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New neutron monitor yield function computed at several altitudes above the sea level: Application for GLE analysis

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At present the world wide neutron monitor (NM) network provides continuous information about cosmic ray (CR) variations in the vicinity of Earth. In addition, the analysis of ground level enhancements (GLEs) is also based on NM data records. It is very important to have precise information for NM yield function for primary CRs, which is the main point for an analysis of GLEs. Here we present a newly computed yield function of the standard 6NM64 neutron monitor for primary proton and α CR nuclei. The computations have been carried out with Planetocosmics and CORSIKA codes as standardized Monte-Carlo tools for atmospheric cascade simulation. The secondary neutron and proton flux is obtained with Planetocosmics code. A realistic curved atmospheric model is applied. An updated information concerning NM registration efficiency for secondary neutrons and protons was used. The NM yield function is obtained by convolution of the secondary particle flux with the NM registration efficiency. In addition, the effect of the geometrical correction of the NM effective area is considered, which have been previously neglected. This correction enhances the relative impact of higher-energy cosmic rays, namely with energy above 5-10 GeV/nucleon in neutron monitor count rate. Thus the new computation resolves the long-standing problem of disagreement between the theoretically calculated spatial variability of cosmic rays over the globe and experimental latitude surveys in a realistic manner. The newly calculated yield function, corrected for this geometrical factor is fully consistent with the experimental latitude surveys of neutron monitors performed during three consecutive solar minima in 1976-77, 1986-87 and 1996-97.

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1. Introduction

Neutron monitor (NM) is an instrument that measures the intensity of high-energy particles impacting Earth from space. It provides continuous recording of cosmic ray (CR) intensity [1]. In particular, the measurements performed by the worldwide network of NMs are used to determine characteristics of solar energetic particles (SEPs). For this purpose it is necessary to establish a functional relationship between NM count rate and primary particle flux. A convenient formalism is based on a yield function. The NM yield function incorporates the full complexity of the atmospheric cascade development, secondary particle propagation and attenuation in the Earth's atmosphere and the detection efficiency of a NM. The NM yield function for primary protons is determined by parametrization of latitude survey observations [2, 3, 4, 5, 6, 7] or calculation of cosmic ray particles transport in the atmosphere [1, 8, 9]. Recently we proposed new NM yield function considering the finite lateral extend of cosmic ray induced atmospheric cascade [10]. The new computation resolves the long-standing problem of disagreement between the theoretically calculated spatial variability of cosmic rays over the globe and experimental latitude surveys. Here we extend our computations at several altitudes above the sea level.

2. Newly computed yield function at several altitudes above the sea level

The counting rate of a NM could be presented as:

$$N(P_c,h,t) = \int_{P_c}^{\infty} \sum_i Y_i(P,h) J_i(P,t) dP = \int_{P_c}^{\infty} W_T(P,h,t) dP \tag{2.1}$$

where $N(P_c,h,t)$ is the NM counting rate, P_c is the local geomagnetic cutoff, h is the atmospheric depth and t represents time. The term $Y_i(P,h)$ represents the NM yield function for primaries of particle type i, $J_i(P,t)$ represents the rigidity spectrum of primary particle of type i at time t and W_T is the total differential response function. Accordingly the NM yield function is defined as

$$Y_i(P,h) = \sum_i \int \int A_i(E,\theta) F_{i,j}(P,h,E,\theta) dE d\Omega \tag{2.2}$$

where $A_i(E,\theta)$ is the detector area multiplied by registration efficiency, $F_{i,j}$ is the differential flux of secondary particles (neutrons, protons, muons, pions) per primary i, E is respectively the secondary particle's energy, θ is the angle of incidence of secondaries. The yield function is obtained on the basis of extensive simulations of the atmospheric cascade with the GEANT4 [11] based PLANETOCOSMICS code [12] assuming a realistic atmospheric model NRLMSISE2000 [13] and updated NM efficiency [6]. A geometric correction similarly to [10] is carried out. In Fig.1 we present the results for standard 6NM64 yield function at several altitudes above the sea level, namely the sea level 1033 g/cm^2, 700 g/cm^2 ($\approx$ 3000 m above the sea level) and 500 g/cm^2 ($\approx$ 5000 m above the sea level). This new NM yield function demonstrate good agreement with [14] (see Fig.2a,b).

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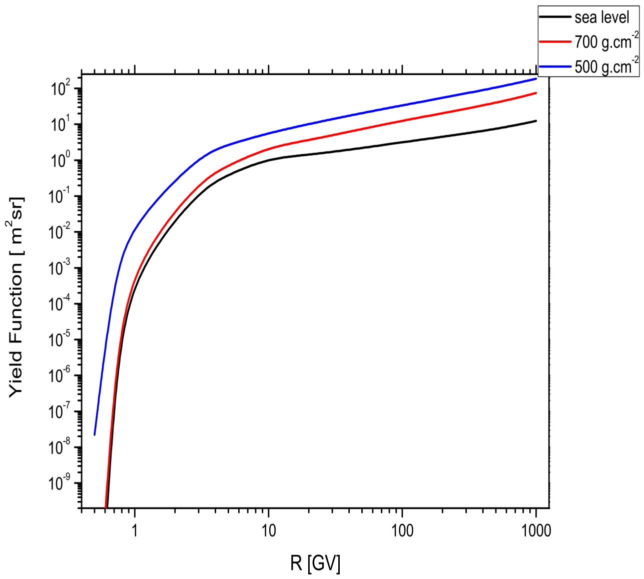
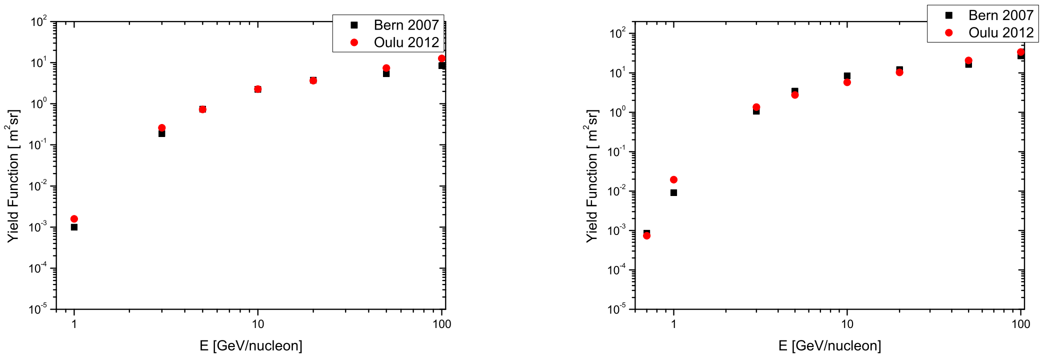


Figure 1: New yield function for 6NM64 at several depths, sea level, 700 g/cm^2 ($\approx$ 3000 m above the sea level) and 500 g/cm^2 ($\approx$ 5000 m above the sea level) .



(a) 700 g/cm^2 ($\approx$ 3000 m above the sea level) (b) 500 g/cm^2 ($\approx$ 5000 m above the sea level)

Figure 2: Comparison of newly computed NM yield function with BERN 2007 model [14] at several observation depths.

3. Applications

The newly computed yield function is applied for the analysis of GLEs based on NM data. Details of the used model are given elsewhere [15]. In general the relative count rate increase of a given NM can be expressed as:

$$\frac{\Delta N(P_{cut})}{N} = \frac{\int_{P_{cut}}^{P_{max}} J_{||sep}(P)Y(P)G(\alpha(P))dP}{\int_{P_{cut}}^{\infty} J_{GCR}(P,t)Y(P)dP} \tag{3.1}$$

where $J_{||sep}$ is the primary solar particles rigidity spectrum, $J_{GCR}(P,t)$ is the rigidity spectrum of

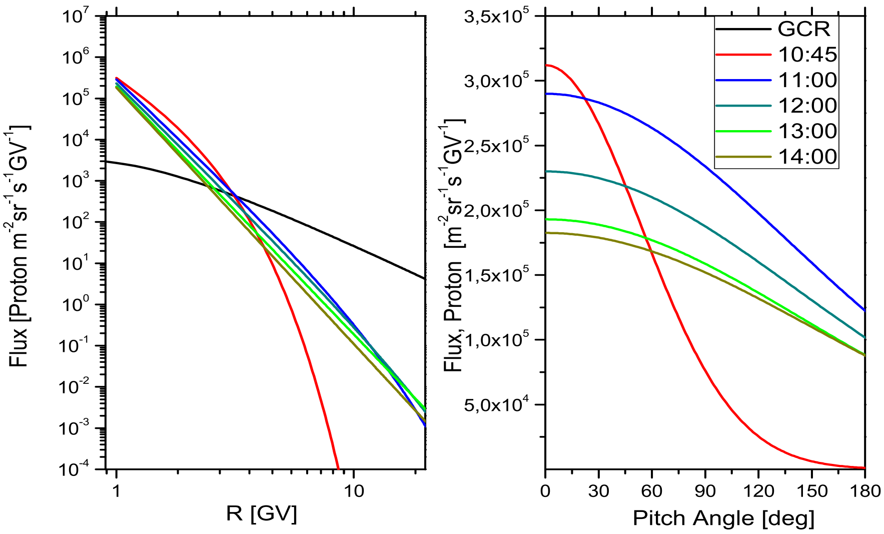


Figure 3: Derived spectral and angular characteristics of SEPs for GLE 59 on 14 July 2000.

GCR, Y(P) is the NM yield function, $G(\alpha(P))$ is the pitch angle distribution, N is the count rate due to GCR, $\Delta N(P_{cut})$ is the count rate increase due to solar particles, P_{cut} is the minimum rigidity cut-off of the station, accordingly P_{max} is the maximum rigidity considered in the model, assumed to be 20 GV. In the model we assume a modified power law rigidity spectrum of SEP $J_{||}(P) = J_0 P^{-(\gamma+\delta\gamma(P-1))}$, where $J_{||}$ is particle flux arriving from the Sun i.e. with zero pitch angle. Accordingly the pitch angle distribution is assumed as a Gaussian $G(\alpha(P)) \sim exp(-\alpha^2/\sigma^2)$. Subsequently we solve an inverse problem applying the Levenberg-Marquardt algorithm [16, 17] with the Minpack code [18].

The newly computed NM yield functions at various altitudes above the sea level allow us to perform a realistic modelling of NM response i.e. without normalization of count rates of high altitude NM stations to the sea level using the two attenuation lengths method [19]. We apply the newly computed NM yield function for analysis of GLE 59 on 14 July 2000 and GLE 70 on 13 December 2006.

3.1 Results of GLE modelling

The Bastille day event was related to X5.8/3B solar flare and associated full halo CME, started at 10:03 UT, reached peak at 10:24 UT and ended at 10:43 UT [20]. Accordingly, the GLE onset began between 10:30 and 10:35 UT at several stations with strongest increases recorded at South Pole 58.3 % and SANAE 54.4 % [21, 22]. On 13 December 2006, NOAA active region 10930, located at S06W26 triggered a X3.4/4 B solar flare with maximum at 2:40 UT. It was associated with Type II and Type IV radio bursts and a fast full-halo CME accompanied by a strong solar proton event [23, 24]. The global NM network recorded the event with maximum at Oulu and Apatity NMs $\sim$ 90 %). In Fig.3 we present the derived spectral and angular characteristics of SEPs for GLE 59 on 14 July 2000, accordingly in Fig. 4 for GLE 70 on 13 December 2006.

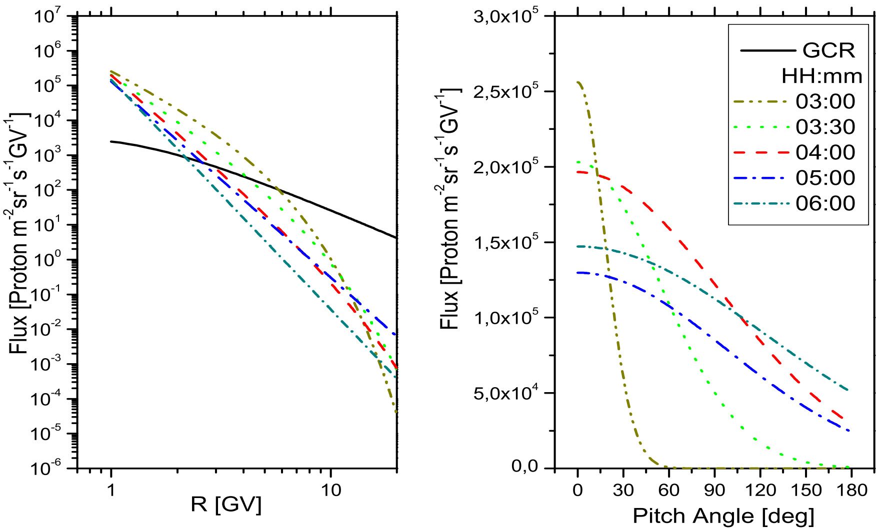


Figure 4: Derived spectral and angular characteristics of SEPs for GLE 70 on 13 December 2006.

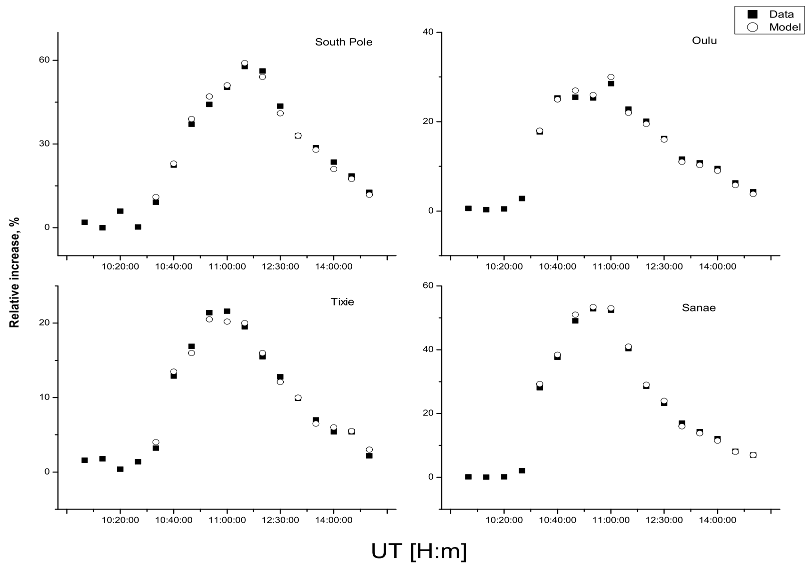


Figure 5: Modelled and observed responses of several NM stations during GLE 59 on 14 July 2000.

Using the newly computed NM yield function we reduce considerable the uncertainty in confidence limits of the derived model parameters to about 5-8 %, instead of 10-12%. As a result we achieve difference of about 2-4 % between modelled and observed NM relative increase for the Bastille day event (Fig.5). Accordingly for GLE 70 we achieve maximal difference of about 3-5 % between modelled and observed NM relative increase (Fig.6). In addition, the convergence of the process is faster and the maximal residual is smaller. This resulted on a fit with improved quality [25].

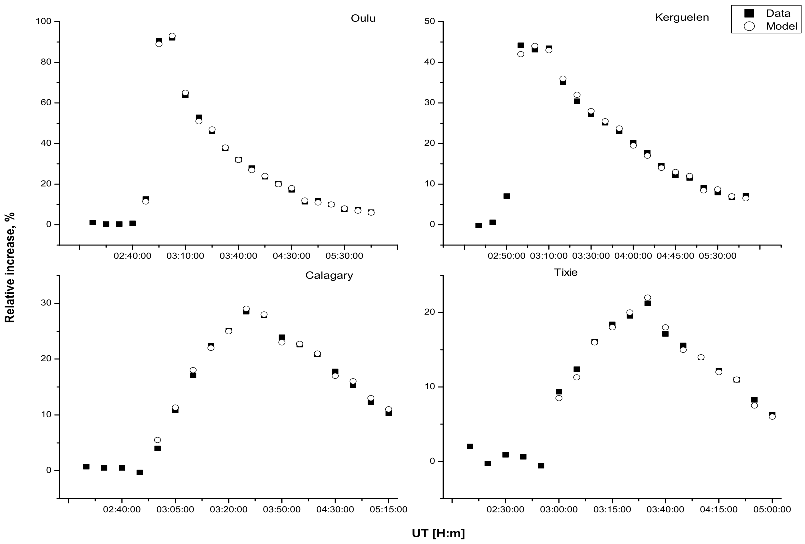


Figure 6: Modelled and observed responses of several NM stations during GLE 70 on 13 December 2006.

4. Conclusion

We have applied an extensive Monte Carlo simulations in order to obtain a new NM yield function at several observation depths. This allow us to perform an analysis of GLEs of solar cycle 23 in a realistic manner and to improve compared to our previous study the method for obtaining the spectral and angular characteristics of SEPs. A significant improvement of parameter derived model parameter error estimation is achieved. Both events considered in this study are relatively strong events. They appeared at different solar activity conditions. They are characterized by relatively strong anisotropy during the initial phase, which decreased rapidly over the following 30 minutes of GLE 59, accordingly 50 minutes for GLE 70.

Acknowledgements

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