Atmospheric Effects on Muon Flux at Project GRAND

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Abstract: GRAND consists of 64 proportional wire chamber detector stations located just north of the University of Notre Dame and has been used to detect muon events since 1995. In this study, the data has been analyzed to investigate the contribution of atmospheric pressure and temperature, and calculate correction coefficients. This study used GRAND single track muon flux data and NOAA balloon and weather station data from 4 October 2005 through 31 November of 2009 to investigate trends in muon flux caused by temperature changes as well as surface pressure variations. To easily consider the effect of temperature, the upper air data sets were reduced to the altitude of the pressure corresponding to the interaction length of a 50 GeV proton, 8.53 kPa. This analysis yields a pressure correction coefficient of -0.98 and a temperature correction coefficient of -0.57.

Keywords: Temperature Correction, Pressure Correction, Cosmic Ray, Weather

1 Introduction

In order to better understand the nature of cosmic rays using muons, it is important to understand the behavior of both the primary and secondary particles as they interact with the atmosphere. Atmospheric pressure measured at the detector is inversely correlated with muon flux as increases in pressure or air mass means that the muons lose more energy before reaching the surface. This phenomena can be corrected for via $N=N_0\exp[\beta (P-P_0)/P_0]$ where N is the corrected rate, N_0 is the measured muon rate, β is the barometric pressure coefficient, P is the measured air pressure at that time, and P_0 is a reference pressure. This relationship can be approximated by a linear equation since $\beta (P-P_0)/P_0$ is sufficiently small.

The temperature is likewise inversely proportional to low energy muon flux since as the average temperature of the atmosphere increases, the atmosphere expands causing the cosmic ray primary to interact at a higher altitude. This forces the muon to travel a longer distance before reaching the detector so it has a higher probability of decaying. To easily consider the effect of temperature on atmospheric expansion and to allow for easy temperature correction in the future, instead of looking directly at the temperature of different air layers and calculating an effective temperature, the mean altitude of pion creation was used. This is closely linked to the height of muon creation since pions have short decay times and so muons are created close to the point of pion creation.

The altitude of mean pion creation was assessed for a 50 GeV proton which has an interaction cross-section of 278 millibarns (mb) [2] so on average it will interact at height with an air pressure of 8.52 kPa. Because of the similarity between the pressure and temperature affects, the same correction can be done using $N=N_0\exp[\alpha (H-H_0)/H_0]$ where N is the corrected rate, N_0 is the measured muon rate, α is the temperature coefficient, H is the height of mean muon creation at that time, and H_0 is a reference height; for small variations the same linear approximation can be made.

The low energy single track muon flux data used for this study was the sum of the four huts with the highest counting rate during each 10 minute time period thus conservatively eliminating stations with non uniform response during this time period.

2 Background

Project GRAND is an array of 64 detector stations located north of the University of Notre Dame at 41.7° N and 86.2° W at an altitude of 220 m above sea level. Two experiments are run simultaneously at the array: the tracking of low energy single muon events and the detection of high energy air showers. The single track muon experiment is increasingly sensitive to primary energies >10 GeV with a median value of 50 GeV for vertical tracks. Each station contains four proportional wire chamber (PWC) plane pairs. Each station contains eight 1.29 m^2 PWC planes yielding a total active area of 82 m^2. Each of the four chambers in a detector contains a horizontal plane of wires running north-south and another plane of wires running east-west. When a charged particle passes through the chamber, it leaves a trail of ions which accelerate toward the closest signal wire. As they gain energy, they collide with more gas molecules and release more charged particles in a process known as gas amplification which further increases the charge collected on the signal wire resulting in a small current. By identifying the hit wires in each plane and comparing the event position for each vertical plane, the angle of the muon track can be reconstructed to within 0.5°, on average, in each of two projected planes: up/east and up/north. A 50 mm thick steel plate is situated above the bottom two PWC planes to discriminate between muon tracks which penetrate the steel and electron tracks which stop, shower, or are deflected by the steel. The array collects data at a rate of ~2000 identified muons per second. Added details are available at: http://www.nd.edu/~grand.

3 Pressure

In order to study the effect of barometric pressure on low energy muons, hourly pressure data from NOAA taken at the South Bend Airport [3] was correlated with observed muon flux. Because seasonal temperature variations dilute the effect of atmospheric pressure over long periods of time, only sudden changes in pressure corresponding to fronts passing through the area were used to isolate the effect of pressure on flux. Nineteen fronts were analyzed using simple regression analysis. These fronts were identified by looking for regions in the pressure data where the atmospheric pressure changed by at least 0.068 kPa per hour for at least 10 consecutive hours with at most only one hour's pressure gradient less than this threshold; an example can be seen in Figure 1. A linear fit was then applied to the fractional change in pressure and flux values and the slope was taken to be the barometric correction factor. The fractional change in flux was calculated with respect to the windowed average of the 100 muon flux and pressure values surrounding the front event in order to decrease the effect of seasonal variations. In order for the fit to be used for the experiment, the correlation coefficient for pressure and flux data had to be less than -0.8 corresponding to a r-square value of 0.64. These fits reveal a wide range of possible barometric correction coefficients ranging from -0.50 to -1.65 but averaged around -1.00 +/-0.03 see Table 1.

4 Temperature

Flux and temperature data were monitored for four years to investigate seasonal variations due to temperature. Atmospheric datasets of temperature, pressure, and altitude were provided by NOAA via their weather balloon flights every 12 hours [3]. During each of these flights, the balloon's data recorder tracks the temperature and altitude at a preprogrammed set of barometric pressures. Five NOAA stations were selected in the region around

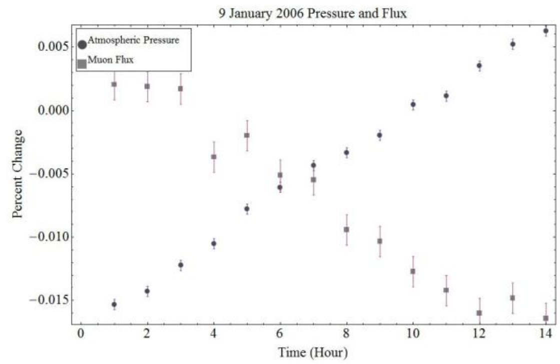

Figure 1. Percent Change in atmospheric pressure and muon flux over 14 hours as a front moved through the area causing a large suddent change in pressure.

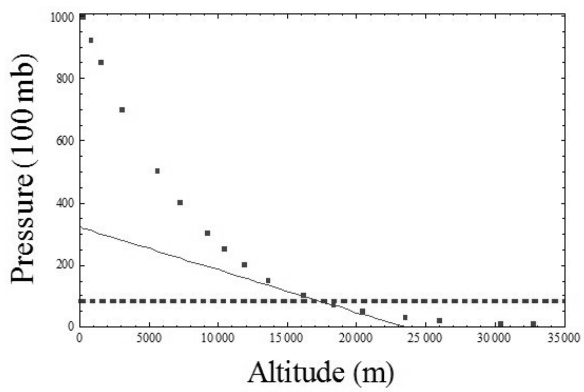

Figure 2. Sample model of pion creation height where the data points represent NOAA balloon altitude and pressure data, the dotted line indicates the pressure corresponding to pion creation and where the fitted line intersects the dotted line is the mean creation altitude.

Northern Indiana as seen in Table 2. For each atmospheric profile of a balloon flight the mean pion creation altitude for a 50 GeV Proton corresponding to the altitude with a pressure of 8.53 kPa was found using a simple linear interpolation between the two closest data points, the altitudes corresponding to 7 kPa and 10 kPa an example of which can be seen in Figure 2. The pion creation height at GRAND was then interpolated using the weighted average of the five stations based upon inverse distance for which at least three balloon stations had to contribute data at that hour. Because the number of uniformly active detectors for the first year of data was significantly lower than the other 3 years this data was analyzed separately. By comparing this interpolated muon creation height with the muon flux data summed over 10 days, a correlation coefficient of -0.83 was found. Comparing the percent change of altitude versus percent change of muon flux, a correction coefficient of -0.57 +/-0.04 was calculated by fitting a linear trend line through the origin as can be seen in Figure 3. The 2005 data was also individually analyzed but was scaled using the 2005 mean muon count instead of the 2006-2008 value, revealing the same relationship between muon flux and temperature through pion creation height.

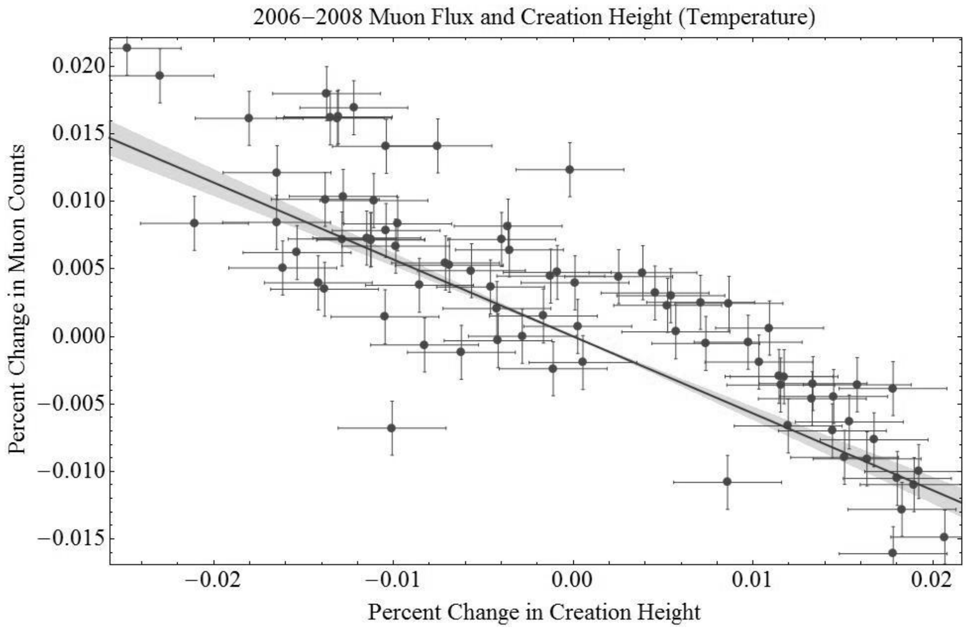

Figure 3. Correlation between muon flux and pion creation height in the atmosphere based upon fitted data from NOAA balloon flights. The line show is the fit of the data corresponding to a correction value of -.57 +/- 0.04.

5 Conclusion

This analysis has examined the record of GRAND data dating back to 2005 in order to investigate the relationship between pressure, temperature, and muon flux and to establish correction coefficients. The analysis of sudden variations in atmospheric pressure reveals an average correction factor of 1.00 however there was significant variation throughout the experiment probably caused by sensor or seasonal variations. The effect of temperature was investigated by estimating the altitude pion creation using NOAA weather balloon flights. By relating the mean pion creation altitude with flux summed over 10 days, a temperature correction of 0.57 was found. This temperature correlation coefficient however also shows non trivial variation between different regions in the time series. This might be due to variations in the sensor as the detector electronics themselves respond to changes in ground temperature.

Pressure and temperature corrections are essential toward using GRAND's extensive collection of muon flux data for time series analysis. Both pressure and temperature introduce periodic trends in the muon flux data that are not necessarily present in the primaries. As an example, the effect of pressure introduces a one, two, and three cycle/day trend in the muon data. Thus it is important to carefully correct for the Earth's atmospheric effects of pressure and temperature in order to study, for example, the solar effects of the IMF and coronal mass ejections on the cosmic ray primaries.

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7 References

[1] J. Poirier et al. Status report on project GRAND. 30th International Cosmic Ray Conference, paper #1001, 2007.
[2] T.K. Gaisser, Cosmic Rays and Particle Physics, (Cambridge University Press, 1990).
[3] National Climatic Data Center Website, 2009 http://www.ncdc.noaa.gov/oa/ncdc.html
[4] Nagoya Multi-Directional Muon Telescope Website, 2010: www.stelab.nagoya-u.ac.jp/ste-www1/div3/muon/dbtext22.pdf
[5] Dorman, L. (2004), Cosmic Rays in the Earth's Atmosphere and Underground, Springer Verlag.
[6] Serap Tilav for the IceCube Collaboration (2009) Atmospheric Variations as observed by IceCube. 31th International Cosmic Ray Conference, paper #1398, 2009

Date	Barometric Coefficient	Error	R^2	Pion Creation Altitude (Meters)	Duration (Hours)
1/9/06	-0.945	0.06	0.96	17212	14
1/24/06	-1.205	0.15	0.86	17122	12
1/28/06	-0.802	0.11	0.85	17220	9.6
2/16/06	-0.881	0.04	0.97	17163	16.8
4/3/06	-0.499	0.09	0.79	17233	9.6
12/1/06	-0.885	0.09	0.90	17247	14.4
12/31/06	-0.976	0.06	0.94	17374	16.8
2/19/07	-0.960	0.13	0.80	17017	14.4
12/22/07	-0.99	0.16	0.81	17218	9.6
1/26/08	-1.65	0.10	0.95	17091	12
3/31/08	-1.458	0.32	0.70	17212	9.6
4/8/08	-1.378	0.23	0.69	17248	19.2
5/10/08	-0.698	0.06	0.93	17309	12
1/16/09	-0.992	0.09	0.91	16744	12
2/11/09	-1.057	0.06	0.97	17193	9.6
2/26/09	-0.637	0.07	0.86	17086	14.4
3/10/09	-1.153	0.08	0.93	17276	14.4

Table 1. Examples of weather fronts traveling through the area around the detector corresponding to sudden changes in atmospheric pressure and muon flux.

Station	Latitude	Longitude	Weight
DAVENPORT, IA	41.62	-90.58	0.18
CINCINNATI, OH	39.42	-83.75	0.20
WHITE LAKE, MI	42.7	-83.47	0.26
GAYLORD, MI	44.9	-84.72	0.17
GREEN BAY, WI	44.48	-88.13	0.19

Table 2. The five closest NOAA weather balloon stations to South Bend, IN. The weights correspond to normalized inverse distance to GRAND.