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Variation of the shower lateral spread with air temperature at the ground

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Abstract: The vertical profile of air density at a given site varies considerably with time. Well understood seasonal differences are present, but sizeable effects on shorter time scales, like day-to-day or day-to-night variations, are also present. In consequence, the Molière radius changes, influencing the lateral distribution of particles in air showers and therefore may influence shower detection in surface detector arrays. In air shower reconstruction, usually seasonal average profiles of the atmosphere are used, because local daily measurements of the profile are rarely available. Therefore, the daily fluctuations of the atmosphere are not accounted for. This simplification increases the inaccuracies of shower reconstruction. We show that a universal correlation exists between the ground temperature and the shape of the atmospheric density profile, up to altitudes of several kilometers, hence providing a method to reduce inaccuracies in shower reconstruction due to weather variation.

Introduction

In experimental studies of highest energy cosmic rays, the atmosphere serves both as the target in which primary cosmic rays interact and the medium in which extensive air showers develop. Therefore, as precise as possible knowledge of properties of the atmosphere is very important. In particular, the vertical profile of air density is of primary importance.

It was shown in [1, 2, 3] that the time variability of the vertical profile of air density (and consequently, atmospheric depth) is very important. Systematic, site-specific seasonal variation of the atmospheric profile is observed. In addition, irregular variation is observed on shorter time scales like day-to-day or day-to-night. Variation of the atmospheric density implies a variation of the Molière radius and in consequence, the lateral spread of air shower particles varies accordingly. Therefore, uncertainties of the profile of air density influence air shower detection in surface detector arrays. A trigger bias may result from inaccurate accounting for lateral spread of shower particles. Thus it is important to account for atmospheric variation as accurately as possible to avoid errors in shower reconstruction.

In this paper we use UK Met Office data [4] to study the vertical profile of air density. These data contain temperature and pressure profiles measured by radiosondes at a worldwide network of balloon launching stations. In the following we present an analysis of data collected in years 2002–2004 at the station in Salt Lake City (USA) and at the station in Mendoza (Argentina), located near the site of the southern Pierre Auger Observatory.

Lateral particle distribution

The lateral particle distribution in a shower is determined by the Molière radius, which is inversely proportional to air density. This distribution observed at the ground level is shaped mainly in a lowest layer of the atmosphere, about two cascade units thick, above the ground.

The vertical distribution of air density, and consequently the Molière radius, varies a lot from the model distribution usually assumed in air shower studies. It was shown in [3] that this variation is

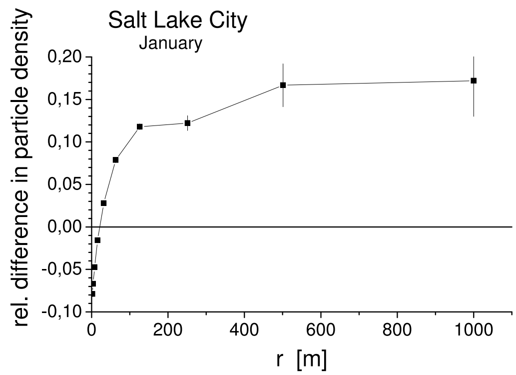

Figure 1: Relative difference in lateral distribution of particle density in a vertical 10^{19} eV proton shower simulated using atmospheric profiles in two extreme January days at Salt Lake City.

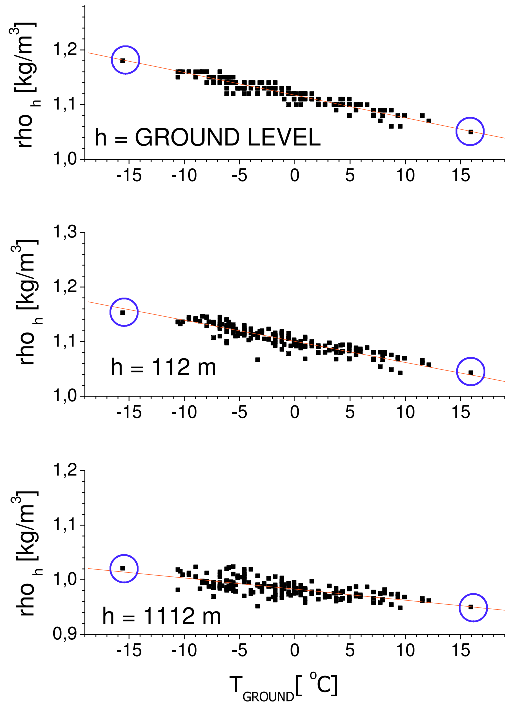

Figure 2: Example of correlation of air density at two different altitudes above ground, with temperature at the ground level. The circles mark the extremely warm and cold days used to prepare Fig.1.

especially large in winter. As an axample, January atmospheric profiles at Salt Lake City were used to simulate shower development. Showers simulated using different atmospheric profiles differ considerably in lateral particle distribution. Lateral distributions of a 10^{19} eV proton shower were simulated with CORSIKA [5] using atmosphere profiles of extremely warm and cold days in January. The relative difference of the lateral particle density is shown in Figure 1. This difference can be as large as 15% at large distances from the shower axis. Although it may be treated as an upper limit rather than a typical value, one should note that the 15% variation in particle density due to weather effects alone is a very large difference. This example demonstrates the need for a profile of atmospheric density as accurate as possible.

Local daily soundings of the atmosphere are rarely available at air shower detector sites, so that one has to use some average profiles of air density in everyday shower reconstruction. Neglecting the daily variation of the atmosphere introduces inaccuracies in shower reconstruction. Therefore, an important question is whether one can approximate the true atmospheric profile based on some easily available data, like temperature and pressure at ground level, when the radiosounding is not available. This is the subject of the current study.

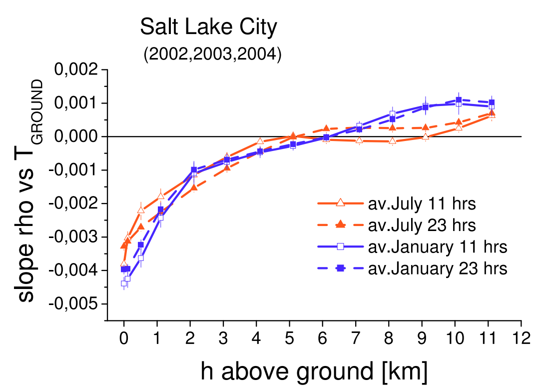

Figure 3: Slope of the correlation shown in Fig.2 as a function of altitude, at different times of day in summer and winter at Salt Lake City.

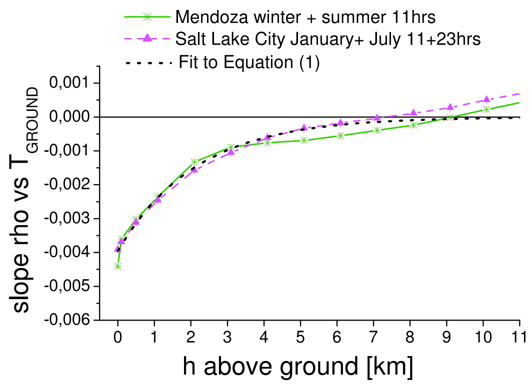

Figure 4: Comparison of the correlation slopes at Salt Lake City and Mendoza. The dotted line represents the fits of Eq.1.

Air density correlation with ground temperature

A correlation exists between air temperature *at the ground level* and air density *at altitudes above ground*, as shown in Fig.2. This correlation can be well approximated by a linear relation. The spread of the data points reflects the influence of atmospheric pressure variation on air density. Thus the variation of temperature appears to be more important.

The slope of the linear correlation of Fig.2 is shown in Fig.3 as a function of altitude above ground. The correlation appears to be quite independent of seasons or time of day. It is strongest at the ground level and fades away with increasing altitude. A similar pattern of air density correlation with the ground temperature is observed in Mendoza. Dependences of the correlation slope on altitude at Salt Lake City and at Mendoza are compared in Fig.4.

The slope of the correlation presented in Fig.4 can be well parameterized by an exponential function

$$\alpha(h) = A\exp(-h/B) \tag{1}$$

where h is the altitude above ground. The fitted values of the parameters for Salt Lake City are: $A = -0.0040 \pm 0.0002$ kg/m^3/°C, $B = 2.15 \pm 0.25$ km and for Mendoza: $A = -0.0040 \pm 0.0002$ kg/m^3/°C, $B = 2.21 \pm 0.23$ km. These fits are shown in Fig.4 by the dotted lines (the two lines overlap). Therefore one can conclude that the correlation of air density *at a given altitude above ground* with temperature *at the ground level* is universal, with very little dependence on site location, season or time of day. If so, this correlation may be used to refine extensive air shower studies.

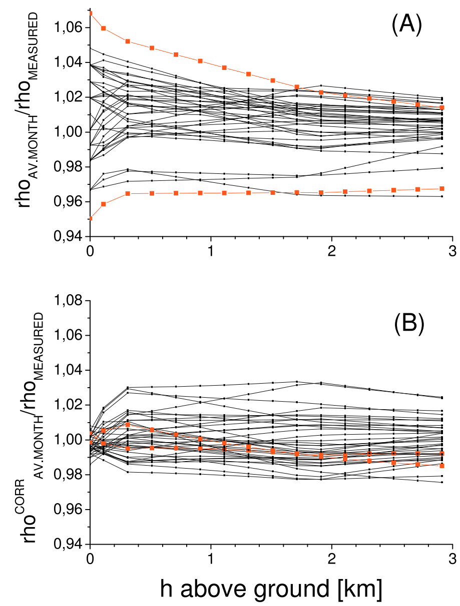

Figure 5: (A) Ratios of the average monthly profile of air density to profiles actually measured in many January days at Salt Lake City; (B) Ratios of the corrected average profile to daily measurements.

Correction to the profile of air density

Results of the previous section indicate that the actual profile of air density $\rho(h)$ can be approximated using an average (e.g. monthly) profile $\rho^{\text{avg}}(h)$, with a correction depending on a deviation of the ground temperature T_G from the average T_G^{avg}:

$$\rho^{\text{corr}}(h) = \rho^{\text{avg}}(h) + \alpha(h)(T_G - T_G^{\text{avg}}) \tag{2}$$

where $\alpha(h)$ is the slope of the linear correlation of air density with ground temperature given by Eq.1.

The actual daily profiles of air density over Salt Lake City are compared with the average monthly

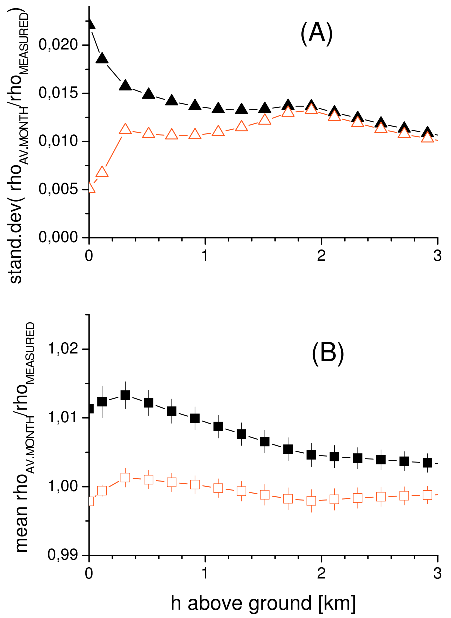

Figure 6: (A) Standard deviation and (B) mean of ratios shown in Fig.5 as a function of altitude. The filled symbols pertain to uncorrected density profiles of Fig.5A, while the open symbols concern the corrected profiles of Fig.5B.

profile. In Fig.5A ratios of the average to the daily measured ones are plotted. A relatively large spread (several percent), especially near the ground level, is seen. In Fig.5B the ratios of $\rho^{\rm corr}(h)$ to the actually measured ones are plotted. It is evident that the correction of Eq. 2 considerably reduces the dispersion of the density ratios at low altitudes. This means that at low altitudes $\rho^{\rm corr}(h)$ approximates the actual profile considerably better than the monthly average does. This is illustrated in Fig.6, in which the mean and standard deviation of the sets of curves plotted in Fig.5 are shown as a function of altitude. The correction effectively works only at low altitudes, as the correlation shown in Fig.4 vanishes with increasing altitude. Nevertheless, we note that the lateral distribution of shower particles at the ground level is determined mainly by the Molière radius over lowest two cascade units, i.e. over lowest $\sim$750 m above ground, in case of the Pierre Auger Observatory.

Conclusion

The observed correlation of ground temperature with air density at altitudes up to several kilometers above ground provides a method to approximate the true profile of atmospheric density. For shower reconstruction it is always best to use the local daily measurement of the atmospheric profile. However, when the actual measurement of the profile is not available for a given day, an approximation of the daily profile can be derived from an average (e.g. monthly) profile, adjusted with a correction depending only on temperature at the ground. Since the temperature reading at ground is always available, this correction helps to reduce inaccuracies in shower reconstruction, especially in surface arrays of detectors.

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