Atmospheric effects on extensive air showers observed with the Surface Detector of the Pierre Auger Observatory

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High-energy cosmic rays (CRs) are measured by recording the extensive air showers (EAS) of secondary particles they produce in the atmosphere. As the atmosphere is the medium in which EAS evolves, its state and variations in pressure P, temperature (T) and air density ($\rho \propto P/T$), affect the lateral and longitudinal development of the air shower.

We have studied the impact of atmospheric variations on EAS with data collected during 4 years with the array of surface detectors (SD) of the Pierre Auger Observatory. The rate of events shows a $\sim 10\%$ seasonal modulation (see Fig. 1), and a $\sim 2\%$ diurnal one, that can explained by a model including the effects associated with the variations of P and ρ. The former is related to the total amount of matter traversed by the shower, while the latter influences the Molière radius (r_M) and hence the lateral distribution of the shower particles.

The impact on $S(1000)$ (the experimental observable related to the shower energy) can then be modeled with a Gaisser-Hillas and Nishimura-Kamata-Greisen profile, which describe respectively the longitudinal and the lateral distribution of the electromagnetic component of the EAS. In fact, the relevant value of r_M is the one corresponding to the air density two radiation lengths (X_0) above ground in the direction of the incoming EAS [1]. Due to the thermal coupling of the lower atmosphere with the surface of the Earth, the variation of ρ at $2X_0$ is the same as at the ground on large time scales (e.g. on daily average), while it is smaller on shorter time intervals. Introducing the average daily density ρ_d and the instantaneous departure from it, $\rho - \rho_d$, we have that the signal measured by the SD detector is:

$$S = S_0[1+\alpha_P(P-P_0)+\alpha_\rho(\rho_d-\rho_0)+\beta_\rho(\rho-\rho_d)] \quad (1)$$

whereS_0 is the signal that would have been measured at some reference atmospheric conditions with pressure P_0 and density ρ_0.

The water-Cherenkov detectors are sensitive to both the electromagnetic (em) component and the muonic component of the EAS: $S = S_{em}+S_\mu$. Since the muonic component is almost insensitive to atmospheric variations, as confirmed by simulations, the coefficients will depend on the electromagnetic fraction of the signal $F_{em} = S_{em}/S$, whose value and zenith angle dependence is obtained by full shower simulations.

$$\alpha_P = -F_{em}(\theta)\,\frac{1}{g}\left[1-\frac{\hat{X}_{max}}{X}\right]\frac{\sec\theta}{\Lambda} \quad (2)$$

where $X = X_v \sec\theta$ is the slant depth with X_v the grammage at the detector site. Λ is an effective attenuation length associated to the longitudinal development of the EAS at 1 km from the axis and g is the acceleration of gravity. The depth of the EAS maximum at 1 km from the axis is $\hat{X}_{max} = X_{max} + 150\,\mathrm{g\,cm^{-2}}$, with X_{max} being the average value of the EAS maximum at the core measured by the FD [2].

The ρ correlation coefficient describing the daily averaged modulation of S is:

$$\alpha_\rho = -F_{em}(\theta)\,\frac{4.5-2s}{\rho} \quad (3)$$

where $s = 3/(1+2\cos\theta\; X_{max}/X_v)$ is the shower age. Concerning the modulation on short time scale, we adopt:

$$\beta_\rho = \exp(-a\cos\theta)\,\alpha_\rho \quad (4)$$

where a characterises the amplitude of the daily ρ variation in the lower atmosphere and is completely independent of the EAS development.

It can be demonstrated [4,5] that the modulation of the trigger rate and, more in general, of the rate of SD events with a reconstructed energy higher than an arbitrary E_{th} value, is similar to the modulation of the signal (eq. 1). In

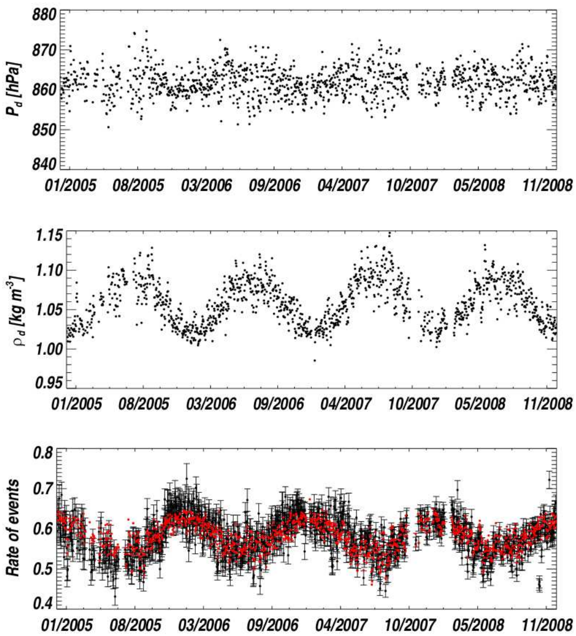

Figure 1. Seasonal modulation of pressure (top) and and air density (centre) measured at ground at the site of the Pierre Auger Observatory (daily averages). The rate of triggering events (bottom, black) is mainly affected by the air density variation. Red points show the result of the data fit (see text). A similar modulation, with smaller amplitude, can be observed on diurnal scale.

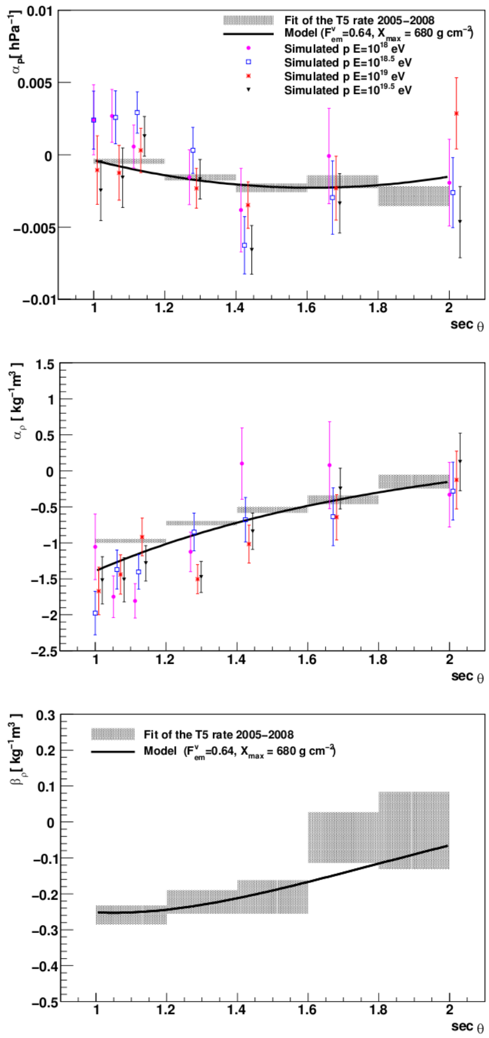

Figure 2. Weather coefficients as a function of the zenith angle. Lines represent the prediction of our model (with X_{max} and vertical electromagnetic fraction indicated in the box), dashed rectangles were obtained by fitting the experimental rate of triggering events, points refer to full air shower simulations in different atmospheric profiles.

this case the coefficients are proportional to the signal ones, with a common proportionality constant, independent on the weather effects. Hence a maximum likelihood fit of the rate (red points in the bottom panel of Fig. 1) allows to extract the experimental value of the weather correlation coefficients.

Finally, the model is validated with full CORSIKA [6] simulations of extensive air showers at fixed energies and fixed angles using seasonal averages of atmospheric profiles obtained with radiosonde measurements at the site of the Observatory [7].

A comparison of the experimental coefficients with the simulation results and the prediction of the model is shown in Fig. 2. An overall good agreement is obtained not only for the description of the modulation of the total rate, but also for the zenith dependence of the atmospheric effects.

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