefficient k_T (i.e. $W_T(50 < h < 200g/cm^2)$) of the following relation: $\frac{\Delta C}{C} = k_T \cdot \Delta T$ is $k_T^{sim} = (2.5 \pm 0.6) \cdot 10^{-3} K^{-1}$ for $E_{\mu,thr} > 220$ GeV such as for the Baksan case [3], indicating that most of the effect seen by the Baksan experiment ($k_T^{exp} = 3.72 \pm 0.38) \cdot 10^{-3} K^{-1}$ has to be attributed to the upper layers as mentioned before. On the other hand, the same simulation applied to the EAS-TOP experiment [6] ($E_{\mu,thr} > 3$ MeV), gave as a result $k_T^{sim} = (-6.7 \pm 1.3) \cdot 10^{-4} K^{-1}$. The signs of the two k_T coefficients (EAS-TOP and Baksan) also confirm the theoretical motivations. A remark has to be done here. Due to the completely different statistics involved in experiments with MeV or GeV $E_{\mu,thr}$ (~10 Hz for Baksan and ~3000 Hz/station in EAS-TOP), experiments with MeV thresholds are in principle sensitive to daily variations of the atmospheric temperature while underground detectors are only sensitive to seasonal variations.

Finally, it has been mentioned that the muon flux is also related to the primary cosmic ray flux which depends on extra-atmospheric effects. In the past, cosmic ray physisists have always corrected the μ flux for the atmospheric effects in order to study the primary cosmic ray variations, however, if atmospheric effects are the object of investigation, the correction has to be done, oppositevely, on the primary flux. The best way of operating in this sense is to use the data from Neutron Monitors which detect the neutron component of the atmospheric radiation that is only sensitive to the barometric effect.

Instruments and Detectors

The analysis has been performed by correlating the atmospheric μ flux detected by the Electromagnetic Detector (EMD) of EAS-TOP [6] at Gran Sasso National Laboratory (LNGS) (42.27° N, 13.34° E) with the atmospheric temperatures measured by the radio soundings of Aeronautica Militare at Pratica di Mare (Rome). The data of the Neutron Monitor in Rome have also been used to correct for modulations on the primary cosmic ray flux. All the three experiments were located at relative distances < 100 km, justifying the assumption that at high altitudes the atmospheric conditions were similar. The data of the three detectors used in this analysis cover the period November 1992 - July 1993.

The EMD detector at the time of the present analysis was an array of 29 stations (10 m^2 each) of plastic scintillators (NE102A, 4 cm thick). Each station was divided into 16 scintillator units (80 cm × 80 cm each), each unit being wieved by a Philips XP3162 photomultiplier. Photomultiplier signals were discriminated at 0.3 m.i.p. threshold level ($E_{\mu,thr}$ = 3 MeV) and counted on a scaler. The array was covering an area of 500 × 300 m^2 at an atmospheric depth of 810 g/cm^2, being sensitive to the charged component of the cosmic radiation (mainly e, μ). The typical μ rate of EMD was ~3 kHz/station. Each EMD station provided the μ counts every 100 s together with the local atmospheric pressure and temperature.

The radio-soundings were operated by Aeronautica Militare 2 - 4 times/day at 00, 06, 12 and 18 h UTC from the Pratica di Mare Station (41.66° N, 12.45° E) by launching Vaisala probes, model RS 80. The radio-soundings were providing different information, among others the temperature at several atmospheric layers (every few mb, till 3 mb height, with 0.1 mb resolution and ± 0.2 mb accuracy), with 0.1 °C resolution and ± 0.2 °C accuracy.

The Neutron Monitor in Rome [7] (41.90° N, 12.52° E) is a standard NM-64 type with 18 proportional counters divided in 3 detectors with 6 counters each. Further characteristics are 6.2 GV rigidity and 150 Hz counting rate.

Evaluation of the temperature effect for EAS-TOP

The periods used for the analysis were selected based on stable conditions of the apparatus and no influence from local atmospheric effects (see

period	$K_p[mb^{-1}] \times 10^3$	$k_T[K^{-1}] \times 10^4$	$k_T[K^{-1}] \times 10^4 - N.M.$
A: 11/27 - 12/15	-3.43 ± 0.05	-2.6 ± 2.1	-4.5 ± 2.1
B: 02/11 - 03/15	-3.96 ± 0.07	-6.3 ± 2.2	-7.6 ± 2.2
C: 05/01 - 06/03	-3.89 ± 0.08	-9.6 ± 1.1	-9.5 ± 2.1

Table 1: Barometric and temperature coefficients obtained for EAS-TOP in the three different periods of analysis. The last column reports the temperature coefficients when the correction for the Neutron Monitor data is applied.

tab. 1). In particular, the technique has been elaborated on period C and then repeated for periods A and B. Each EMD station is considered independent from the others and the dependence is searched by looking to a common effect of several EMD stations. First of all, the stability of the EMD detector was studied. The data of each station showed a poissonian behaviour on a 100 s time scale (σ_{100s} = 1.6 - 2.9 $\cdot 10^{-4}$). The stability on a daily and monthly scale was σ_d = 0.5% and $<$1% respectively. The correction for the primary flux eliminated systematic effects and slightly reduced the data dispersion.

The relative variation of countings has been searched according to the following relationship: $\frac{\Delta C}{C} = k_p \cdot \Delta P + k_T \cdot \Delta T$. As the barometric effect (k_p) is one order of magnitude higher (see tab. 1), it has to be corrected first. For the barometric dependence an average counting ($\overline{C}$) and pressure ($\overline{p}$) is calculated every run (average duration about one week). The data are then corrected for the barometric effect and the temperature one is extracted. For the temperature dependence, μ data have been integrated for 2 hours around the temperature data and the correlation has been searched. A study has been performed on the dependence of k_T from the temperature in the layer 50 - 300 mb, and the most significant effect was obtained by averaging the temperature in the 50 - 200 mb layers. Fig. 1 shows an example of $\frac{\Delta C}{C}$ versus ΔT for 2 modules in period C, while on the bottom of the same figure, the distribution of 23 k_T values, during the same period, is shown. Several checks have been performed in order to verify that the effect was related to the temperature in the low stratosphere No significant dependence was obtained by correlating $\frac{\Delta C}{C}$ with the local temperature (T_{loc}) and no significant correlation was found between the local pressure (p) and the temperature in low stratosphere (T_{100}). No residual pressure effects were found. A $\pm$ 6 h shift was applied to the T_{100} values and the correlation almost disappeared: k_T(-6 h) = (2.3 $\pm$ 1.4)$\cdot 10^{-4}$K^{-1}, k_T(+6 h) = (-1.3 $\pm$ 1.4)$\cdot 10^{-4}$K^{-1}.

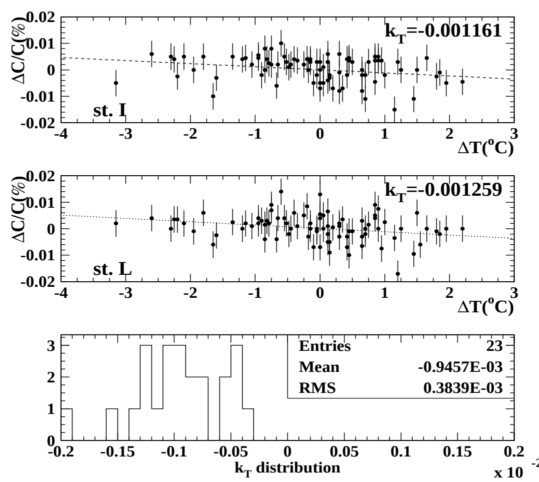

Figure 1: $\frac{\Delta C}{C}$ versus ΔT for 2 modules in period C in the top part of the figure, while the distribution of the 23 k_T values, during the same period, is shown in the bottom part.

In order to verify that the dependence was not related to the primary cosmic ray flux, the μ data renormalized by the barometric effect were first corrected for the neutron monitor variations and then the temperature effect was searched. Results are shown in the last column of tab. 1, and show that the temperature coefficient becomes even more significative (B and A). Finally, the k_T values are negative and of the same magnitude as expected from the simple simulation mentioned in section 1.

Monitoring temperature variations

The significant correlation between muon counting rates and temperature variations in the low stratosphere, suggested the possibility to monitor temperature variations in the low stratosphere by means of the muon flux. Periods A and B, were also periods in which the upper atmosphere was characterized by sudden and significant temperature variations lasting $\sim$1 week each. In order to find such effect, this time, after the correction for the barometric effect, the coefficient K_T was extracted from the following relationship: $\frac{C-\overline{C}}{\overline{C}} = K_T \cdot (T - \overline{T})$, where $\overline{C}$ and $\overline{T}$ represent the average counting rate and temperature in the 12 days (period B) of the sudden temperature variation (see fig. 2). By inverting such relationship $T_\mu = \frac{1}{K_T} \cdot \frac{C-\overline{C}}{\overline{C}} + \overline{T}$ we can estimate how the muon flux is able to reproduce the temporal dependence of the temperature in the stratosphere. Fig. 2 shows that the general trend of the temperature in such period is fairly reproduced. The same techinque applied also to the first part of period A, when no effect related to the primary cosmic flux was present, is satisfactory too. From the dispersion of the T_μ values around the true ones, the uncertainty of this technique can be deduced and it is on the order of σ_T = 2.1 °C.

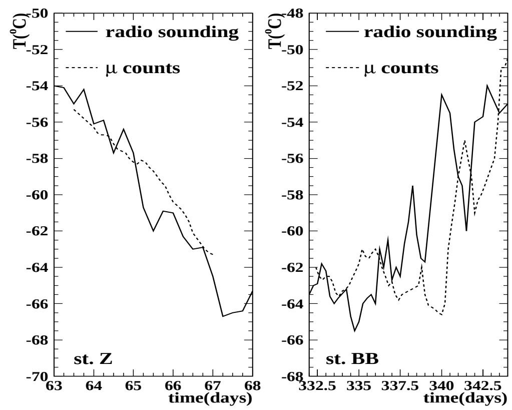

Figure 2: Original temporal behaviour of the temperature in the low stratosphere (average of layers 50 - 200 mb) and temporal pattern of the temperature as extracted from the variations in the μ counts at EAS-TOP. Left figure refers to period B and right figure to period A for one station. Similar patterns are obtained for the other stations.

Conclusions

It has been shown that the EMD detector was sensitive to the temperature variations in the lower stratosphere. The results are in fair agreement from the expectations of a simplified model. The technique was applied to estimate temperature variations in the low stratosphere by looking at the variations of the μ counts with $E_{\mu,thr} > 3$ MeV. In a couple of cases, with strong temperature variations in the low stratosphere it was possible to follow the true temporal behaviour of the temperature. This result shows that temperature variations such as those happening during *sudden stratospheric warmings* [8], in principle, could be monitored by a muon detector. A similar result was recently obtained by [9]. The importance of a neutron monitor has to be stressed, in order to avoid or correct effects related to the primary cosmic ray flux.

Few improvements are suggested: a) very well insulated detector to avoid local temperature effects on the detector; b) coincidence of two photomultipliers to reduce noise effects; c) a lead layer on top of the detector to have a better discrimination between muon and electron components.

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