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

M. Bertaina\textsuperscript{a,b}, L. Briatore\textsuperscript{a}, A. Longhetto\textsuperscript{a}, G. Navarra\textsuperscript{a,b} and EAS-TOP Coll.
\textsuperscript{a} Dipartimento di Fisica Generale dell’Università Torino, Italy
\textsuperscript{b} Istituto Nazionale di Fisica Nucleare Torino, Italy
bertaina@to.infn.it

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\textsuperscript{2} each, $E_{\mu,thr} > 3$ MeV) with the atmospheric temperature (up to few mb level) monitored by the radiosoundings 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 ($\pi$ and $k$) whose decay originates the $\mu$ flux, and the life time of the $\mu$ 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 $\mu$ flux have been the object of different studies in the past, among others [6, 4, 2, 8] and they have been mathematically treated and summarized by Dorman in [5]. In particular, Dorman has parametrized the variation of the $\mu$ flux (C) related to the variation of atmospheric parameters with the following expression: 

$$\frac{dC}{dh_0} = k_p \delta h_0 + \int_0^{h_0} W_T(h) \delta T(h) dh,$$

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 absorption of the $\mu$ 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 [6] 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 $\mu$ with a higher probability of decaying on flight. On the other hand, experiments with $E_{\mu,thr}$ in the GeV [4, 2] or TeV [8] 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 $\pi$ 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 $\mu$ 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
The atmospheric muon flux in correlation with temperature variations

The analysis has been performed by correlating the atmospheric $\mu$ flux detected by the Electromagnetic Detector (EMD) of EAS-TOP [1] 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 m² each) of plastic scintillators (NE102A, 4 cm thick). Each station was divided into 16 scintillator units (80 cm × 80 cm each), each unit being viewed 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 m² at an atmospheric depth of 810 g/cm², being sensitive to the charged component of the cosmic radiation (mainly $e^\pm, \mu^\pm$). The typical $\mu$ rate of EMD was ~3 kHz/station. Each EMD station provided the $\mu$ 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...
The daily and monthly scale was \( \sigma \) shows an example of the temperature in the 50-200 mb layers. Fig. 1 most significant effect was obtained by averaging the data of each station. First of all, the stability of the EMD stations was studied. The data of each station showed a poissonian behaviour on a 100 s time scale (\( \sigma_{100s} = 1.6 \cdot 2.9 \cdot 10^{-4} \)). The stability on a daily and monthly scale was \( \sigma_d = 0.5\% \) 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: \( \Delta C = k_p \cdot \Delta P + k_T \cdot \Delta T \). 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, \( \mu \) 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 \( \Delta C \) versus \( \Delta T \) 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.

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.

<table>
<thead>
<tr>
<th>period</th>
<th>( K_p [mb^{-1}] \times 10^4 )</th>
<th>( k_T [K^{-1}] \times 10^4 )</th>
<th>( k_T (K^{-1}) \times 10^4 - N.M. )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: 11/27 - 12/15</td>
<td>(-3.43 \pm 0.05)</td>
<td>(-2.6 \pm 2.1)</td>
<td>(-4.5 \pm 2.1)</td>
</tr>
<tr>
<td>B: 02/11 - 03/15</td>
<td>(-3.96 \pm 0.07)</td>
<td>(-6.3 \pm 2.2)</td>
<td>(-7.6 \pm 2.2)</td>
</tr>
<tr>
<td>C: 05/01 - 06/03</td>
<td>(-3.89 \pm 0.08)</td>
<td>(-9.6 \pm 1.1)</td>
<td>(-9.5 \pm 2.1)</td>
</tr>
</tbody>
</table>

Figure 1: \( \Delta C \) versus \( \Delta T \) 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.

sphere (\( T_{100} \)). No residual pressure effects were found. A \( \pm 6 \) h shift was applied to the \( T_{100} \) values and the correlation almost disappeared: \( k_T(-6 \ h) = (2.3 \pm 1.4) \cdot 10^{-4} K^{-1} \), \( k_T(+6 \ h) = (-1.3 \pm 1.4) \cdot 10^{-4} K^{-1} \).

In order to verify that the dependence was not related to the primary cosmic ray flux, the \( \mu \) 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 ~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:

$$\frac{C - \bar{C}}{\bar{C}} = K_T \cdot (T - \bar{T}),$$

where $\bar{C}$ and $\bar{T}$ 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

$$T_{\mu} = \frac{1}{K_T} \cdot \frac{C - \bar{C}}{\bar{C}} + \bar{T},$$

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 technique 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 $T_{\mu}$ values around the true ones, the uncertainty of this technique can be deduced and it is on the order of $\sigma_T = 2.1 ^\circ C$.

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 $\mu$ 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 [9], in principle, could be monitored by a muon detector. A similar result was recently obtained by [3]. The importance of a neutron monitor has to be stressed, in order to avoid or correct effects related to the primary cosmic ray flux.

References