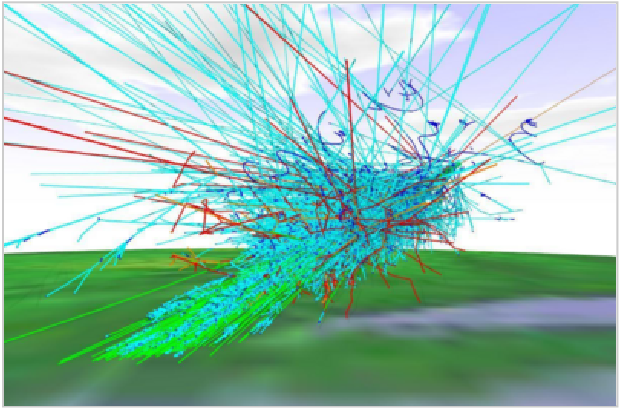
Seasonal Variations in Atmospheric Muon Rate

From IceCubeWiki



A cosmic ray nucleus striking an atmospheric nucleus creates an air shower.

Seasonal Variations in Muon Rate are caused by widespread changes in atmospheric conditions throughout the year which lead to differences in pion and kaon absorbtion after cosmic rays interact in the upper atmosphere. The variations arise from seasonal changes in temperature which cause changes in density of the atmosphere at different heights and times of the year, for more information see physics below. Depending on specific atmospheric conditions, the atmospheric muon rate varies between approximately 450 Hz and 560 Hz in winter and summer, respectively.

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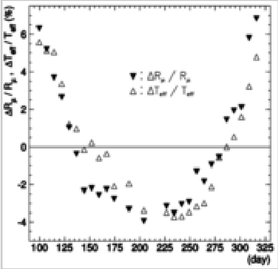


A. Bouchta's plot of relative effective temperature and muon rate variation vs. Day, 1999.

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 in Physical Review, November, 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 were not named yet.) This paper also investigated a potential link between muon intensity and barometric pressure, but found no positive correlation.

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."

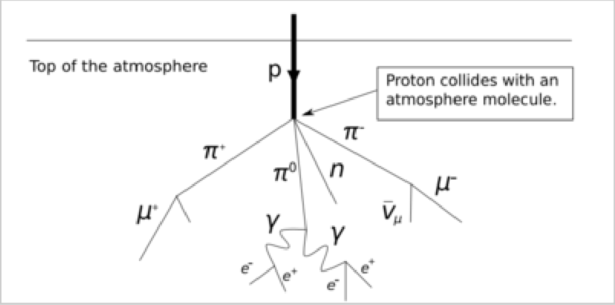
In 1999, Adam Bouchta, working for the AMANDA Collaboration, authored a paper which documented the seasonal variation in muon flux as seen by AMANDA for the year 1999. For this analysis, both muon rate and temperature data were averaged into one-week bins. This paper found a strong correlation for the 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.

Wissing's ozone hole split.

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.

Physics of Muon Rate Variations

The seasonal temperature effect arises from differing atmospheric density throughout the year. After a cosmic ray particle interacts with an atmospheric neucleus, it creates a shower of pions or kaons. These secondary particles have both a chance of losing their energy in the atmosphere, or decaying into muons. Muons are more penetrating particles, so pions and kaons will only reach the IceCube detector if they decay into muons before they lose all of their energy in the atomosphere.



A cosmic ray striking an atmospheric nucleus creates pions, which possibly decay into muons, assuming they don't lose their energy first. Notice that this diagram violates conservation of charge, and therefore is merely for the sake of illustration.

Summer

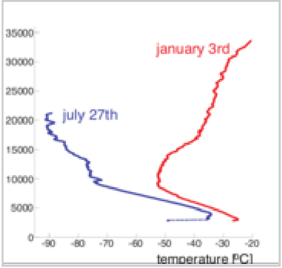
During the summer, the atmosphere is warmer, taller, and less dense. After a cosmic ray interaction far above the Earth, pions and kaons propogate through a long stretch of atmosphere which is not very dense. These pions and kaons lose less energy, and more often decay into muons.

Winter

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 quickly begin to lose energy and have a lesser likelihood of decaying into muons.

Effective Temperature

When one is trying to correlate temperature to muon rate, one question arises immediately: "Which temperature?" Although the temperature at the earth's surface can change dramatically on a day to day basis, higher in the atmosphere the temperature generally remains constant over several days. Atmospheric temperature varies significantly throughout the seasons and varies independently at different heights. The plot at right shows altitude versus temperature for two days of the year, July 27th in blue and January 3rd in red. An animated view of this plot can be seen here. (http://icecube.wisc.edu/~drocco/WeatherVideos/weather.gif) The animation shows temperature versus altitude with a frame for each day.



A plot of the height versus temperature at two different times of the year. For an animated view, click here. (http://icecube.wisc.edu/~drocco/WeatherVideos/weather.gif)

The solution to the problem of which temperature to use is called "effective temperature." Effective temperature is a weighted average which takes into account temperature and pressure values at all levels of the atmosphere, as well as attenuation length of pions. Effective temperature is defined (Barrett, et al; 1952) as:

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

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

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

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

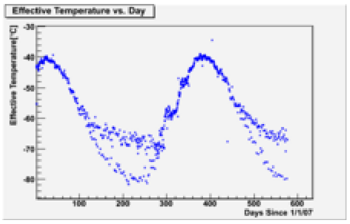
$$\frac{\Delta R_\mu}{< R_\mu >} = \alpha \frac{\Delta T_{eff}}{< T_{eff} >},$$

where α is a temperature coefficient.

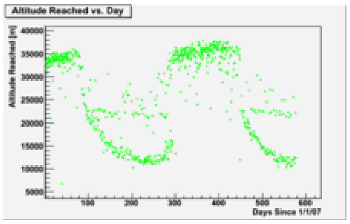
Coincidentally, the NOAA (National Oceanic and Atmospheric Association) launches weather balloons from the south pole, in close proximity to IceCube. When conditions allow it, they launch two balloons daily. During the summer, conditions are sufficient enough to consistently launch two flights daily. 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 -40°C in the summer. The plots below show effective temperature, balloon altitude, and the last pressure level reached for each balloon flight.

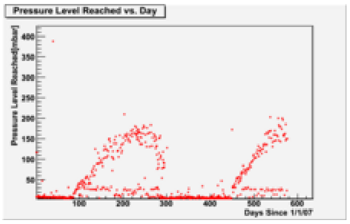
Balloon flights: January 2007 through July 2008



Effective temperature [°C] versus day, January 2007 to July 2008.



Maximum balloon height versus day, January 2007 to July 2008.

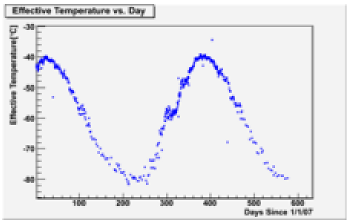


Pressure level reached versus day, January 2007 to July 2008.

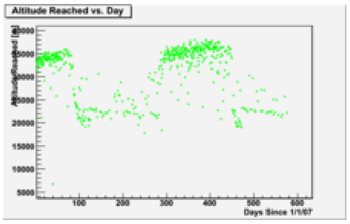
Above, the leftmost plot shows effective temperature versus day from January 2007 to July 2008, it contains a data point for each balloon flight in this time interval. In the Summer, the effective temperature shows a definite peak; in the Winter, the minimum has two branches. The bottom branch, which 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 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.

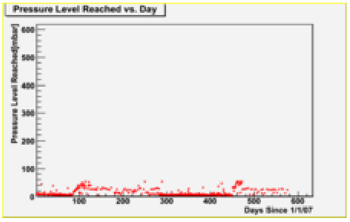
Balloon flights: Cutting out flights failing to reach 55 mbar or less



Effective temperature [°C] versus day, January 2007 to July 2008.



Maximum balloon height versus day, January 2007 to July 2008.



Pressure level reached versus day, January 2007 to July 2008.

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.

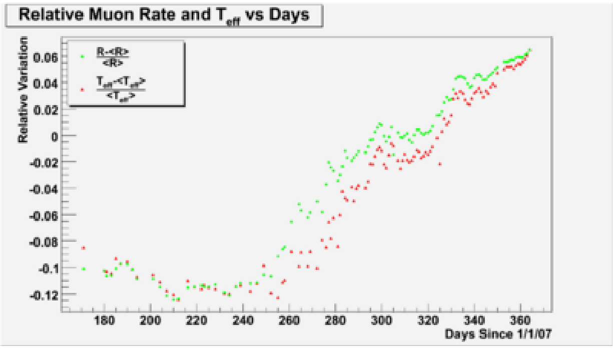
The lowest points in the altitude plot, have been removed, and the swooping arms have disappeared from the pressure level plot, leaving a straight line at the bottom. These cuts appear to leave a clean, periodic effective temperature variation, which can be compared to muon rate.

DST Data

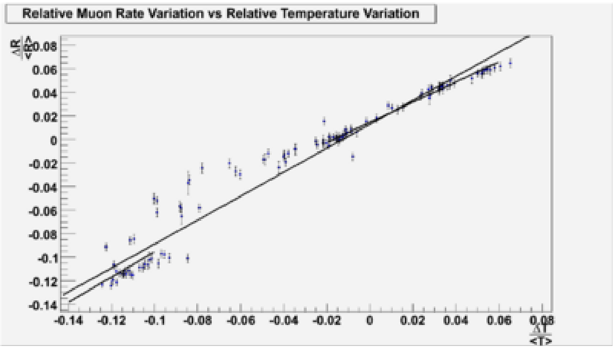
For this analysis, two sets of IceCube DST data are being used; IC-22 DST data for 2007 and IC40 data for 2008. DST data is in a compact format designed for processing high statistics, it stores less data about each event so that it can be processed relatively quickly. With a muon flux varying between 450 Hz and 550Hz, it is important to process events quickly and easily. DST data is unfiltered, it contains contains all events at all zenith angles, another important feature for this study.

Raw DST data is split into hundreds of runs per day, for each of these runs, an average muon rate can be calculated. For each day, an average muon rate is calculated by a Gaussian fit over 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 is a large discontinuity at day 366, January 1st, 2008 which was caused a change in the detector. Due to this discontinuity, effective temperature cannot be correlated to muon rate for the whole duration of DST data; two seperate correlations must be made, one for 2007 and another for 2008.

Temperature Coefficient



The easiest way to compare muon rate variation to effective temperature variation is to calculate the relative muon rate variation [ΔR/<R>] and relative effective temperature variation [ΔT/<T>]. 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. Examining this plot closely, one can see many peaks in effective temperature which line up perfectly with peaks in muon rate. During the spring, however, the two lines separate slightly, a phenomenon possibly caused by the rapid warming of the atmosphere. Methods of normalizing this data are under investigation, as well as possible causes for the phenomenon.



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 is quite simply the slope of the line of best fit. The slope of this plot, however, is not consistent. This inconsistency possibly comes from the disparity in the previous plot in the spring, during rapid warming. The inconsistency could also come from zenith and energy dependences. Alpha is know to vary such that:

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

where E_{th} is the threshold energy of the detector, and ε_π is epsilon_pi.

Future

- Investigate methods of normalizing relative variations data.
- Investigate zenith and energy dependencies.

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