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Atmospheric Monitoring Using Radiosonde Data for TA

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Atmospheric monitoring for air shower analysis in the Telescope Array (TA) experiment has been investigated. We carried out Monte Carlo studies of air shower reconstructions by using the radiosonde data obtained around the times of the shower events, which are available through the World Wide Web, and examined the systematic errors in the shower parameter determinations as for $X_{\rm max}$, the atmospheric depth at the shower maximum. We found that by using the radiosonde data, sufficient accuracies in the parameter determination can be obtained, while a stationary atmospheric modeling as the US Standard Atmosphere model is not suitable for an air shower experiment with fluorescence detectors. The accuracy in the $X_{\rm max}$ determination is evaluated as smaller than 10 g/cm^2 when we employ the atmospheric data obtained by radiosondes launched from the nearest station of the TA site at a time within 6 hours of shower events.

1. Introduction

The existence of the super-GZK cosmic rays observed with AGASA [1] is one of the important unsolved problems in astrophysics. The Telescope Array (TA) experiment, of which the detectors are now under construction in Utah, has been planned to clarify the origin of cosmic rays at the highest energies (ultra high energy cosmic rays, hereafter UHECRs). In the TA experiment, we observe air showers of UHECRs both with a ground detector array and with fluorescence telescopes [2]. With this hybrid observation, we can measure the primary energies and arrival directions of UHECRs with good accuracies [3].

The key in the air fluorescence technique is how accurately the atmospheric condition is measured. The variations in atmospheric condition such as the pressure or the temperature affect the atmospheric depths, the fluorescence yields, and the photon scatterings, which lead to uncertainties of air shower reconstructions. Above all, the atmospheric depths directly affect the longitudinal developments of air showers, and therefore affect determination of $X_{\rm max}$ (the depth at the maximum shower development), which is an important parameter to identify the primary particles.

A use of the US Standard Atmosphere model (US-SA model) [4] is one of the ways to include atmospheric conditions in shower analysis. However, it is not clear whether the actual atmosphere at the moment of an air shower event is the same as such a stationary model because of the temporal and spatial variations in the atmospheric conditions. In this work, we consider to use the atmospheric data obtained by radiosondes, launched at the meteorological observatories near the TA site, for the analysis of air showers observed with fluorescence detectors. We carried out Monte Carlo studies to generate air shower events and to reconstruct shower profiles by using the atmospheric parameters calculated from the US-SA model and the radiosonde data, respectively. By estimating systematic errors in the shower parameter determinations in each case, we examine the feasibility of the use of the radiosonde data for atmospheric monitoring in TA.

2. Variations in Atmospheric Condition

A radiosonde is a meteorological instrument carried by a balloon to measure the pressures and the temperatures etc. up to an altitude of about 30 km. Each state of the U.S. has more than one meteorological observatory to launch such radiosondes every 12 hours, and the data are available through the World Wide Web [5]. In the present analysis, we use the data at the six stations near the TA site (Table 1). The nearest station, SLC, is 180km away from the TA site, and the second, Elko, is 320km away.

Table 1. Radiosonde Observatories Near the TA Site

Station Name	State	Latitude [deg]	Longitude [deg]	Elevation [m]
Flagstaff	Arizona	35.23N	111.82W	2179
Grand Junction	Colorado	39.12N	108.53W	1472
Boise	Idaho	43.57N	116.22W	871
Elko	Nevada	40.87N	115.73W	1608
Salt Lake City	Utah	40.77N	111.97W	1288
Riverton	Wyoming	43.06N	108.47W	1688

First, we examined seasonal variations in the atmospheric condition. The atmospheric depths as a function of altitude (the atmospheric depth profile) were calculated from the measurements at SLC in February, May, August, and November, 2004. The left panel of Figure 1 shows the differences between the average atmospheric depths for each month and the atmospheric depths calculated from the US-SA model. In this figure, it is found that the seasonal variations are about 25 g/cm^2 at altitudes of 8-10km while they are small at higher altitudes.

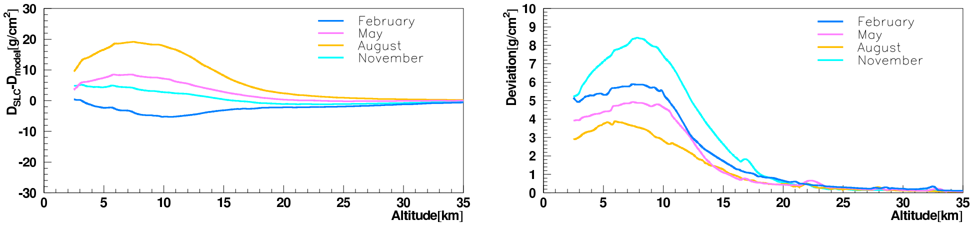

Figure 1. Left: Differences between the average atmospheric depths for each month and the atmospheric depths calculated from the US-SA model, Right: Standard deviation in the atmospheric depths from the average

Next, we can see daily variations in the right panel of Figure 1, which shows the standard deviation in the atmospheric depths from the average. The deviation is the largest at altitudes of 8-10km, 8 g/cm^2 in November for example, and is small at higher altitudes. Moreover, the variations are moderate in summer compared to in autumn or winter: the maximum deviation is 4 g/cm^2 in summer, while 8 g/cm^2 in autumn.

We also investigated the atmospheric depth profiles at the six stations listed in Table 1. Figure 2 shows the relative differences between the profiles at SLC and those at other stations in February and in August, respectively. The maximum difference in the atmospheric depths is 4±5 g/cm^2 in winter, and 3±3 g/cm^2 in summer at altitudes of 8-10km. However, the differences are small compared to the daily variations.

3. Influence on Air Shower Analysis

As seen in the previous section, there are temporal and spatial variations in atmospheric conditions, hence in atmospheric depths. Thus it must be investigated how an uncertainty in the atmospheric depths at the time and at the position of an air shower event affects the shower reconstruction. In this section, we describe Monte Carlo studies to evaluate the systematic errors in shower reconstructions in various atmospheric conditions.

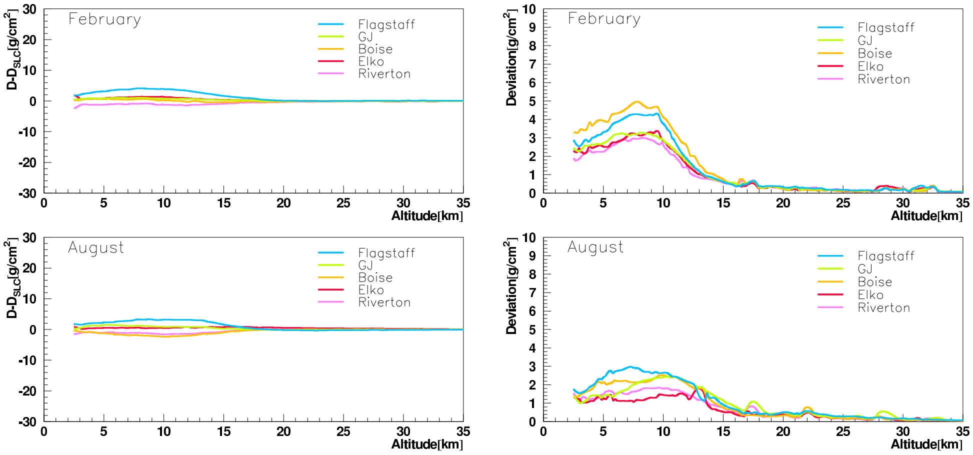

Figure 2. Differences between the atmospheric depth profiles at SLC and those at other stations (Left: average, Right: standard deviation)

3.1 Seasonal Variations

First we consider seasonal variations in the atmospheric conditions. 5,000 proton-induced showers with a fixed energy of 10^{20} eV and with various incident zenith angles were generated, using two data sets of radiosondes launched at SLC on one day in February or August. Then each shower was reconstructed using two atmospheric conditions; one is derived from the radiosonde data and the other is from the US-SA model.

Table 2. Differences between the shower parameters of reconstructed events by using the radiosonde data and those by using the US-SA model

	$\Delta \log E$ [eV]	$\Delta X_{\rm max}$ [g/cm^2]	$\Delta\theta$ [deg]
February	-0.007 ± 0.002	+4.84 ± 4.62	0.00 ± 0.05
August	-0.001 ± 0.012	-33.64 ± 11.57	0.02 ± 0.05

Table 2 lists the differences between the shower parameters of reconstructed events by using the radiosonde data and those by using the US-SA model. The effects on the determination of the primary energies and the arrival directions are negligible. However, significant differences in $X_{\rm max}$ in the reconstructed showers are found. The systematic error in $X_{\rm max}$ determination is about 5 g/cm^2 in February and 30 g/cm^2 in August. From these investigations, we can conclude that stationary atmospheric models as the US-SA model are not satisfactory for air shower analysis and the actual atmospheric condition should be monitored as accurately as possible.

3.2 Daily and Spatial Variations

Next we investigate the systematic error in $X_{\rm max}$ determination due to the daily and spatial variations in the atmospheric conditions. We generated 3,000 proton-induced showers with a fixed energy of 10^{20} eV and a fixed incident zenith angle of 60 degrees, using randomly sampled radiosonde data obtained at SLC in February and

November. Each generated shower was reconstructed using several types of radiosonde data sets, obtained at different time from air shower events or at different stations from SLC.

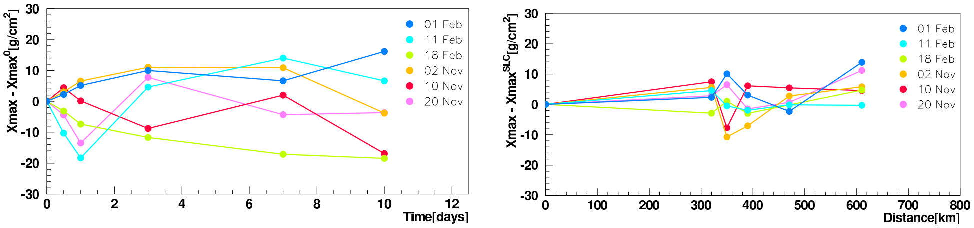

Figure 3. Left: Systematic errors in $X_{\max}$ determination due to the daily variations, Right: Systematic errors in $X_{\max}$ determination due to the spatial variations

The results are shown in Figure 3. The left panel shows the systematic errors in $X_{\max}$ determination due to the daily variations in atmospheric conditions, versus time differences from the shower events, and the right panel shows those due to the spatial variations versus distance from SLC. In the left panel, it is found that when we use atmospheric data at the time within 6 hours of the air shower event, the systematic errors in determination of $X_{\max}$ are smaller than 5 g/cm^2. However, when we employ off-day data neglecting the atmospheric conditions at an event, the errors increase up to 20 g/cm^2. We also found in the right panel of Figure 3 that the systematic error of $X_{\max}$ due to the spatial variations is small compared to that caused by the daily variations. At Elko, which is 320 km away from SLC, the error is 8 g/cm^2 at most. Recalling that the TA site is 180km away from SLC and 320km away from Elko, we can say that the systematic error in $X_{\max}$ is smaller than 8 g/cm^2 using the measurements at SLC for TA.

As a result, when we use the radiosonde data taken at SLC at a time within 6 hours of the shower event for atmospheric monitoring in TA, the systematic error in $X_{\max}$ determination due to the temporal and spatial variations in atmospheric condition is smaller than 10 g/cm^2.

4. Conclusions

We considered to use the atmospheric data measured by the radiosondes launched at meteorological observatories for the analyses of air showers observed with the TA fluorescence detectors. Through Monte Carlo studies, we found that the variations in atmospheric conditions affect $X_{\max}$ determination significantly and the stationary atmospheric model is inadequate for the air shower analyses. However, when we use such public radiosonde data for atmospheric monitoring in TA, sufficient accuracy can be obtained. The systematic error in $X_{\max}$ determination due to the temporal and spatial variations in atmospheric conditions is smaller than 10 g/cm^2 when we use the radiosonde data at SLC at a time within 6 hours of air shower events.

References

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