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Analysis of sub-GLE and GLE events using NM data: space weather applications

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Abstract. Detailed study of solar energetic particle events is important to understand their acceleration and propagation in the interplanetary space and allows one to model various processes related to space weather and space climate e.g. radiation environment at flight altitudes and atmospheric ionization. A special class of events, called ground level enhancements, registered by ground based detectors, can dramatically change the radiation environment in the Earth's atmosphere. New recently installed high-altitude polar neutron monitors NMs, namely DOMC/B and historically installed South Pole, have made the worldwide neutron monitor network more sensitive to strong solar energetic particle events, registered at ground level. The two high-altitude polar stations are able to detect lower energy events, which most likely would not be registered by the other (near sea level) neutron monitor stations. Here, using the worldwide neutron monitor database (NMDB) records and an optimization procedure combined with simulations, we assess the spectral and angular characteristics of a new class of events sub-GLEs. With the estimated spectral characteristics as an input, we evaluate the effective dose rate in polar and sub-polar regions at typical commercial flight altitude during such events as well as during GLEs.

1. Introduction

Detailed study of solar energetic particle events (SEP) events is important in order to clarify their acceleration and transport mechanisms in the interplanetary space [1, 2]. In addition, possessing information about their spectra and angular distributions, makes it possible to assess processes related to space weather, such as exposure to radiation, henceforth exposure, at flight altitudes [3, 4]. The exposure in the vicinity of Earth and in the Earth's atmosphere is variable and highly dynamic. It is governed by the galactic cosmic rays (GCRs). The Earth is constantly hit by high-energy particles, which collide with nucleus of the atmosphere and produce new, energetic particles, which also collide with nuclei etc...Each collision adds a number of particles to the developing a cascade – an extensive air shower. Another important but sporadic source, which makes the radiation environment in the vicinity of Earth and within its atmosphere highly dynamical is related to eruptive solar processes, namely solar flares and coronal mass ejections, leading to production of SEPs [5, 6]. A special class of SEP events, called ground level enhancements (GLEs) [6, 7], registered by ground based detectors e.g. neutron monitors (NMs), can dramatically change the radiation environment in the Earth's atmosphere [8]. GLEs can be studied using the worldwide NM network [9, 10].

New recently installed high-altitude polar NMs, namely DOMC/B and historically installed both South Pole NMs, have made the worldwide NM network more sensitive to strong SEPs and GLEs. The two high-altitude polar NM stations are able to detect lower energy SEP events, which most likely would not be registered by the other (near sea level) NMs. Here, on the basis of NM records and an optimization procedure, we assess the spectral and angular characteristics of GLE and sub-GLE particles and subsequently evaluate the exposure at typical commercial flight altitude during such events.

2. Analysis of GLE and sub-GLEs using NM data

According to recently adjusted definition, a GLE event is registered when there is a simultaneous statistically significant increase of the count rate of at least two differently located NM stations accompanied with a statistically significant increase of SEP flux observed by a space-borne instrument(s). A new sub-class of events sub-GLEs, accordingly is registered when there are simultaneous statistically significant increase of the count rates of at least two differently located high-altitude NMs with corresponding enhancement in SEP flux measured by a space-borne in-instrument(s), but no statistically significant enhancement in the count rates of NMs near to the sea level, for details see [11]. For the analysis of such events we employ a method similar to that applied to earlier GLEs [12, 13], which detailed description is given in [14, 15, 16].

The method consists of: computation of asymptotic viewing cones and cut-off rigidities of the NMs used for the analysis of the corresponding event; initial guess of the optimization procedure by assuming the apparent source position along the interplanetary magnetic field (IMF) line derived from ACE satellite measurements, the latter being estimated from the 20-minute averaged measurements explicitly considering the time shift of the field direction at the nose of the Earth's bow shock [16]; optimization over modelled and measured NM responses assuming a corresponding set of unknown parameters.

The relative count rate increase of a given NM can be expressed as:

$$\frac{\Delta N(P_{cut})}{N} = \frac{\int_{P_{cut}}^{P_{max}} J_{||SEP}(P,t)Y(P)G(\alpha(P,t))A(P)dP}{\int_{P_{cut}}^{\infty} J_{GCR}(P,t)Y(P)dP} \tag{1}$$

where $J_{||SEP}(P,t)$ is the rigidity spectrum of the primary SEPs with a given rigidity P in the direction of the maximal flux along the IMF, $J_{GCR}(P,t)$ is the rigidity spectrum of GCR at a given time t with the corresponding modulation, $Y(P)$ is the NM yield function, $G(\alpha(P,t))$ is the pitch angle distribution (PAD) of SEPs, $A(P)$ is a discrete function with $A(P)$=1 for allowed trajectories (proton with rigidity P can reach the station), accordingly $A(P)$=0 for forbidden trajectories (proton with rigidity P cannot reach the station), N is the count rate due to GCR, $\Delta N(P_{cut})$ is the count rate increase due to SEPs, P_{cut} is the lower cut-off rigidity of the station and P_{max} is the maximal rigidity of SEPs considered in the model to be 20 GV, respectively. In this study we used a newly computed NM yield function, which provides good agreement with experiments and models [17, 18, 19]. In our model the rigidity spectrum of SEPs is described by a modified power law:

$$J_{||}(P) = J_0 P^{-(\gamma+\delta\gamma(P-1))} \tag{2}$$

where $J_{||}(P)$ is the particle flux with given rigidity P in [GV] arriving from the Sun along the axis of symmetry whose direction is defined by geographic coordinate angles Ψ and Λ (latitude and longitude), γ is the power-law spectral exponent at rigidity P = 1 GV, $\delta\gamma$ is the rate of the spectrum steepening. In Eq. (1) we can consider also an exponential spectrum similarly:

$$J_{||}(P) = J_0 \exp(-P/P_0). \tag{3}$$

where $J_{||}$ is defined as in Eq. (2) and P_0 is a characteristic proton rigidity. The PAD is assumed to be a superposition of two Gaussians, which allows to model a complicated particle flow:

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$$G(\alpha(P)) \sim \exp(-\alpha^2/\sigma_1^2) + B.\exp(-(\alpha-\pi)^2/\sigma_2^2) \quad (4)$$

where α is the pitch angle, σ_1 and σ_2 are parameters corresponding to the width of the pitch angle distribution, B is a parameter corresponding to the contribution of the particle flux arriving from the anti-sun direction. The optimization is performed using the Levenberg-Marquardt method [20, 21] with variable regularization [22, 23, 24]. The magnetospheric computations are performed with the MAGNETOCOSMICS code [25] using a combination of Tsyganenko 1989 (external) [26] and IGRF (internal) [27] geomagnetic models, which allows one to compute straightforwardly the cut-off rigidity and asymptotic directions with reasonable precision [28, 29, 30].

In the case of sub-GLEs we possess information only from two NMs with statistically significant count rate increase. Therefore, for the analysis of sub-GLEs we simplify the model by assuming a simple power law or exponential rigidity spectrum of SEPs, with one directional Gaussian PAD. We also assume the apparent source position to be along the IMF derived from ACE satellite measurements, but not as a free parameter. Subsequently we derive a set of solutions with similar quality and with the mean we performed a simulation of the global NM network response. The best fit of the global NM network response from the forward modelling is assumed as the final apparent source position. Therefore, by optimization over a limited set of parameters and simulation of the global NM network response (fixing one and/or several of the parameters, but varying the others) after several iterations we assessed the spectral and angular characteristics of sub-GLE particles and accordingly their spectral constraints, the details are given in [16].

3. Examples of sub-GLE analysis

As an example, we demonstrate the analysis of a sub-GLE event on 29 October 2015 (Fig.1). Details for the analysis of this event as well several other sub-GLEs is given elsewhere [16].

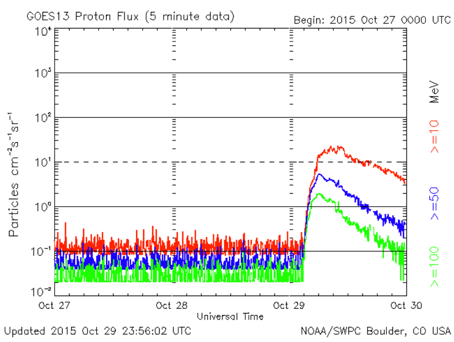

Figure 1. Profile of the time variation of GOES 13 proton flux during sub-GLE event on 29 October 2015.

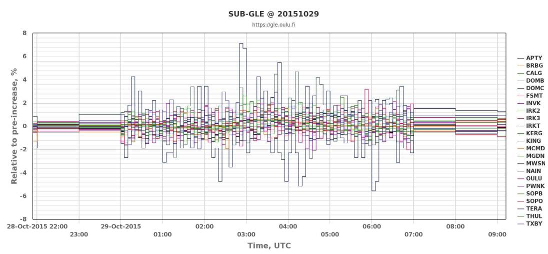

Figure 2. Profile of the time variation of NMs count rate during sub-GLE event on 29 October 2015
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The derived spectra and PAD of the studied sub-GLEs are compared with those of a weak event – GLE 71 and with a moderately strong event – GLE 70, the results are presented in Fig.3a,b.

The derived rigidity spectra of sub-GLEs are softer than those of GLEs (Fig.3a). In addition, the proton flux at 1 GV during sub-GLE events is nearly an order lower compared to a weak event as GLE 71.

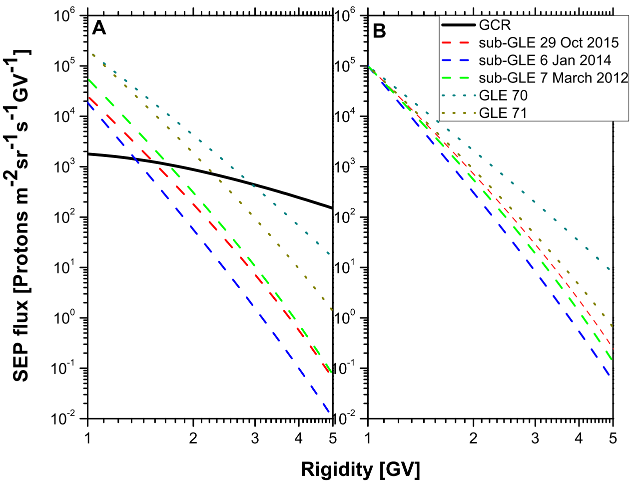

Figure 3. Rigidity spectra during several sub-GLE events compared with GLE 70 on 13 December 2006 and GLE 71 on 17 May 2012 as denoted in the legend. The black solid line in the left panel denotes the average GCR flux.

4. Computation of exposure during GLEs and sub-GLEs

The computation of the dose rate at flight altitudes due to CRs is rather challenging, because the large variability and extended energy range of the produced secondaries. During the last decade several models for assessment of the exposure due to CRs have been proposed e.g. [31, 32, 33]. Here, the exposure at flight altitudes is assessed using the derived spectral and angular parameters of SEPs and employing a recent numerical model based on pre-computed yield functions [34]. The effective dose rate at a given atmospheric depth h induced by a primary CR particle is computed by convolution of the yield function with a corresponding primary CR particle spectrum:

$$E(h) = \sum_i \int_{T_{cut}(P_c)}^{\infty} J_i(T) Y_i(T,h) dT \tag{5}$$

where $J_i(T)$ is the differential energy spectrum of the primary CR arriving at the top of the atmosphere for $i-$th component (proton or $\alpha-$particle) and Y_i is the effective dose yield function for this type of particles. The integration is over the kinetic energy T above $T_{cut}(P_c)$, which is defined by the local cut-off rigidity P_c for a nuclei of type i, $T_{cut,i} = \sqrt{\left(\frac{Z_i}{A_i}\right)^2 P_c^2 + E_0^2} - E_0$, where $E_0 = 0.938$ GeV/c^2 is the proton's rest mass.

Accordingly, the effective dose yield function Y_i is defined as:

$$Y_i(T,h) = \sum_j \int_{T^*} F_{i,j}(h,T,T^*,\theta,\varphi) C_j(T^*) dT^* \tag{6}$$

where $C_j(T^*)$ is the coefficient converting the fluence of secondary particles of type j (neutron, proton, γ, e^-, e^+, μ^-, μ^+, π^-, π^+) with energy T^* to the effective dose, $F_{i,j}(h,T,T^*,\theta,\varphi)$ is the fluence of secondary particles of type j, produced by a primary particle of type i (proton or $\alpha-$particle) with a given primary energy T arriving at the top of the atmosphere from zenith angle θ and azimuth angle φ.

According to our analysis the contribution of SEPs during sub-GLE event is comparable to the contribution of GCR, the details re given in [16]. In addition, we performed analysis of the GLE 72 on 10 September 2017, which appeared as a week event. Details about the GLE 72 analysis are given in [35] and these proceedings. The distribution of the effective dose rate as a function of the geographic coordinates at altitude of 35 kft due to high energy GLE and GCR particles during the peak phase of GLE 72 is given in Fig. 4.

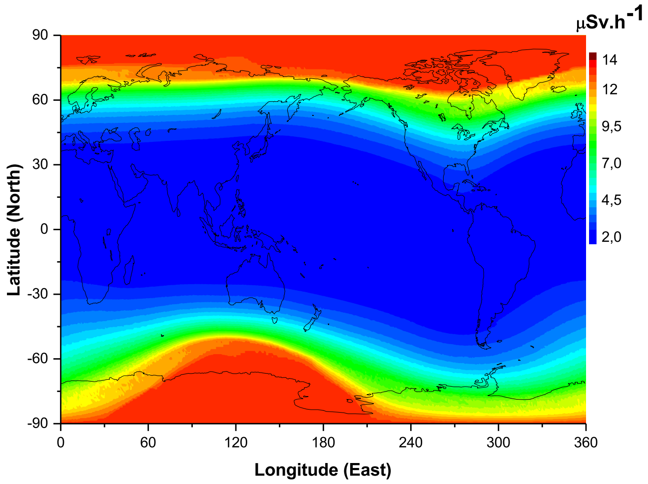

Figure 4. Distribution of the effective dose rate at altitude of 35 kft during GLE 72

5. Conclusions

In the work presented here we have studied several candidates for a new subclass of SEP events, sub-GLEs, which are of special interest for space weather applications. On the basis of data retrieved from different NMs and using a combination of a full simulation of the global NM network response and optimization procedure over a set of unknown parameters describing the SEP features, we have assessed the spectral and angular characteristics of sub-GLE particles. With the estimated spectral characteristics and using a previously developed model, we have assessed the effective dose rate in a polar and sub-polar region at commercial flight altitudes of 35 kft. During those computations a conservative scenario concerning the contribution of sub-GLE to the exposure was assumed [36]. It was shown that the contribution of sub-GLE particles to the exposure is at least comparable to the GCRs contribution. In addition, a similar analysis of GLEs was performed, their spectra derived and distribution of the exposure over the globe obtained. The derived spectra and assessed exposure during various stages of sub-GLEs and GLEs allow one to compute to quantify the radiation radiation environment in the troposphere and stratosphere [37, 38]. In this study, we demonstrated that the global NM network is a useful tool to estimate an important space weather effect, namely the exposure of aircrew due to CR of galactic and solar origin. The derived spectra and angular distributions will be integrated into the GLE database [39].

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