Seasonal Variations in Muon Rate with Ice-Cube

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Abstract

Seasonal Variations in Muon Rate are caused by large scale changes in atmospheric conditions throughout the year. As atmospheric temperature and density vary across the seasons, so do the absorption rates of cosmic ray secondaries in the atmosphere. The IceCube neutrino detector array can track both large and small scale variations in atmospheric muon rate and daily, detailed weather data is available at the location of the detector. Depending on specific atmospheric conditions, IceCube's 22-string atmospheric muon trigger rate varies between approximately 450 Hz and 560 Hz in winter and summer, respectively.

1 History

Seasonal variations in muon rate have been documented since the late 1940s. The first report of the temperature effect can be found in a letter to the editor published in Physical Review in 1947. M. Forro reported that there was a strong positive correlation between air temperature at sea level and intensity of "the most penetrating component of cosmic radiation." (Muons had not been named yet.) This paper also investigated a potential link between muon intensity and barometric pressure, but found no positive correlation. [1]

Later, the temperature effect appeared in a 1952 paper by Paul H. Barrett, et al. The paper, Interpretation of Cosmic-Ray Measurements Far Underground, derived integrals for calculating Effective Temperature as well as established an expected temperature effect which was described as "percentage change of intensity per degree of change in temperature." [2] Another prominent paper on the subject was published by the MACRO collaboration in 1997 [3]

In 1999, Adam Bouchta, working for the AMANDA Collaboration, authored a paper which documented the seasonal variation in muon flux as seen by AMANDA for the year 1999. For this analysis, both muon rate and temperature data were averaged into one-week bins. This paper found a strong correlation for the effect at the south pole, however, AMANDA only took data from February to November, he was only able to document the effect for the middle of the year. [4]

In 2003, Henrike Wissing investigated the temperature effect, also working with AMANDA data. She still found a strong correlation, but still only had rate data for the middle parts of the year, when AMANDA was taking data. She found a strange peak in the muon rate towards the end of 2002, and upon investigating the peak, she found that the ozone hole over the south pole split into two separate holes, leading to a change in muon flux through the detector. A talk she gave on the subject suggested using AMANDA for atmospheric profiling using cosmic rays.

2 Physics of Muon Rate Variations

As atmospheric temperature varies across the season, so does its density; this varying density is the cause of the variations in atmospheric muon rate. After a cosmic ray particle interacts with an atmospheric nucleus, it creates a shower of pions or kaons. These secondary particles have both a chance of interacting with atmospheric molecules like oxygen or nitrogen, or decaying into muons. Muons are more penetrating particles, so pions and kaons will only be detected with IceCube if they decay into muons before they interact in the atmosphere.

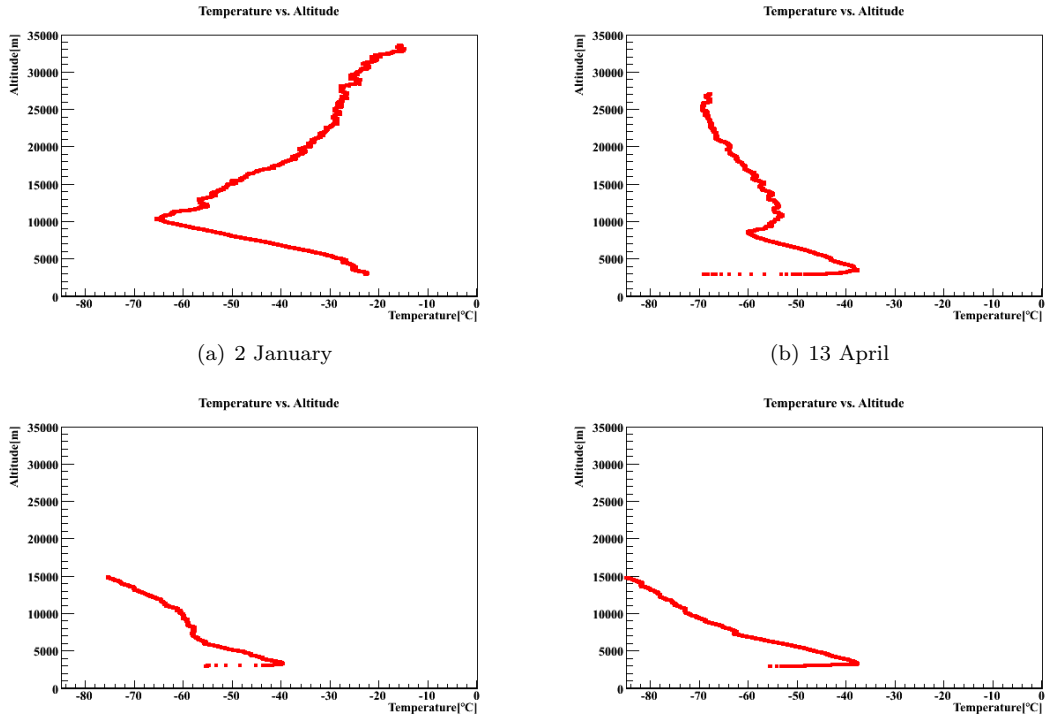
During the summer, the atmosphere is warmer, taller, and less dense. After a cosmic ray interaction far above the Earth, pions and kaons propagate through a long stretch of atmosphere which is not very dense. These pions and kaons are less likely to interact, and more often decay into muons.

During the winter, the atmosphere is colder, shallower and more dense. Cosmic ray interactions happen closer to the Earth's surface, in a more dense environment. In this dense environment, pions and kaons have a larger liklihood of interacting and a lesser likelihood of decaying into muons.

3 Effective Temperature

If we wish to study a muon rate dependence on temperature, we need to have some measure of atmospheric temperature. If the atmosphere was isothermal, this would not be a challenge at all, but temperature

varies with height, so we must find an effective average temperature. Average atmospheric temperature remains fairly constant across several days; although the temperature at the earth's surface can change dramatically on a day to day basis, higher in the atmosphere the temperature does not vary as quickly. Atmospheric temperature varies significantly throughout the seasons and varies independently at different heights. Figure 1 shows altitude versus temperature for four days of the year.



(a) 2 January

(b) 13 April

(c) 27 June

(d) 11 August

Figure 1: Temperature profiles throughout the year.

We will call our effective average temperature "effective temperature." Effective temperature is the temperature of an isothermic atmosphere that reflects the temperature of the real atmosphere with its varying conditions, assuming all muons come from pions and neglecting the kaon contribution. Effective temperature takes into account temperature and pressure values at all levels of the atmosphere, as well as attenuation length of pions. Effective temperature is defined [2] as:

$$T_{eff} = \frac{\int_0^\infty \frac{dX}{X} T(X)(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N})}{\int_0^\infty \frac{dX}{X}(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N})}.$$

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Therefore, effective temperature is a weighted average of temperatures at different atmospheric depths whereΛ_π and Λ_N are the attenuation lengths of pions and nucleons, respectively, and X is vertical atmospheric depth, defined [5] as:

$$X_v = \int_{h'}^{\infty} \rho(h) dh,$$

where ρ(h) is density as a function of height above the earth. Slant depth carries units of g / cm^2. Effective temperature is defined such that:

$$\frac{\Delta R_\mu}{< R_\mu >} = \alpha \frac{\Delta T_{eff}}{< T_{eff} >},$$

where α is a temperature coefficient[2].

Coincidentally, the NOAA (National Oceanic and Atmospheric Association) launches weather balloons from the south pole, in close proximity to the IceCube detector. When conditions allow it, they launch two balloons daily. During the summer, conditions are sufficent enough to consistently launch two weather balloons daily. Summer balloon flights typically reach the top of the atmosphere. During the Winter, however, conditions typically allow one balloon flight daily. Of these once-daily flights, many of them fail to reach the top of the atmosphere, and tend to return an effective temperature which is higher than expected. Balloon flights which don't reach the top of the atmosphere are considered "bad" flights, and need to be removed from the data set. Regardless of the quality of the balloon flight, equipment attached

to the balloon takes readings of temperature and pressure every two seconds and transmits these readings back to Earth. These readings are written into a text file, and in this format, numerical integration for effective temperature is easy as pie.

As expected, there is a seasonal variation in effective temperature. Effective temperature varies between $-85°C$ in the winter and -40C in the summer. The plots below show effective temperature, balloon altitude, and the atmospheric pressure reading at the highest recorded altitude for each balloon flight.

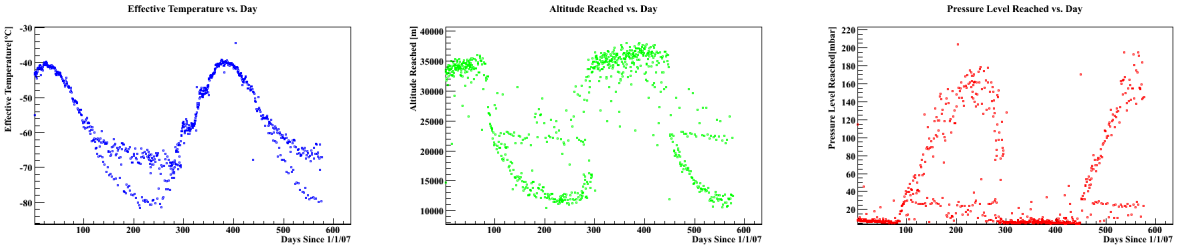


Figure 2: Effective temperature, balloon altitude and final pressure pressure reading vs. day since 1/1/07

Above, the leftmost plot shows effective temperature versus day from January 2007 to July 2008, it contains a data point for each balloon flight in this time interval. In the Summer, the effective temperature shows a definite peak; in the Winter, the minimum has two branches. The bottom branch, which approaches a distinct minimum, is comprised of all of the good balloon flights. The more linear segment, above the minimum, contains all of the bad flights. The next plot to the right is balloon altitude versus day. In the Summer, balloons consistently reach high altitudes. In the winter, we see the same two branch phenomenon, however, on this plot, the high flat branch contains good flights, whereas the lower, curved branch is comprised of bad flights. The third plot shows the last pressure value read for each balloon versus day. Pressure decreases as a function of altitude, so in this plot, the points at the bottom, near zero, represent good balloon flights. Each arc that swoops far above the axis represents a winter, one for 2007 and one for 2008; these arcs are those which we would like to cut out.

Good balloon flights reach a different altitude in the Summer than they do in the winter. With the maximum altitude of balloon flights varying widely throughout the year, cuts based on altitude are, to at least some degree, ineffective. The final pressure reading of the balloon, however, is a good indicator of what portion of the atmosphere the balloon was able to survey. Atmospheric pressure decreases as a function of height, so smaller pressure readings imply that and I got to dissect a fish today for my first lab! 6:38pmElizabeth has gone ashore.the balloon reached higher into the atmosphere, recording more data in the upper reaches. A balloon which reaches only up to the 100 millibar pressure level does not record data for as much of the atmosphere as a balloon which reaches the 10 millibar pressure level or less, which has surveyed most of the atmosphere. The plots below are of the same scale as the previous ones and show the same data, except after removing with balloon flights which did not surpass the 55 millibar pressure level.

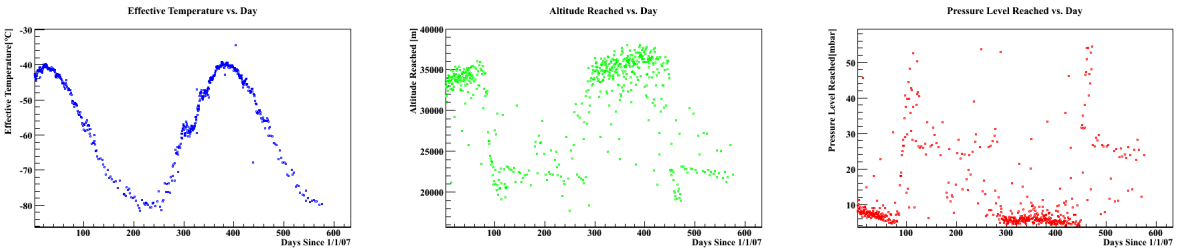


Figure 3: Cut: Flights reaching 55 mBar Pressure level

With bad balloon flights removed, we now see a clear maximum and minimum in effective temperature. We also see the effect of the cut in the maximum altitude and pressure level plots. The lowest points in the altitude plot, have been removed, and the swooping arms have disappeared from the pressure level plot, leaving a straight line at the bottom. These cuts appear to leave a clean, periodic effective temperature variation, which can be compared to muon rate.

4 DST Data

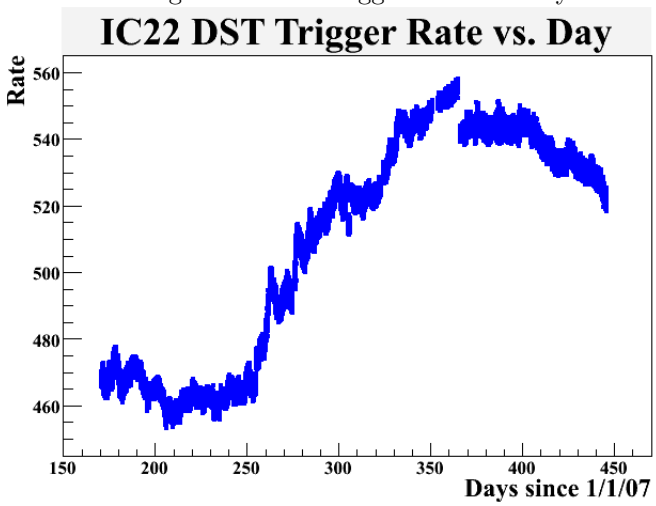
This analysis uses IceCube DST data from the 22-string and 40-sting detector configurations. DST data is in a compact format designed for processing high statistics, it stores less data about each event so that

it can be shipped north and processed relatively quickly. With a muon rate varying between 450 Hz and 550Hz, it is important to process events quickly and easily. DST data is unfiltered, it contains all events at all zenith angles, another important feature for this study. Figure 4 shows the DST trigger rate versus day for IC-22

Raw DST data is split into hundreds of runs per day, for each of these runs, an average muon rate can be measured. For each day, an average muon rate is calculated by a Gaussian fit over the rate for each run. As expected, there is a seasonal variation in muon rate throughout the year, between 450 Hz in the Austral Winter and and 560 Hz in the Austral Summer.

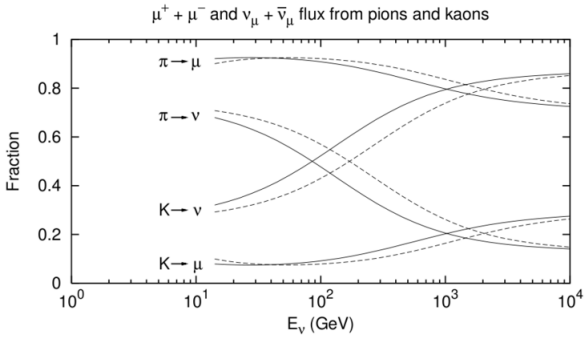
There are a few discontinuties in the DST rate. The DST trigger rate changes drastically in April 2008 when IceCube switched from its 22-string configuration to its 40-string configuration. Also, the DST trigger configuration changed twice during the IC-22 operating period, once during September 2007 and again at the beginning of January 2008. Artificial changes in rate complicate the study due to the fact that we are looking for true changes caused by temperature change. To overcome this complication, the differing rates are normalized to correspond to the period between September 2007 and December 2007. There is a gap in data acquisition between IC-22 and IC-40, so the rate was extrapolated for IC-40 based on temperature variation and the data was normalized to this extrapolated rate.

Figure 4: DST Trigger Rate vs. Day



Atmospheric muons are created by the decay of atmospheric pions and kaons. IceCube only detects muons which were created in pion decay. The plot below shows ratios of the secondaries which come from pions and kaons.

Figure 5: Pion and Kaon Decay Ratios [5]



5 Temperature Coefficient

The easiest way to compare muon rate variation to effective temperature variation is to measure the relative muon rate variation ($\Delta R/<R>$) and relative effective temperature variation ($\Delta T/<T>$) for each day. When plots of relative muon rate variation versus day and relative effective temperature variation versus day are superimposed, the close correlation between the two becomes extremely evident, as shown

in figure 6(a). Examining this plot closely, one can see many peaks in effective temperature which line up perfectly with peaks in muon rate.

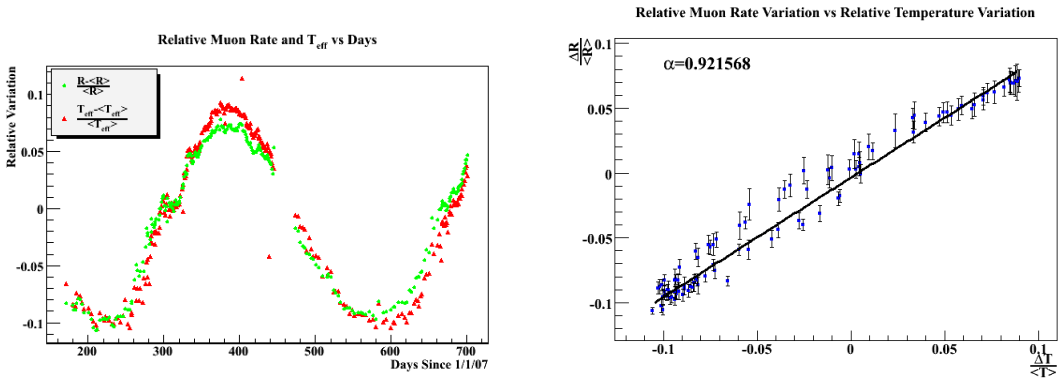


Figure 6: Relative Variations.

Recalling that:

$$\frac{\Delta R_\mu}{< R_\mu >} = \alpha \frac{\Delta T_{eff}}{< T_{eff} >},$$

a major goal of the study is to find α, our temperature coefficient. The value of alpha can be found by plotting ΔR/<R> against ΔT/<T>. After fitting a line to this plot, α_T is quite simply the slope of the line of best fit. Figure 6(b) shows this plot, the fit to the line gives:

$$\alpha_T = 0.92 \pm 0.01$$

This value of α_T is comparable with predicted values given by the formula

$$\alpha_T = \left\langle \frac{1}{1+\frac{\gamma}{\gamma+1}\times\frac{\epsilon_\pi}{1.1 E_{th}\cos\theta}} \right\rangle.$$

6 Conclusions and Prospects

This study had observed 18 months of IceCube data and found a value of the temperature coefficent, α_T which is comparable with theoretical predictions. In the future, we will test the dependence of α_T on zenith and in effect, depth and energy threshold. We will also perform a Fourier analysis to find which frequencies are present in the DST data. Further, a recent paper by the MINOS collaboration suggests sensing of stratospheric warmings due to ozone depletion with variations in muon rate.

References

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[4] A. Bouchta, Seasonal variation of the muon flux seen by AMANDA, in *Proceedings of the 26th International Cosmic Ray Conference. August 17-25, 1999. Salt Lake City, Utah, USA. Under the auspices of the International Union of Pure and Applied Physics (IUPAP)* Vol. 2, 1999.

[5] T. K. Gaisser, *Cosmic Rays and Particle Physics* (Cambridge University Press, 1990).