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Key Points:

- Yield function of a neutron monitor is verified against new data
- Spaceborne PAMELA data on cosmic ray spectra and data on latitude surveys are used
- The new yield function is fully consistent with the experimental data

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Can we properly model the neutron monitor count rate?

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Abstract Neutron monitors provide continuous measurements of secondary nucleonic particles produced in the atmosphere by the primary cosmic rays and form the main tool to study the heliospheric modulation of cosmic rays. In order to study cosmic rays using the world network of neutron monitor and needs to be able to model the neutron monitor count rate. Earlier it was difficult because of the poorly known yield function, which has been essentially revisited recently. We have presented a verification of the new yield function of the standard neutron monitor (NM) using a recently released data on the direct in situ measurements of the galactic cosmic rays energy spectrum during 2006–2009 (the period of the record high cosmic ray flux) by Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics spaceborne spectrometer, and on NM latitude surveys performed during the period of 1994–2007, including periods of high solar activity. We found a very good agreement between the measured count rates of sea level NMs and the modeled ones in very different conditions: from low to high solar activity and from polar to tropical regions. This implies that the count rate of a sea level neutron monitor can be properly modeled in all conditions, using the new yield function.

1. Introduction

Cosmic rays (CRs) are charged subatomic particles, mostly protons and α particles with small addition of heavier nuclei. A standard way to register the cosmic ray flux and its variability is related to the use of the worldwide network of ground-based neutron monitors [e.g., *Simpson*, 2000; *Moraal et al.*, 2000] which are in continuous operation since 1951. Neutron monitors (NMs) detect the nucleonic secondary component of the atmospheric cascade initiated by primary energetic cosmic rays in the Earth's atmosphere [*Dorman*, 2004]. Accordingly, a NM is an energy-integrating device whose count rate is a response to the entire spectrum of cosmic rays above the local geomagnetic rigidity cutoff, and proper modeling is required to evaluate the flux and energy spectrum of cosmic rays from the recorded NM count rates. In order to properly model the galactic cosmic rays (GCR) variability using the NM network, one needs to know the yield function [e.g., *Clem and Dorman*, 2000] which characterizes the response of a standard NM to the unit flux of monoenergetic cosmic ray particles. It is typically calculated by direct Monte Carlo simulations of the atmospheric cascade [e.g., *Debrunner et al.*, 1982; *Clem and Dorman*, 2000; *Flückiger et al.*, 2008; *Matthiä et al.*, 2009]. However, earlier theoretical computations of the yield were shown to be quite uncertain. In particular, they were unable to reproduce the absolute value of the NM count rate [*Usoskin et al.*, 2005]. One way to test the validity of the NM yield function is to analyze data of a latitude survey, when a single NM is cruised over different geomagnetic latitudes thus providing empirically the latitudinal dependence of the NM count rate. As shown by *Clem and Dorman* [2000], all previous NM yield function models fail to model the so-called latitudinal surveys. This lead *Caballero-Lopez and Moraal* [2012] to an idea to propose an empirically derived yield function to overcome this problem.

A new computation of the NM yield function was performed recently [*Mishev et al.*, 2013] which accounts for the previously neglected effect of the finite lateral size of the cosmic ray-induced atmospheric cascade that increase the effective area of the detector for high-energy CR particles. As demonstrated already by *Mishev et al.* [2013], the new yield function resolves the above problems. In particular, it was shown that latitudinal surveys during solar minimum conditions [*Moraal et al.*, 1989] are well reproduced by the model. It was also confirmed independently by *Maurin et al.* [2015] that the geometric correction of the NMs effective area provides a better agreement with data from latitudinal surveys.

Two new data sets have appeared recently that allow us to verify the new NM yield function with an extensive test against the measured data. One is related to direct in situ measurements of the GCR energy spectra by Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) spaceborne experiment for the period of July 2006 through December 2009 [*Adriani et al.*, 2013], which covers the period of the highest ever recorded cosmic ray flux [*Potgieter et al.*, 2014; *Pacini and Usoskin*, 2015]. The other data set analyzed here is related to a series of NM several latitude surveys in a wide range of solar activity levels, from a solar minimum to a solar maximum. The surveys were performed in 1994–2007 [*Nuntiyakul et al.*, 2014] with a NM being placed on board a vessel and cruised along different latitudes to find empirical dependence of the count rate on the latitude.

Here we test the validity of the modern NM yield function [*Mishev et al.*, 2013] in different conditions, using both direct measurements of the cosmic ray energy spectrum outside the Earth's atmosphere and latitudinal surveys of a NM.

2. The Model

The counting rate of a NM at a given location and time, after correction for the barometric pressure, is related to the primary cosmic ray flux as

$$N(h,t) = \sum_{i=1}^{n} \int_{T_{c_i}}^{\infty} Y_i(T,h) \cdot J_i(T,t)\,\mathrm{d}T, \qquad (1)$$

where n is the number of species of the primary CR, viz., protons, α particles, and heavier species, $J_i(T,t)$ is the energy spectrum of the ith specie of GCR outside the Earth's magnetosphere and atmosphere, $Y_i(T,h)$ is the yield function of a NM which depends on the kinetic energy per nucleon, T, of the primary GCR particles and the observational altitude h. As the yield function we consider a recent model by *Mishev et al.* [2013] corresponding to the standard sea level 6-NM64. Integration is above the kinetic energy T_c which corresponds to the geomagnetic cutoff rigidity P_c in the location of the NM:

$$T_{c_i} = \sqrt{\left(\frac{Z_i}{A_i}\right)^2 P_c^2 + T_r^2} - T_r, \qquad (2)$$

where Z_i and A_i are the charge and mass numbers of the specie of type i, and $T_r = 938$ MeV. The yield function includes both development of the atmospheric cascade with different types of secondary particles and the response of a detector to the secondary particles.

The differential energy spectrum of GCR at the Earth's orbit can be described by the force field approximation [e.g., *Caballero-Lopez and Moraal*, 2004; *Usoskin et al.*, 2005] so that the energy spectrum of the ith type of GCR particles at 1 AU can be described as follows:

$$J_i(T) = J_{\mathrm{LIS}_i}(T+\Phi_i)\frac{E^2 - T_r^2}{(E+\Phi_i)^2 - T_r^2}, \qquad (3)$$

where J_{LIS_i} is the unmodulated local interstellar spectrum (LIS), $E = T + T_r$ is the total energy per nucleon, Φ is mean energy loss of the GCR particle inside the heliosphere, as defined by the modulation potential ϕ: $\Phi = \phi \cdot (eZ_i/A_i)$. We note that the exact value of the modulation potential is model dependent [*Usoskin et al.*, 2005] and has no clear meaning but just provides a very useful parametrization of the CR spectrum [e.g., *Vainio et al.*, 2009]. Here we use the LIS in the form of *Burger et al.* [2000] and *Usoskin et al.* [2005]. We implicitly consider both protons and α particles. This is important since the latter (effectively including heavier species) are modulated differently from protons and contribute approximately one third to the overall NM count rate [*Usoskin et al.*, 2011; *Caballero-Lopez and Moraal*, 2012].

3. Comparison With PAMELA Measurements

The PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) space probe, among other scientific goals, is devoted to study cosmic ray transport in the heliosphere and to record CR spectra in the energy range from 80 MeV to hundreds of GeV [*Picozza et al.*, 2007]. PAMELA was launched on 15 June 2006 having on board a neutron detector, a silicon-tungsten electromagnetic calorimeter, a magnetic spectrometer, an anticoincidence system, and a shower tail catcher scintillator. Starting from September 2010,

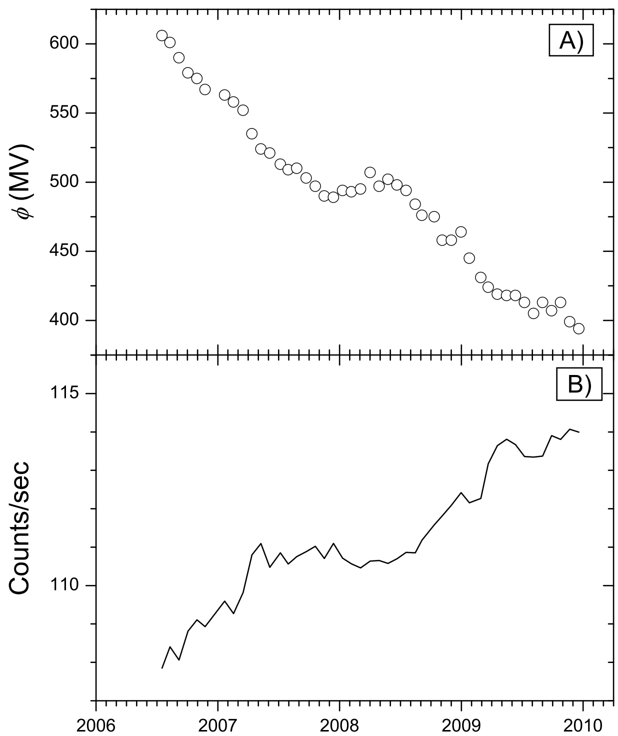

Figure 1. (a) The modulation potential, ϕ, estimated from PAMELA data. (b) Count rate (corrected for barometric pressure and efficiency) of the Oulu NM for the same periods.

the PAMELA's orbit is almost circular, at an altitude of ∼570 km. The inclination of the orbit is 70° [*Adriani et al.*, 2014].

We considered PAMELA data (differential energy spectra for CR protons) for the period of July 2006 through December 2009. This period covers the period of very weak solar activity between solar cycles 23 and 24 [e.g., *Gibson et al.*, 2011]. The month of December 2006 was excluded because of great disturbances of the cosmic ray flux including a major Forbush decrease and a ground level enhancement #70 [*Adriani et al.*, 2011; *Usoskin et al.*, 2015]. The entire period was divided in 47 (unequal) intervals of duration of 1 month or shorter, and for each interval the proton energy spectrum was published by *Adriani et al.* [2013] (the list of the periods and data is available at http://tools.asdc.asi.it/cosmicRays.jsp?tabId=0). We fitted each spectrum with the force field model (equation (3)) to define the best fit modulation potential ϕ. These ϕ values (defined following the formalism described by *Usoskin et al.* [2005]) are shown in Figure 1a. We note that these values are somewhat higher than those defined earlier solely from NMs [*Usoskin et al.*, 2011], which is likely related to the older NM yield function used there. On the other hand, a detailed analysis of PAMELA data for December 2006 shows a consistency between NM- and space-based values of ϕ for disturbed periods [*Usoskin et al.*, 2015].

Next we have collected pressure corrected data from various NMs for the same periods when PAMELA data are available. An example for the Oulu NM is shown in Figure 1b. The criteria for the station selection were the following: NMs should be of NM64 type, sea level (altitude smaller than 300 m), and working throughout the period from July 2006 to December 2009. Details of the considered stations are given in Table 1. We have

Table 1. Parameters of the Neutron Monitors Used in the Calculations for the Period of July 2006 Through December 2009[a]

NM	P_c (GV)	*h* (m)	Geographical Coordinates	Type	Scaling
Athens	8.53	260	23.78°E, 37.97°N	6-NM64	0.9984 ± 0.0009
Rome	6.32	60	12.52°E, 41.9°N	17-NM64	1.1514 ± 0.0011
Hermanus	4.58	26	19.13°E, 34.25°S	12-NM64	1.1083 ± 0.0011
Moscow	2.43	200	37.32°E, 55.47°N	24-NM64	1.2411 ± 0.0020
Newark	2.4	50	75.75°W, 39.68°N	9-NM64	1.1000 ± 0.0013
Kiel	2.36	54	10.12°E, 54.34°N	18-NM-64	1.1855 ± 0.0012
Kerguelen	1.14	33	70.25°E, 49.35°S	18-NM-64	0.9707 ± 0.0007
Oulu	0.8	15	25.47°E, 65.05°N	9-NM6	1.0066 ± 0.0012
Apatity	0.65	181	33.4°E, 67.57°N	18-NM-64	1.2373 ± 0.0012
Fort Smith	0.3	180	111.93°W, 60.02°N	18-NM-64	1.0047 ± 0.0013
Inuvik	0.3	21	133.72°W, 68.36°N	18-NM-64	1.1260 ± 0.0011
McMurdo	0.3	48	166.6°E, 77.9°S	18-NM-64	0.7889 ± 0.0007
Nain	0.3	46	61.68°W, 56.55°N	18-NM-64	1.0125 ± 0.0012

[a]Columns are name, geomagnetic vertical effective cutoff rigidity P_c, altitude *h*, geographical coordinates, and type of the NM, as well as the scaling factor (see text), respectively.

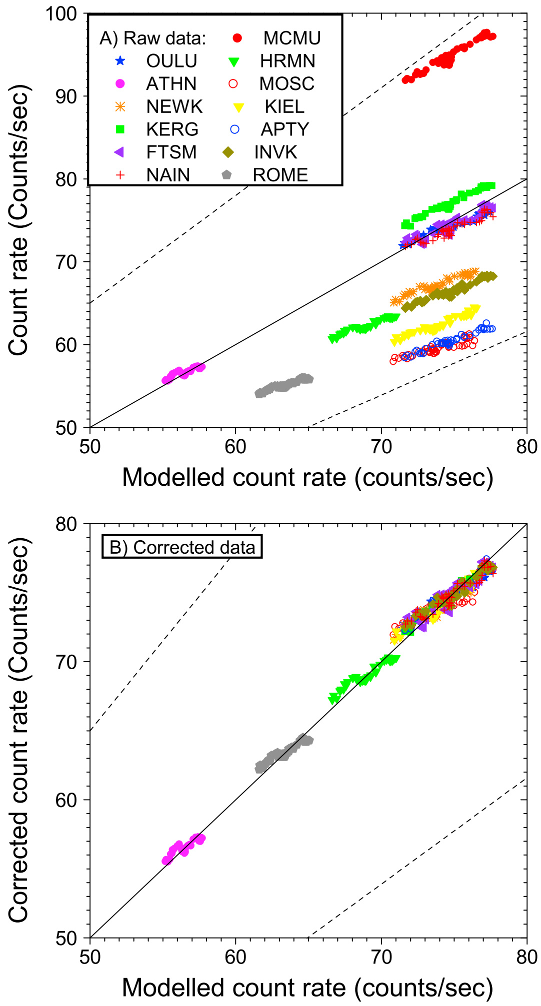

Figure 2. Scatterplot of the actually (vertical axis) recorded versus modeled using PAMELA data count rates of NMs (Table 1) for the time periods when the PAMELA data are available. All count rates are reduced to the 6NM64 standard configuration. (a) Raw data. (b) Data corrected for the scaling factor (Table 1) accounting for the local environment and instrument design.

checked changes of the geomagnetic cutoff rigidity for all the analyzed NMs over the period 2006–2009, using the PLANETOCOSMIC code [*Desorgher et al.*, 2005] with the International Geomagnetic Reference Field and T89 [*Tsyganenko*, 1989] as internal and external geomagnetic field models, respectively. The changes in P_c are below 0.02 GV for all NMs except Newark where it is 0.05 GV over the period. Since such small changes would result to at most 0.1% changes in the NM count rate, we neglect this and consider the value of P_c constant over the studied interval.

Using the values of the modulation potential obtained from the PAMELA data, we have calculated the expected response of each NM to the primary GCR as described in section 2 above. The results of our calculations are presented in Figure 2a as a scatterplot of the computed (as described above) versus actually recorded count rates for the periods under investigation. One can see that there is a clear linear proportionality between the measured and computed count rates. The correlation coefficients are high, varying from $0.985^{+0.010}_{-0.018}$ for Kerguelen NM to 0.887 ± 0.049 for Athens NM. Generally, high-latitude NMs show better agreement with the model while the data from lower latitude NM have a smaller signal-to-noise ratio. However, the relations are not one-to-one. The last column of Table 1 lists the scaling (proportionality) coefficients (the ratio of the computed to the measured count rates), which vary from 0.79 (McMurdo NM) to 1.24 (Moscow NM), i.e., within ±25%. The scaling coefficients were computed for each of the PAMELA time intervals and then averaged over those, providing the mean and the standard error of the mean as listed in the table. In the ideal case one would expect the one-to-one relation (unity scaling); however, the NMs are not ideal and may differ from the “standard” conditions [*Krüger et al.*, 2008; *Aiemsa-ad et al.*, 2015] in the local environment, hardware, electronic setups of each NM, etc. A specific note is regarded Soviet/Russian NMs which use not the original BP28 (NM64) counters produced by the Chalk River Laboratory [*Hatton*, 1971], but Soviet analogs CNM-15 counters. The latter are less effective by 15–20% [*Abunin et al.*, 2011] as they use less pure composition of the filling gas (80% of $^{10}BF_3$) in comparison with the BP28 counters (96% of $^{10}BF_3$) and partly to different types of the front-end electronics (V. Yanke and S. Starodubtsev, private communication, 2015). Accordingly, the actual efficiency of Moscow and Apatity NMs is ~20% lower than the computed one, leading to the high scaling factors for those stations. This partly may affect also Kiel NM which uses BP28 counters but the Russian electronic. All other considered NMs are consistent with the standard conditions within 15%, except for McMurdo NM with too high count rate compared to the expected standard one, but we do not know an exact reason for that.

Then we reduced the measured count rates using the scaling factors listed in Table 1. The result is shown in Figure 2b. One can see that this makes the relation consistent over the entire range of studied stations. Thus, with the new yield function we can properly model the absolute values of individual NMs taking into account their local environmental conditions that can modify the count rate within 10–15% [cf., *Aiemsa-ad et al.*, 2015].

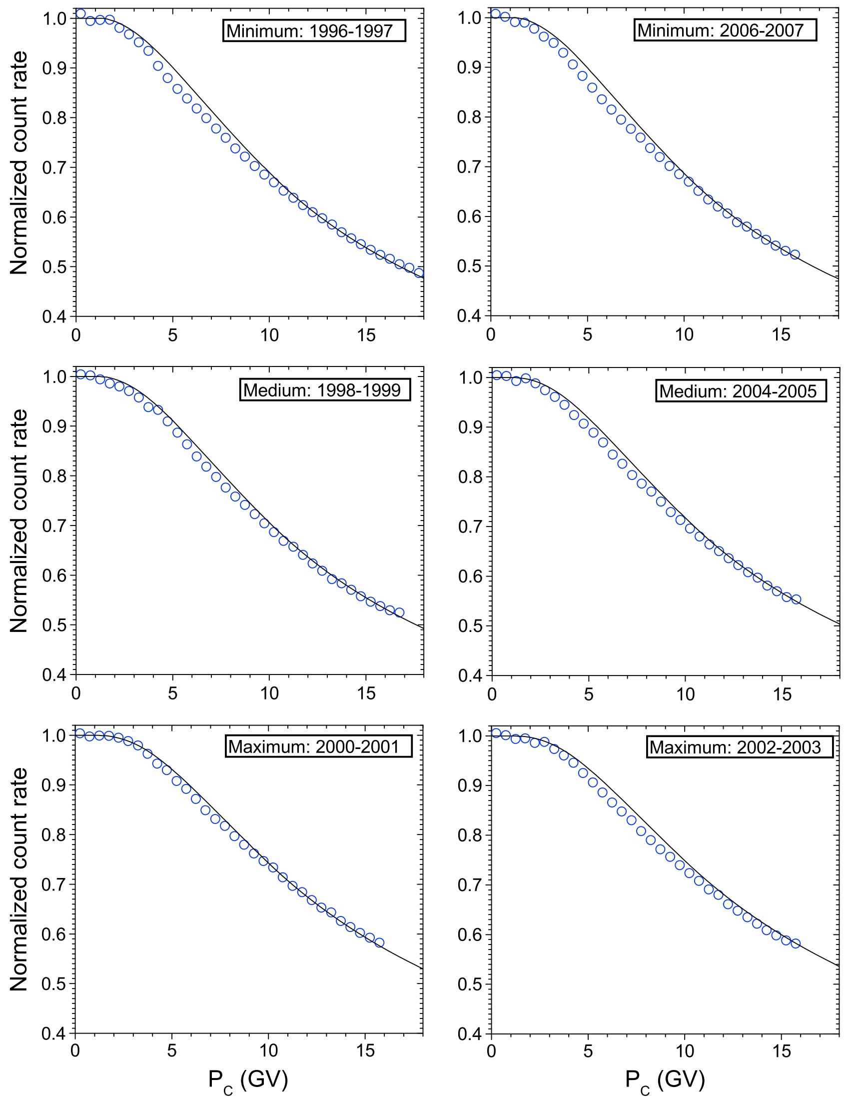

Figure 3. Examples of latitudinal surveys (NM count rates as function of the effective cutoff rigidity) modeled in this study. (top row) Solar maximum, (middle row) medium, and (bottom row) minimum levels of the solar activity. Open dots represent observational points [*Nuntiyakul et al.*, 2014], while the line is the model result for the corresponding period. The count rate is normalized per the mean count rate of the NM for rigidity below 1 GV.

4. Comparison With Latitudinal Surveys

In this section we perform a comparison of the model with latitudinal surveys of a NM that shows the latitudinal dependence of the count rates because of the geomagnetic shielding. Latitudinal surveys are performed by the same instrument (a standard NM) places on board a vessel cruising between tropics and high latitudes. The main reason of conducting such latitudinal surveys is that the NM differential response function can be calculated as the difference in counting rates, measured for different cutoff rigidities, which is fundamental for the primary cosmic rays spectrum above the atmosphere [e.g., *Moraal et al.*, 2000]. A number of such NM latitudinal surveys have been made during the NM era [e.g., *Potgieter et al.*, 1979; *Moraal et al.*, 1989; *Villoresi et al.*, 2000; *Krüger et al.*, 2008; *Nuntiyakul et al.*, 2014]. A preliminary comparison made by *Mishev et al.* [2013] using the data of a latitudinal survey performed during solar minima [*Moraal et al.*, 1989] depicted a good agreement between the model and the data.

Here we test the new NM yield function using latitude surveys [*Nuntiyakul et al.*, 2014] conveyed during the period of 1994–2007, including a full solar cycle from minimum through the maximum to another minimum. The latitudinal surveys were accomplished by the Bartol Research Institute, the University of Tasmania, and the Australian Antarctic Division during 13 semiannual vessel cruises with a 3-NM64 monitor on board [*Nuntiyakul et al.*, 2014]. We have calculated the expected response of a NM to the primary cosmic rays during the periods of the experimental data taking by applying the modulation potential computed for the same periods of time as surveys were taken using the method by *Usoskin et al.* [2011]. Figure 3 displays a comparison of the calculated count rate of a NM and the observational data of latitudinal surveys, normalized for the high-latitude (low-rigidity) part. The figure is divided in several panels, corresponding to the years of the solar minimum, medium, and maximum conditions. One can see that the model precisely reproduces the overall survey ratio (the ratio between the count rates in polar and tropical regions) for all the conditions. Surveys for other years (not shown) are reproduced equally well. The root-mean-square differences between the modeled and measured data points vary from 0.002 for latitudinal surveys during 1998–1999, 1999–2000, and 2000–2001 up to 0.006 for 2001–2002, with the average value 0.0034.

Thus, the yield function of *Mishev et al.* [2013] correctly reproduces, in contrast to earlier models, the latitudinal survey data. This is the first time that a theoretical model is able to directly reproduce them. On the other hand, there is a slight (a few %) discrepancy in the shape of the survey in the range of roughly between 3 and 10 GV cutoff rigidity. This is likely related to an inaccuracy of the used approximation of the vertical effective cutoff instead of a real transmissivity function [*Kudela and Usoskin*, 2004] or/and to a specific way to calculate the cutoff [*Desorgher et al.*, 2009].

5. Conclusions

We have presented a verification of the new yield function of the standard *sea level* NM using recently released data on the direct in situ measurements of the GCR energy spectrum during 2006–2009 (the period of the record high cosmic ray flux) by PAMELA spaceborne spectrometer, and on NM latitude surveys performed during the period of 1994–2007, including the periods of high solar activity. We found a very good agreement between the measured NM count rates and the modeled ones in very different conditions: from low to high solar activity and from polar to tropical regions. This, along with the recently revised LIS based on Voyager spacecraft data beyond the heliopause [*Webber and McDonald*, 2013; *Potgieter et al.*, 2014] and the newly coming measurements from AMS-02 spaceborne spectrometer [*Aguilar et al.*, 2013] calls for a need to revisit the reconstruction of the modulation potential ϕ based on NM network data [*Usoskin et al.*, 2005, 2011]. This work is planned for the nearest future.

Thus, the newly developed yield function of the standard neutron monitor [*Mishev et al.*, 2013] is verified with observational data from latitude surveys and PAMELA measurements. Together with a recent result of the modeling of a Forbush decrease [*Usoskin et al.*, 2015], this implies that the count rate of a sea level neutron monitor can be properly modeled in all conditions, using the model described in section 2. An extension of the work to include high-altitude NMs is also planned.

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