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X_{max} and energy systematic errors due to molecular atmosphere variations.

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The earth's atmosphere serves as a giant calorimeter which can be used to study UHECR by the fluorescence detection method. We use radiosonde data taken daily at SLC airport to study the stability of the atmospheric parameters in the Utah desert. The daily measurements of the pressure, temperature and humidity profiles over the period of 6 years show that the Utah desert's atmosphere is extremely stable. We present a comparison with the atmospheric models used for the HiRes data reconstruction and discuss the effect of the uncertainty in atmospheric parameters on X_{max} and energy.

1. Introduction

We observe ultra high energy (UHE) particles through their interaction with the atmosphere. These interactions are seen as an extensive air shower (EAS). Analyzing EAS development we can estimate physical parameters of the incident particle. The atmosphere is a part of our detector, and knowledge of the atmospheric conditions becomes very important for a high resolution measurement such as the HiRes experiment. It is well known that the atmospheric parameters like pressure, density, relative humidity can change rather quickly over a short period of time. For the UHECR data reconstruction, it is essential to know these characteristics at each point of the EAS as well as on the light propagation path from that point to the detector on a event-by-event basis. Unfortunately, very often this is impossible. One of the ways to handle this problem is to use an atmospheric model. However, one should very carefully investigate the goodness of such an approximation as well as it's limitations. Any model might introduce statistical and systematics errors into our measurements. In extreme cases, the discrepancies between the real atmosphere and the model become drastic [1]. Thus, it is very important to understand what kind of uncertainties are introduced by the model. The main observed parameters of EAS are the energy and the X_{max}. We estimate the energy using a transmission coefficient which strongly depends on the integrated density between the point of interaction and the detector. The X_{max} of EAS is the slant depth of the shower at height of the N_{max}. In other words, we need to know the variations in the atmospheric pressure vertical profile. One of the methods to understand the influence of the model is by studying the radiosonde data.

2. Radiosonde Data

Radiosondes are the balloon-borne instruments that are sent up to a height of 45 km. They carry temperature, pressure and relative humidity sensors, as well as a radio transmitter and a tracking system. During the balloon ascend the equipment can provide information about the atmosphere such as pressure, geopotential height, temperature, dewpoint depression, wind direction and wind speed. The radiosondes at SLC are launched at least twice a day (at 00:00 and 12:00). We analyzed all available data collected at the SLC airport weather station during 1998-2004. The period is chosen to check the long-term atmospheric stability as well as the short-term one. This also coincides with the operational time of the HiRes detectors. The data is available online at http://raob.fsl.noaa.gov/.

3. HiRes Atmospheric Model

The atmospheric model chosen by the HiRes group for data reconstruction is the US Standard Atmosphere 1976 [2]. Three different pressure-density vertical profiles are used to take into account the atmospheric seasonal changes. As seen from Figure 1, such an approximation describes the real atmospheric conditions very well.

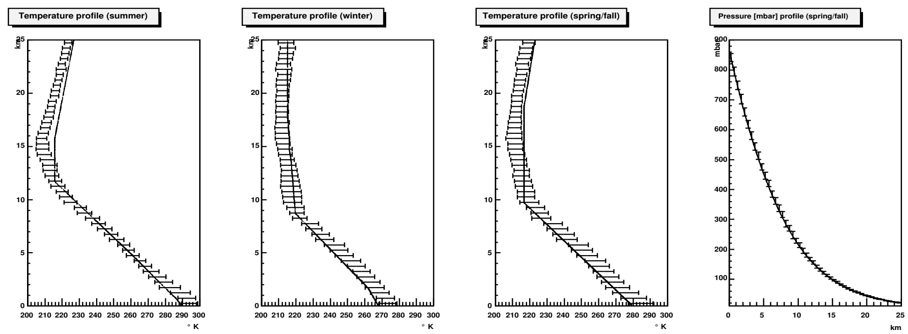

Figure 1. Temperature profiles for different seasons and pressure profile for spring/fall: model (solid line) and radiosonde data (spread shown as a bars).

4. Discussion

4.1 Atmospheric Stability

Figure 2 shows the pressure variations at different heights (2 km, 4 km, 8 km and 16 km above the ground) measured by the radiosonde for the whole data set (6 years) without any cuts. As can be seen, the seasonal changes in pressure prevail over the short-term fluctuations: day-to-day deviations do not exceed 2% for all heights while seasonal changes are up to 6%.

4.2 Energy Reconstruction

The energy of the incident particle is reconstructed from EAS integrated signal.The observed intensity is related to the intensity of the source through the atmosphere transmission correction because of the light scattering between the source of fluorescence and the detector.

$$I \propto I_0 \cdot T^m \cdot T^a, \tag{1}$$

where T^m and T^a are the transmission coefficients for the molecular (Rayleigh) and the aerosol (Mie) scattering. Since the total energy is proportional to the observed fluorescence intensity, the relative uncertainty in energy can be estimated via uncertainties in both transmission factors. In reality, besides molecular and aerosol scattering, the correction for Cherenkov light contamination and multiple scattering also should be taken into account.However, it is a second-order corrections and we do not discuss it in this paper.

Unlike the correction for light scattering in a pure molecular atmosphere, which can be easily derived from the common atmospheric parameters (pressure, temperature, humidity), the correction for Mie scattering depends

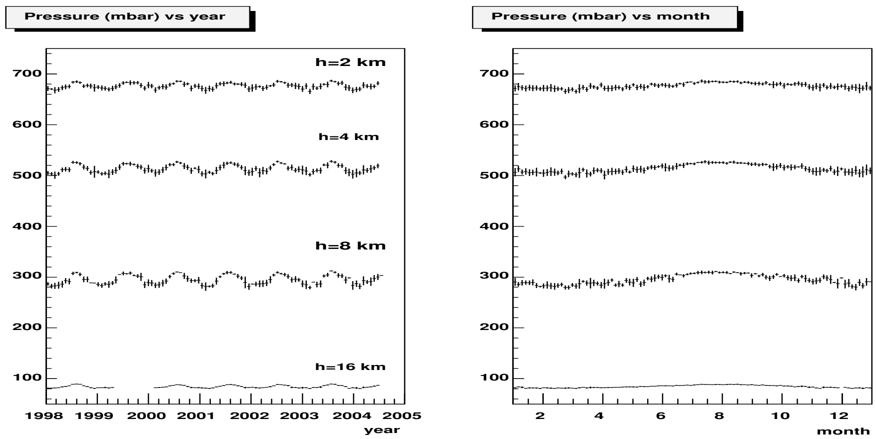

Figure 2. Pressure variations at different heights above the ground.

on the nature of the aerosols (their shape, size, composition) that can not be predicted by a model and usually requires special atmospheric monitoring. These measurements are discussed in [4].

Under the assumption of a 1D atmosphere, the molecular transmission depends on the location of the light source with respect to the detector (height, z, and viewing angle, α), the density of the atmosphere, $\rho(z)$, along a light path and the wavelength of the light, λ:

$$T^m = T^m(z, \alpha, \lambda) = e^{-\int_0^z \frac{\rho(z)dz}{\Lambda^m(\lambda)} \cdot \frac{1}{\sin(\alpha)}}, \tag{2}$$

where $\Lambda^m(\lambda) = 2970 \cdot (\frac{\lambda}{400nm})^4$ gm/cm^2 is the Rayleigh extinction length. At the HiRes site elevation this corresponds to $\Lambda^m \sim 1661 \cdot (\frac{\lambda}{350nm})^4$ gm/cm^2. It is easy to show [3] that the relative uncertainty in T^m can be estimated as:

$$\frac{\Delta T^m}{T^m} \approx \frac{1}{\sin(\alpha)} \cdot \frac{\Delta(\delta P(z))}{\Lambda^m}, \tag{3}$$

where $\delta P(z) = P(0) - P(z)$ is the pressure difference between ground and the height of the source of light and $\Delta(\delta P(z))$ is its uncertainty. We can treat the uncertainty as a difference between radiosonde data and the HiRes model: $\Delta(\delta P(z)) = \delta P(z)_{radiosonde} - \delta P(z)_{model}$ (see Figure 3). This gives us an estimation for the transmission coefficient systematic correction which is less than or equal to 4% for most of the HiRes detectors field of view and does not exceed 10% in the worst case scenario (bad weather conditions, low (3-6°) elevation viewing angles etc.).

4.3 X_{max} Reconstruction

While the energy is deduced from the integrated fluorescence signal the height where EAS reaches its maximum can be directly observed. As discussed before, the pressure-density variations do not distort the shape of the observed signal profile, thus, we would expect an insignificant change in the obtained height of EAS maximum. With the event geometry known, the X_{max} is calculated as the slant depth at that height. Hence the uncertainty in the X_{max} due to the atmospheric fluctuations could be determined as:

$$\Delta X_{max} \sim \Delta P(z_{max}) \cdot \frac{1}{\cos(\theta)}, \tag{4}$$

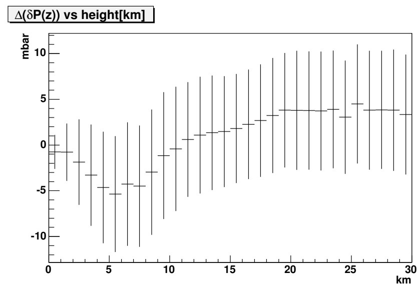

Figure 3. Uncertainty in pressure difference between ground and the height of the source of light. No cuts applied.

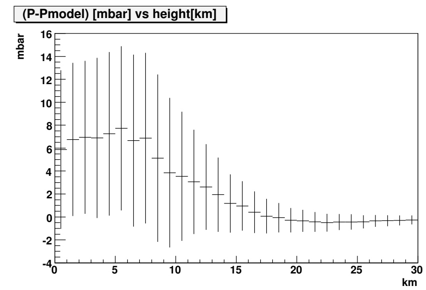

Figure 4. Uncertainty in pressure at given height.

where z_{max} is the height of shower maximum, θ is the zenith angle of the EAS and $\Delta P(z_{max})$ is the difference between the radiosonde data and the HiRes model at the height of z_{max}(see Figure 4). With z_{max} in range of 1-8 km and the average $\cos(\theta)$ of the order of 0.83, this gives us a systematic shift in X_{max} about +10 gm/cm$^2\pm$ 10 gm/cm^2. Knowing that z_{max} only depends on the energy of the incident particle and the uncertainty $\Delta P(z_{max})$ is almost constant over all range of z_{max}, we can conclude that this correction is practically uniform for all energies.

5. Conclusions

We analyzed the radiosonde data to study the features of the Utah molecular atmosphere which appears to be very stable with clearly pronounced seasonal variations. These variations are taken into account by the HiRes atmospheric model. The diurnal fluctuations appear to be small and they introduce insignificant errors in energy and elongation rate measurements, while X_{max} measurements require a systematic correction of order +10 gm/cm^2, if one uses the HiRes seasonal model instead of radiosonde data.

6. Acknowledgements

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