Continued decline of South Pole neutron monitor counting rate

John Bieber,[1] John Clem,[1] Paul Evenson,[1] Suyeon Oh,[2] and Roger Pyle[1]

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[1] The counting rate of a neutron monitor at South Pole, Antarctica, displays a long-term decline over the 49 year span from March 1964 to the present. The counting rate follows an 11 year cycle with maxima at times of low solar activity. However, after adjusting for the unusually high overall cosmic ray fluxes in 2009, we find that the 2009 peak rate (based on 27 day averages) was approximately 10% lower than the 1965 peak rate. This change is much larger than that recorded by any other neutron monitor. We suggest that the South Pole monitor, owing to its unique position at both high latitude and high altitude may have a hitherto unsuspected sensitivity to secular changes in the magnetic field of the Earth.

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1. Introduction

[2] The neutron monitor at the Amundsen Scott Station, located at the geographic South Pole, has operated with some interruptions since 1964. Neutrons detected by such monitors are secondary cosmic rays, byproducts of nuclear interactions of primary cosmic rays (predominantly protons and helium nuclei) with Earth's atmosphere. The neutron counting rate at South Pole follows an 11 year cycle with maxima at times of low solar activity, but over the entire interval exhibits an apparently steady decline, totaling approximately 10% by 2013. We have worked extensively to identify possible instrumental or environmental sources of this decline but to date have found none. Conventionally, the geomagnetic cutoff at South Pole is assumed to be negligible and therefore any possible changes are irrelevant. This is certainly true for the vertical cutoff, but our calculations indicate that there are areas of quite high cutoff at large zenith angles and that the solid angle subtended by these areas is increasing as the geomagnetic field evolves with time. In this paper we document the continuing decrease of the count rate with time and explore the question of whether the increasing cutoff at high zenith angle could influence the radiation environment at the surface of the polar ice cap.

[3] An IGY type neutron monitor [*Simpson*, 2000] recorded data at the geographical South Pole from March 1964 until October 1974. Following a hiatus of more than 2 years, measurements resumed in January 1977 when a three-tube NM64 type monitor was installed at the station. This instrument operated until 22 November 2005, when operation was suspended. The detector tubes were removed and placed in heated storage, but much of the monitor superstructure (lead producer, polyethylene moderator, and reflector) remained in place at South Pole. In a retrospective analysis of the entire data set, *Bieber et al*. [2007] reported that the overall counting rate of the neutron monitor, corrected for equipment differences, declined by approximately 8% from 1965 to 1997. After considering many possible instrumental causes for the decline their ultimate conclusion was that it represented a true decline in the radiation environment at the detector. Discounting any effects due to the changing geomagnetic field, *Bieber et al*. [2007] proposed two possible, but still unlikely, causes for this decline. One was a significant change in the environment of the monitor as surrounding structures were slowly covered by snow while the monitor itself was repeatedly raised to stay above the snow surface. Another possibility was a subtle, secular change in the spectrum of cosmic rays in the rigidity range 1 to 3 GV. Because of its unique location and construction they showed that there was no other directly comparable detector available either to confirm or dispute such a possibility.

[4] The neutron monitor was reactivated in February 2010 after a four-year, three month gap, and has since been equipped with an enhanced array of "bare" neutron detectors [*Evenson et al*., 2011]. The new configuration is designed to enhance the ability of IceTop, the surface component of the IceCube neutrino observatory at the South Pole, to determine spectra and element composition of solar energetic particles in the energy range 1–10 GeV. Neutron detectors, whose response function is primarily due to hadrons, have a different dependence on energy and element composition from those of the ice Cherenkov detectors in IceTop which respond primarily to photons and leptons.

[5] Reactivation also allows us to address directly our speculative causes for the long-term decline. Calibration before and after moving the main part of the monitor to a new location essentially excludes the environment as a cause. Response of the reactivated monitor to the unusually high cosmic ray fluxes at all energies in 2009 makes it less likely that a subtle change in the cosmic ray spectrum caused the decline. By all other measures the cosmic ray flux reached record levels in 2009 yet the monitor at Pole barely came

[1]Department of Physics and Astronomy, University of Delaware, Newark, Delaware, USA.
[2]Department of Astronomy and Space Science, Chungnam National University, Daejeon, Republic of Korea.

Corresponding author: P. Evenson, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA. (evenson@udel.edu)

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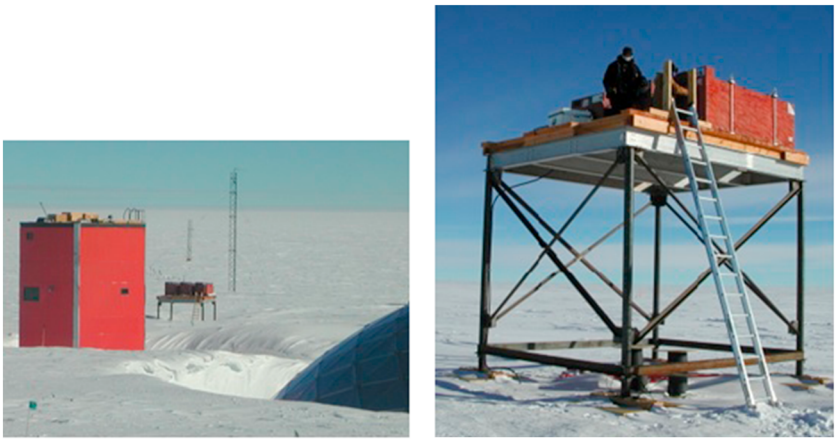

Figure 1. South Pole neutron monitor in (left) old location and (right) new location.

back to its 1987 level. The secular decline is real and indeed continuing. We conclude that we must re-examine in more detail our dismissal of a change in the geomagnetic cutoff as a cause of the decline.

[6] In the remainder of this paper we first discuss the reactivation of the monitor and the calibration in the new location. We then discuss the counting rate of the monitor after reactivation in the context of the record counting rate recorded by other neutron monitors and spacecraft detectors near that time. Finally, we explore a possible geomagnetic origin of the decline and outline further work that is required to either confirm or eliminate changes in the geomagnetic cutoff as a cause.

2. Reactivation and Calibration of the South Pole Neutron Monitor

[7] The neutron monitor was formerly located approximately 30 m from the iconic "dome" structure that formerly housed the Amundsen-Scott Station and 10 m from the "SkyLab" building. In Figure 1, at the old location, Skylab is the red building at left while the edge of the dome can be seen at right. The neutron monitor is the smaller structure near the center. Both the Dome and SkyLab remained in place over the lifetime of the NM64 monitor, but snow gradually built up around them. The monitor platform was raised several times to keep the detectors themselves above the snow. Thus, there were two changes in the environment of the monitor, namely it rose with respect to the structures, and large voids developed in the snow close to the monitor. We had no specific evidence that this process affected the count rate of the monitor. Simple numerical simulations indicated that there should be no effect but we had no comprehensive empirical way to test this.

[8] Restarting the monitor in a new location, approximately half way between the station and the Clean Air Facility, allowed us to investigate the environment issue directly. The platform and detectors were moved as a unit, although the structure under the platform was slightly different. Another complication was that all of the cabling leading to the old platform had been removed, disconnecting the power for the heaters that keep the detectors at their operating temperature. It was economically impossible simply to restart the monitor in the old location before moving it. Instead, we constructed insulated housings for the neutron detector electronics and a battery powered data acquisition system housed in an insulated tool box. When the neutron detectors were installed in the 3NM64 shell the configuration was nonstandard because the insulation on the electronics prevented full insertion of the detector tubes. However, the nonstandard configuration of the detectors and electronics could be exactly reproduced at the old and new locations. The test at the old location took place on 25 November 2009 and at the new location on 25 January 2010.

[9] Table 1 summarizes the data taken at both locations. Data from all three detectors were first examined individually, but were found to be statistically equivalent. The counting rates therefore have been summed to produce the numbers shown in the table. Each run comprised approximately 10 min of good data. The barometer readings were taken from station meteorology data and have not been corrected for any difference in altitude to the detectors. The altitude of the detectors before and after the move was not surveyed accurately but it was the same to approximately 5 m. A 5 m error would cause an inaccuracy of the relative barometer reading of 0.27 mmHg, corresponding to a counting rate correction of 0.27%. The temperature was measured by sensors on the detectors. We also show the pressure corrected McMurdo neutron monitor counting rate at the time of the tests. Barometer and temperature correction factors were calculated using our standard procedures. The modulation correction was derived from a linear regression of the South Pole and McMurdo monitor counting rates for the two month period after the Pole monitor had been restarted in its standard configuration (27 January 2010 to 27 March 2010).

Table 1. Summary of Calibration of the South Pole Neutron Monitor in the Old and New Locations

	25 November 2009 (Old Location)	25 January 2010 (New Location)
Measured Counting Rate	350.5 ± 0.8/s	323.8 ± 0.8/s
Barometer	511.99 mmHg	520.52 mmHg
Detector Temperature	−29.5°C	−17.4°C
McMurdo Counting Rate	290.3 ± 0.3/s	287.5 ± 0.3/s
Correct Barometer to 510.0 mmHg	1.01984	1.10941
Correct Temperature to minus 10°C	1.01716	1.00651
Correct Modulation to 25 January 2010	0.9856	1.0000
Corrected Counting Rate	358.4/s	361.6/s

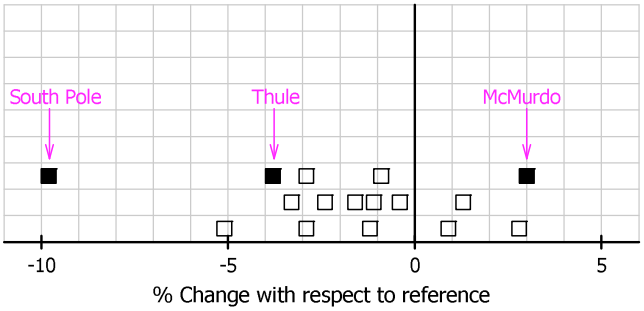

Figure 2. Long-term change of high- and midlatitude neutron monitors from 1964 to 2009 as determined by *Oh et al.* [2013]. Results from the current analysis of South Pole have been added.

[10] Since the difference in corrected counting rate from one location to the other is only about 1%, it is now clear that the long-term decline of 8% reported by *Bieber et al.* [2007] cannot be explained by the presence of the Dome and/or SkyLab. Indeed, the measured difference of only 1% speaks to the general issue of neutron monitor stability. Thus, it appears that the primary conclusion remains that the radiation level at the South Pole indeed declined systematically with time and our primary focus should be on identifying the source of the decline. We therefore next examine the speculation of *Bieber et al.* [2007] that peculiarities of the cosmic ray spectrum in a small range of energy only accessible at the South Pole neutron monitor might be sufficient to cause this decline.

3. Continued Decline of South Pole Counting Rate

[11] Long-term trends in neutron monitor counting rates are problematic and frustrating to those who operate the monitors. The most common cause is a change in the geomagnetic cutoff. For high latitude monitors, we have heretofore considered this irrelevant, as all of the stations operate where the geomagnetic cutoff is either zero or well beneath the "atmospheric cutoff." Otherwise, neutron monitors are so simple and inherently stable — a tribute to the genius of John Simpson [*Simpson et al.*, 1953] — that it is difficult to imagine what would cause a drift. When we built three new Spaceship Earth [*Bieber et al.*, 2004] stations in different parts of Canada, the absolute counting rates were within a few percent of each other. However, in the context of a study of the recent record cosmic ray maximum [*Mewaldt et al.*, 2010; *Moraal and Stoker*, 2010], *Oh et al.* [2010] reviewed the stability of neutron monitors in general and our stations at McMurdo and Thule in particular. This discussion was continued by *Ahluwalia and Ygbuhay* [2010].

[12] In spite of unexplained long-term instabilities in individual monitors, *Oh et al.* [2013] showed that the record neutron monitor levels could be characterized as an "excess flux," i.e., the increase above historic levels, described by a power law in rigidity that is consistent with increases seen at lower energy by spacecraft. To adjust for the instability of individual monitors, they constructed a reference based on an average of eight high latitude stations and used this reference to make a phenomenological correction for apparent long-term changes in individual neutron monitors. Figure 2 shows the deviation of individual, high and mid latitude, neutron monitors from the reference of the fitted linear trend over the interval 1964 to 2009 [*Oh et al.*, 2013, Table 2]. We have done an identical analysis comparing South Pole to the same reference and included the result in Figure 2. We also highlight the points for Thule and McMurdo since both of these stations have operated for a similar period of time as Pole with similar detectors and electronics. The decline of the Pole counting rate stands out clearly from the distribution of the other monitors. Using the cluster of other monitors to define a mean and standard deviation, Pole is a 3.6 sigma outlier.

[13] In Figure 3, we show the observed South Pole counting rate in gray, corrected as suggested by *Bieber et al.* [2007] for the transition from the IGY to the NM-64 monitor. The counting rate is presented as Bartels rotation averages. Note that during the period of record cosmic ray fluxes in 2009 the South Pole counting rate barely returned to its 1987 level. However, when detrended following the method of *Oh et al.* [2013], the levels in 2009 clearly stand out as a record in relative terms (red curve in Figure 3). Thus, we see not only confirmation of a long-term decline but also specific evidence that the decline is continuing to the present.

[14] The key finding of *Oh et al.* [2013] was that the record flux level in 2009 spanned the entire cosmic ray spectrum from spacecraft energies to over 6 GeV. Figure 4 shows the "excess flux" determined by *Oh et al.* [2013] at the maximum Bartels rotation average for each monitor individually as a function of cutoff. The excess flux is the fractional increase (in the detrended data) in 2009 relative to the 1987 cosmic ray maximum. The red line is a fit by *Oh et al.* [2013] expressing the excess as a power law in rigidity. We have added the excess determined for South Pole using the same method (large green dot). Observations from Pole resumed in Bartels rotation 2407, and the maximum excess for a full rotation (5.2% as plotted) occurred in rotation 2408. It is quite likely that we missed the absolute peak at Pole, since *Oh et al.* [2013] reported that no monitor peaked after rotation 2406, when several monitors peaked. We have also highlighted

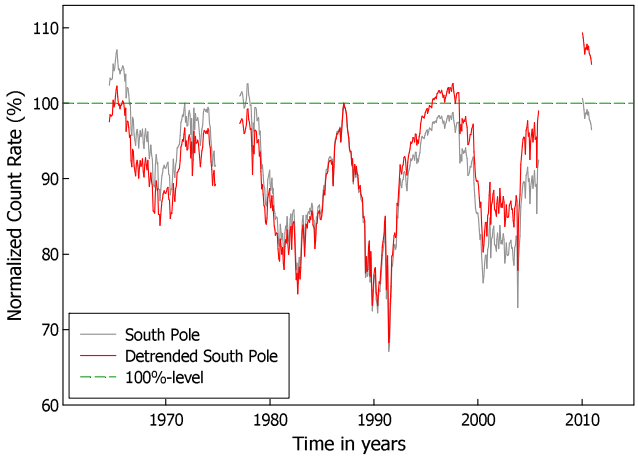

Figure 3. The observed counting rate of the South Pole neutron monitor as a function of time is shown in gray. The detrended counting rate calculated by the method of *Oh et al.* [2013] is shown in red. Both curves are normalized to 100% in 1987.

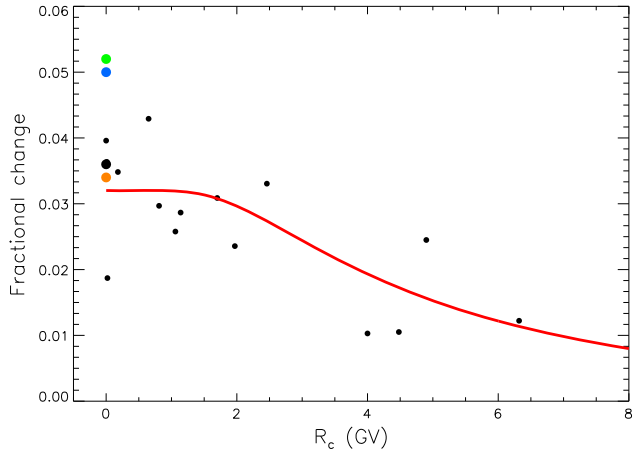

Figure 4. Fractional increase in 2009, relative to the 1987 cosmic ray maximum, of several neutron monitors (black points with McMurdo emphasized) with the best fit model shown as a red line. (after *Oh et al*. [2013]). We have added the observed increase at Pole (green dot) and our calculation of the increase at McMurdo (orange dot) and Pole (blue dot) as discussed in the text.

the determination for McMurdo as a large black dot. The excess at South Pole is significantly higher than that of any other neutron monitor. Qualitatively, this is in keeping with the high altitude location of Pole.

[15] The calculation presented by *Oh et al*. [2013] (red line in Figure 4) cannot be repeated exactly for the Pole excess because it is based on a sea level response function reported by *Moraal et al*. [1989]. Therefore, to estimate the excess we have used the formulation of *Nagashima et al*. [1989], which incorporates altitude dependence explicitly, to generate a response function at 510 mmHg atmospheric depth for 1987. We then follow the *Oh et al*. [2013] procedure of multiplying the response function by the assumed excess, expressed as a power law in rigidity, and numerically integrating. (We did not use the *Nagashima et al*. [1989] modulation correction to generate this response function because the 2009 flux levels are out of the range of validity of their formula.) The calculated increase for McMurdo (orange dot) is nearly identical to the estimate from the *Moraal et al*. [1989] response function. The calculation for Pole is shown as a large blue dot. The near perfect agreement with the measurement is likely fortuitous, but qualitatively the agreement of the calculation with the observation is certainly quite good. We will not repeat the arguments of *Bieber et al*. [2007] regarding the difficulty of calculating yield functions for Pole. The *Nagashima et al*. [1989] formula incorporates altitude dependence but the authors warn that it has deficiencies. As an example, when we calculate the expected ratio of McMurdo counting rate to Pole counting rate (on a per detector basis) using the *Nagashima et al*. [1989] formula the result is 13.96, whereas the observed value is 7.24.

[16] If, instead of following the *Oh et al*. [2013] analysis, we extrapolate the trend reported by *Bieber et al*. [2007] through 2009 we would have a total decline of 11% (rather than 9.8%) and a resulting excess of 6.8% (rather than 5.2%). We regard these as essentially identical to the results discussed in detail above. The decrease clearly continues beyond 1987, but there is no way to determine whether it is linear or not.

[17] The behavior of the Pole monitor in response to the excess flux in 2009, right in line with other monitors and spacecraft, argues against our conjecture [*Bieber et al*., 2007] that the decreasing radiation level at Pole could be due to a secular modification of the shape of the low energy cosmic ray spectrum. Further evidence comes from the PAMELA investigation [*Adriani et al*., 2013] which is the first long-term spacecraft observation that spans the traditional gap between spacecraft and neutron monitor measurement. Unfortunately, for the present work the *Adriani et al*. [2013] study covers a time interval when the Pole monitor was not operating so direct intercomparison is not possible. However, this study showed that the spectrum evolves from 2006 to the record levels in 2009 with a smooth evolution in shape. There is thus no evidence that some type of spectral deficit has developed over time. It is still possible that Pole has been sensitive to a spectral enhancement with rigidity 1–3 GV that disappeared rather uniformly from 1965 to the present. However, we find this type of explanation more and more unlikely as evidence accumulates.

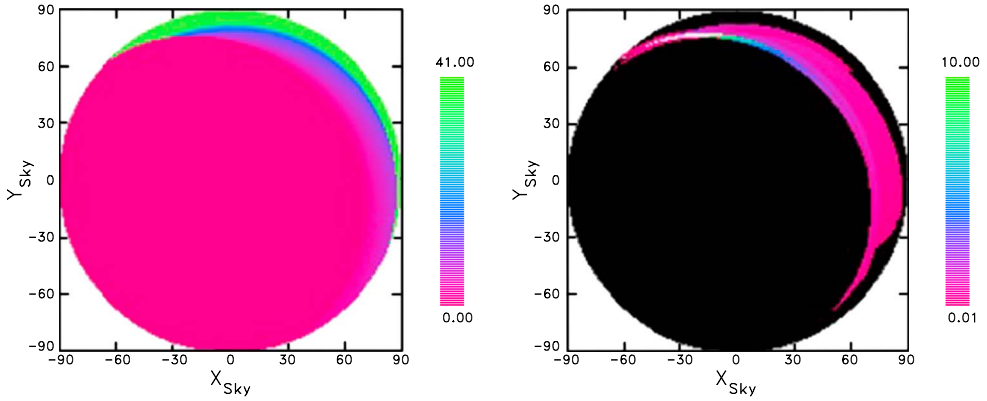

Figure 5. (Left) Geomagnetic Cutoff "Sky Map" at South Pole in 2005 and (right) change from 1969 to 2005. Color scales give the cutoff and change in cutoff in units of GV. Black indicates no change. Virtually, all directions have either increased or unchanged cutoffs. (Cutoffs >40 GV are treated as equal to 40 GV so no change is reported at these high rigidities.)

4. Conclusions

[18] We are now at a point where, in our view, it is clear that there has been a systematic decline in the radiation level, specifically neutrons of approximately 100 MeV, at the South Pole over the past 50 years and that this decline is continuing at the present. We cannot say that this decline is linear with time, but a linear assumption provides a good description. We find it unlikely that this is due entirely to a secular modification of the basic shape of the cosmic ray spectrum.

[19] We thus reconsider a basic assumption that has so far remained unchallenged, namely that geomagnetic effects can be ignored for all high latitude monitors. For relatively low rigidity particles (typical of solar flares) with steep spectra, particles arriving at higher angles of incidence can be ignored because the cascades from these low energy particles can barely penetrate to the surface for near vertical incidence, let alone at larger slant depths.

[20] We cannot make such a reassuring statement for the much harder Galactic cosmic ray spectrum. One thing is quite clear: geomagnetic cutoffs do exist at South Pole and these cutoffs show significant change with time. Figure 5 illustrates this in terms of "Sky Maps" [*Clem et al*. 1997] for South Pole calculated using the code developed by *Lin et al*. [1995]. The calculation is done, as is typical, for particles arriving at an altitude of 20 km. The full map for 2005 shows that the cutoff is near zero over most of the sky, but in some directions near the horizon the cutoff is very high, including areas where it is higher than the 40 GV limit of the calculation. The differential map also shows significant changes between 1969 and 2005, in that the high cutoff region is advancing across the sky.

[21] This increase in the area of high cutoff will clearly reduce the secondary cosmic ray flux at Pole, but whether the change could be large enough to account for the observed decline is not at all obvious. By putting "tracking" in the code of *Lin et al*. [1995], we determined that high energy particles arriving from the regions where the cutoff is changing have typically traversed 400 g/cm^2 of air in reaching an altitude of 20 km as opposed to approximately 55 g/cm^2 for vertically incident particles. Most 40 GV particles would have interacted after 400 g/cm^2, but the resulting cascade would still be propagating. The cascade from a 40 GV particle easily propagates through 1000 g/cm^2 to produce the signal of a sea level monitor. The additional 600 g/cm^2 is also roughly the amount of air between 20 km and the neutron monitor at Pole which is located at a pressure altitude of 3300 m. Of course, the cascades have a significant "memory" of the direction of the primary so oblique cascades are not as effective at producing surface radiation as are vertical cascades. We conclude that all parameters are arguably significant and no clear approximation emerges in which to work the problem. At this time therefore we believe that there is a solid justification for a program to investigate in detail geomagnetic cutoff change at South Pole and its influence on the radiation environment.

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