Simulation of atmospheric temperature effects on cosmic ray muon flux

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Abstract. The collision between a cosmic ray and an atmosphere nucleus produces a set of secondary particles, which will decay or interact with other atmosphere elements. This set of events produced a primary particle is known as an extensive air shower (EAS) and is composed by a muonic, a hadronic and an electromagnetic component. The muonic flux, produced mainly by pions and kaons decays, has a dependency with the atmosphere's effective temperature: an increase in the effective temperature results in a lower density profile, which decreases the probability of pions and kaons to interact with the atmosphere and, consequently, resulting in a major number of meson decays. Such correlation between the muon flux and the atmosphere's effective temperature was measured by a set of experiments, such as AMANDA, Borexino, MACRO and MINOS. This phenomena can be investigated by simulating the final muon flux produced by two different parameterizations of the isothermal atmospheric model in CORSIKA, where each parameterization is described by a depth function which can be related to the muon flux in the same way that the muon flux is related to the temperature. This research checks the agreement among different high energy hadronic interactions models and the physical expected behavior of the atmosphere temperature effect by analyzing a set of variables, such as the height of the primary interaction and the difference in the muon flux.

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INTRODUCTION

The atmospheric muon flux produced by extensive air showers (EAS), which is originated mainly by pions and kaons decays, has a known dependency with the effective temperature (T_{eff}) of the atmosphere. This is due to the fact that their chance of interaction is correlated to the atmosphere's density profile. The correlation with the atmosphere's effective temperature and the final muon flux was detected by many experiments, such as AMANDA, Borexino, IceCube, MACRO and MINOS. The results shown by these experiments demonstrate that the variation in the muon flux (R_μ) has a linear correlation with a change in T_{eff}, described by $\Delta R_\mu/\langle R_\mu\rangle = \alpha_T \Delta T_{eff}/\langle T_{eff}\rangle$, with $\alpha_T = 0.86 \pm 0.05$ [1]; $\alpha_T = 0.93 \pm 0.04$ [2]; $\alpha_T = 0.9$ [3]; $\alpha_T = 0.83 \pm 0.013$ [4]; and $\alpha_T = 0.873 \pm 0.009$ [5]. Since different experiments have detectors in different mwe depths, each experiment detects the muon flux in different energy ranges, which explain the different values for α_T. A higher value for T_{eff} implies in a major number of meson decays, resulting in a higher muon flux, hence the positive value for α_T.

SIMULATION OF THE TEMPERATURE EFFECT

CORSIKA simulates an isothermal model of the atmosphere, which is the same effective model used on Ref. [1, 2, 3, 4, 5] and its atmosphere is composed by 78.1% of N_2, 21.0% of O_2 and 0.9% of Ar. The model has 5 flat, parallel to the ground, layers, 4 of them having an exponential profile for the depth step function $X(h) = a_i + b_i \exp(-h/c_i)$, where i is the layer, while the last (above 100 km altitude) has a linear dependency $X(h) = a_5 + b_5 h/c_5$ [6]. The set of all 15 parameters (a_i, b_i and c_i) defines the atmosphere's parameterization and it varies according to time and position around the globe.

The change in the muon flux caused by a variation in the atmosphere's temperature can not be seen directly in a simulation, since CORSIKA's framework does not provide the control of T_{eff}. Therefore, we change this variable indirectly by changing the atmosphere parameterization. For this, we used two widely known parameterizations of the U.S. standard atmosphere: Linsley's [7] and Keilhauer's [7, 8] parameterizations (figure 1 (a)).

The set of all 15 parameters defines the atmosphere density profile, thus, a change in the parameterization produces a variation in its T_{eff}. This implication results in an indirect method to simulate the physics seen by Ref. [1, 2, 3, 4, 5], where the change in the depth step function can be correlated to the muon flux by the form $\Delta R_\mu/R_\mu = \alpha_X \Delta X/X$ in the same way that the variation in the effective temperature is also related to the variation in the final muon flux. Here, $\Delta R_\mu/R_\mu = (R_\mu^L - R_\mu^K)/R_\mu^K$ represents the difference in the final muon number produced by each parameterization, while $\Delta X/X = [X(h)_L - X(h)_K]/X(h)_K$ is the relative difference between both parameterizations and it is shown in figure 1 (b).

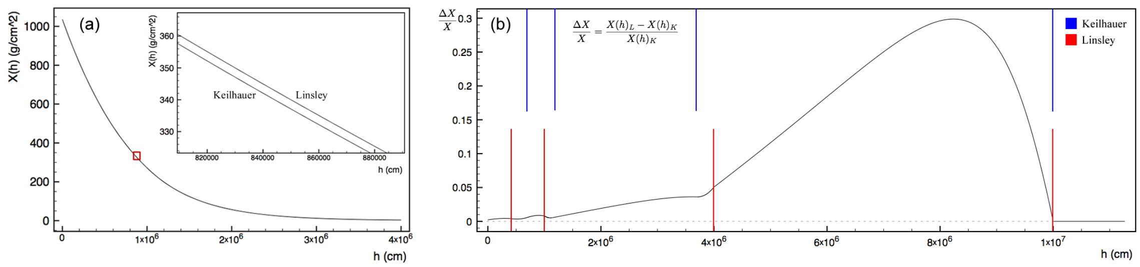

FIGURE 1. (a) Plot of $X(h)$ and a comparison between Linsley's and Keilhauer's depth functions. (b) Relative difference between Linsley's and Keilhauer's parameterizations according to the altitude. The red (Linsley) and blue (Keilhauer) lines represent the layers limits for each parameterization.

In order to check this temperature effect, we have generated a set of simulations using version 6.99 of CORSIKA [7]. For each result we have done a pair of simulations, which changes the atmosphere parameterization and maintain all other parameters fixed. Every simulation run produced 10^6 EAS and the effect was checked within a set of 3 primary fixed energy values (10 TeV, 50 TeV and 100 TeV) and 3 primary compositions (H, He and Fe). This was repeated for 3 different high energy hadronic interaction models, resulting in a total of 54 simulation runs. To check the validity of the high energy models only, muons with less than 85 GeV were neglected by the simulations.

RESULTS

The method for simulating the temperature was confirmed by checking a set of predicted behaviors. The first expected result is due to the fact that $X(h_0)_L > X(h_0)_K$ for any random h_0. This implies that the EAS will interact with less atmosphere below h_0 for Linsley's parameterization, resulting in a higher T_{eff} and a major number of muons for such parameterization, leading to a positive value for $\Delta R/R$ (results presented on table 1). The $\Delta R/R$ has a small value because the difference between the first interaction distribution on both parameterization is also small, as is presented on figure 2 (a). A threshold energy cut of 600 GeV was made for muons at the observational level in order to produce a more evident temperature effect. Low energy muons (with at least 85GeV, produced in lower altitudes of the atmosphere) still produce this effect, but they lead to smaller values for $\Delta R/R$. Another expected result presented on table 1 is that the mean altitute of first interaction ($\langle h_i \rangle$) is always higher for Linsley's parameterization. The third expected result refers to the mean height of first interactions for different chemical compositions: the cross section is bigger for heavier nuclei, thus we expect that the mean altitude of first interaction grows accordingly to the nuclei's mass (see figure 2 (b) and table 1). Higher values for $\langle h_i \rangle$ implies in higher values for $\Delta X/X$, which leads to bigger gaps between the mean values of the height of first interactions for heavier nuclei (result that is also shown on table 1). The same value for $\Delta X/X$ shown on table 1 for each model and composition is due to the fact that the distribution of the height of first interaction is very similar in all studied models, as is shown on figure 2 (c).

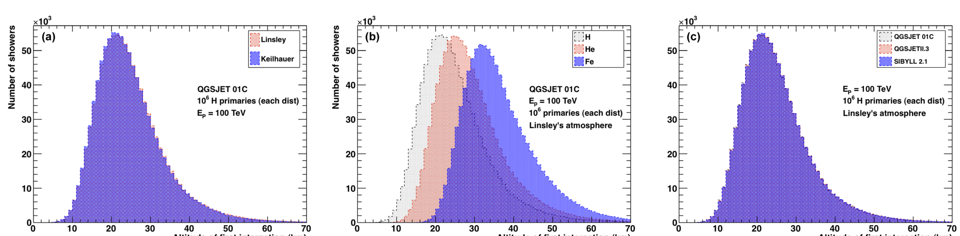

FIGURE 2. The figure shows the altitude of first interactions according to (a) both parameterizations, (b) three different chemical composition (c) three different high energy hadronic interaction models.

TABLE 1. Table with all variables analyzed in this study. The results considers a threshold energy of 600 GeV for muons at the observational level. This table presents the results only for EAS with 100 TeV of primary energy. Other energy values (10 TeV and 50 TeV) are in agreement with the presented results.

Model	Composition	R_μ ($\times 10^3$) Linsley	R_μ ($\times 10^3$) Keilhauer	$\langle h_L \rangle$ (km)	$\langle h_K \rangle$ (km)	$\Delta R_\mu / R_\mu (\times 10^{-3})$	$\Delta X/X$
QGSJET 01C	*H*	$(1{,}922 \pm 1)$	$(1{,}909 \pm 1)$	25.0 ± 8.9	24.8 ± 8.8	7.2 ± 1.0	$0.026^{+0.009}_{-0.013}$
	He	$(2{,}431 \pm 1)$	$(2{,}412 \pm 1)$	29.2 ± 9.2	28.9 ± 9.0	8.1 ± 0.9	$0.031^{+0.004}_{-0.013}$
	Fe	(184 ± 0.4)	(182 ± 0.4)	36.7 ± 9.7	36.3 ± 9.4	11.6 ± 3.3	$0.036^{+0.014}_{-0.007}$
QGSJETII.3	*H*	$(1{,}913 \pm 1)$	$(1{,}902 \pm 1)$	25.0 ± 9.0	24.8 ± 8.8	5.9 ± 1.0	$0.026^{+0.009}_{-0.013}$
	He	$(2{,}461 \pm 1)$	$(2{,}441 \pm 1)$	29.2 ± 9.2	29.1 ± 9.0	8.1 ± 0.9	$0.031^{+0.004}_{-0.013}$
	Fe	(295 ± 0.5)	(292 ± 0.5)	36.6 ± 9.7	36.1 ± 9.4	9.3 ± 2.6	$0.036^{+0.014}_{-0.007}$
SIBYLL 2.1	*H*	$(1{,}926 \pm 1)$	$(1{,}915 \pm 1)$	25.1 ± 9.0	24.8 ± 8.8	5.3 ± 1.0	$0.026^{+0.009}_{-0.013}$
	He	$(2{,}394 \pm 1)$	$(2{,}379 \pm 6)$	28.6 ± 9.2	28.3 ± 9.0	6.0 ± 0.9	$0.031^{+0.005}_{-0.013}$
	Fe	(466 ± 0.7)	(462 ± 0.7)	36.6 ± 9.7	36.2 ± 9.4	9.7 ± 2.1	$0.036^{+0.014}_{-0.007}$

CONCLUSIONS

The described method for simulating temperature effects on CORSIKA v6.99 agrees consistently with all expected fore mentioned behaviors for an increase in the effective temperature of the atmosphere within the primary energy range from 10 TeV to 100 TeV, with all high energy hadronic interaction models (QGSJET 01C, QGSJET II.3 and SIBYLL 2.1) and all primary composition tested.

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