Ionization effect of strong solar particle events: Low-middle atmosphere

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***Abstract*. Using a new reconstruction of the proton energy spectra in Ground Level Enhancement (GLE) events, based on fits to measurements from ground-based and satellite-borne instruments covering a wide energy range, we quantitatively evaluate the possible ionization effects in the low and middle atmosphere for the GLEs of Solar Cycle 23. The ionization computations are based on the numerical 3D CRAC:CRII model. It is shown that the direct ionization effect is negligible or even negative, due to the accompanying Forbush decreases, in all low- and mid-latitude regions. The effect is positive only in polar atmosphere, where it can be dramatic in the upper atmosphere during major GLE events.**

***Keywords*: cosmic rays, atmosphere, ionization, solar energetic particles**

I. INTRODUCTION

While the ionization effect of galactic cosmic rays (GCR) in the atmosphere is well known and can be properly modelled (see a review [1]), solar energetic particles (SEPs) can produce additional instantaneous atmospheric effects during the relatively short periods of SEP events, potentially affecting the Earth's environment [2]. During typical SEP events with enhanced flux of low energy SEPs (<100 MeV for protons), the effect is limited to the upper atmosphere, and it is sufficient to apply an analytical approximation (the so-called thin target approach) of direct ionization (e.g., [3], [4], [5]). However, during so-called Ground level Enhancement (GLE) events, solar proton spectra can extend up to ∼1-10 GeV, energies that are high enough to induce cascades of particles in the atmosphere. Neglecting these cascades leads to potentially large errors in the lower-atmosphere ionization as computed by analytical ionization models. Here we straightforwardly compute, using the Monte-Carlo CRAC:CRII model [6], ionization of lower and middle atmosphere during GLE events of solar cycle 23, using new reconstructions of the energy spectra of SEP protons. We discuss in detail the ionization effect of the extreme SEP event of 2005-Jan-20, which was one of the largest GLEs ever observed ([7], [8]). For the other GLEs of cycle 23 we briefly summarize the results. GLE events often occur on the background of reduced GCR flux (Frobush decrease), so that the reduction of GCR flux overcompensates the enhancement due to SEPs, leading to the negative (reduced ionization) net atmospheric effect, contrary to naive expectations. A systematically positive ionization effect is observed only in the polar middle and upper atmosphere.

II. COSMIC RAY INDUCED IONIZATION

Nucleonic-electromagnetic cascade initiated by energetic cosmic rays in the Earth's atmosphere leads to permanent ionization of the ambient air at different altitudes, called the cosmic ray induced ionization (CRII) of the atmosphere. Generally CRII rate (number of ion pairs produced in one gram of the ambient air per second) at a given atmospheric depth h can be represented as follows [1]:

$$q(h, P_c, t) = \sum_i \int_{E_{c,i}}^{\infty} S_i(E, t) \cdot Y_i(h, E)\, dE, \qquad (1)$$

where the summation is performed over different i-th species of CR (protons, α-particles, heavier species), $Y_i(h, E)$ is the ionization yield function (the number of ion pairs produced at altitude h in the atmosphere by the unit flux of CR particles of the i-th type with kinetic energy E), $S_i(E, t)$ is the differential energy spectrum of galactic or solar cosmic rays. Integration is performed above $E_{c,i}$, which is the kinetic energy of a particle of i-th type, corresponding to the local geomagnetic cutoff rigidity P_c. Full details of the CRII computations by the CRAC:CRII model, used here, are given in ref. [6]. Note that CRII at a given location and time depends on three variables: altitude h via the integrand yield function Y (available in the tabular form from [6]), geographical location via the geomagnetic cutoff rigidity P_c (integration limits), and time via the integrand CR spectrum S. Since these three variables are mutually independent, they can be separated in order to solve the problem numerically in an efficient way. The GCR spectrum was parameterized by the force-field approach by fitting the measured quiet-time data from the world-wide neutron-monitor (NM) network (see [9] for details).

We similarly computed the SEP-induced ion production during GLEs. For this purpose, we used event-integrated solar proton spectra derived by the method described in [11]. The method begins by extracting the solar proton spectrum above 1 GV (430 MeV) from the

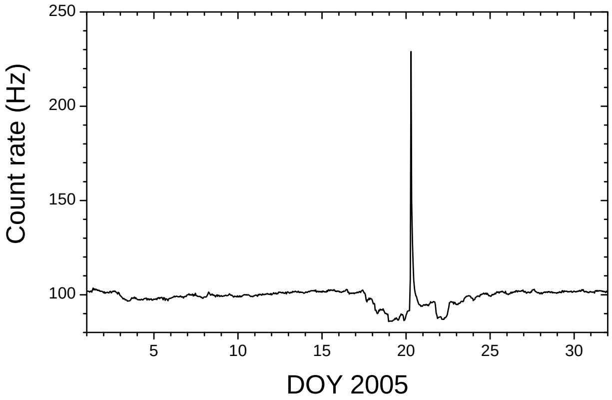

Fig. 1: Time profile of Oulu NM hourly averaged count rate for January 2005 (http://cosmicrays.oulu.fi).

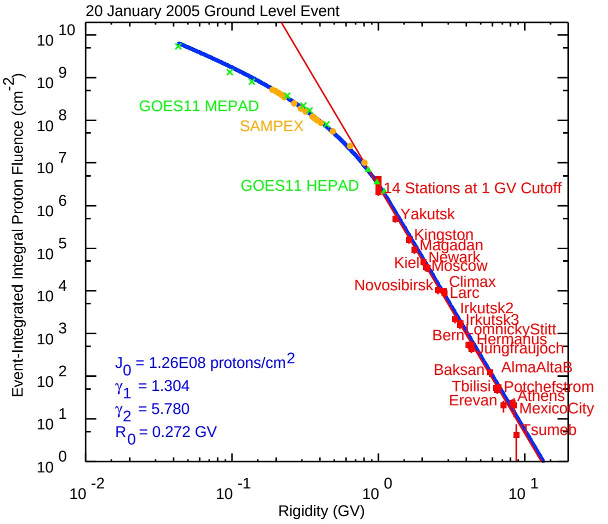

Fig. 2: Band-function fit to event-integrated proton spectrum for the 2005-Jan-20 GLE [11].

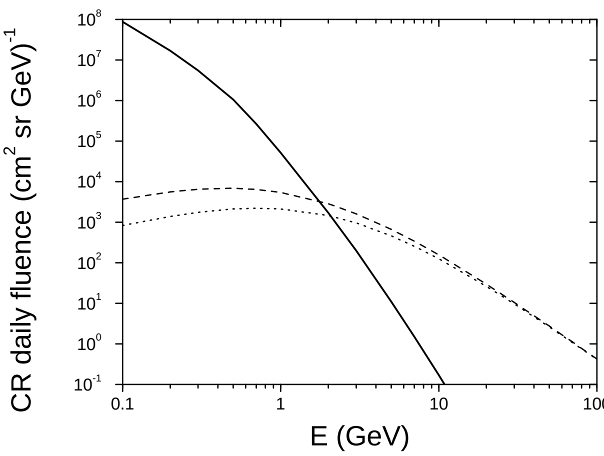

Fig. 3: Differential fluence of solar protons from the 2005-Jan-20 event (solid line – cf. Fig. 2) and the daily fluence of GCR protons for the day of 2005-Jan-20, including the effect of the Forbush decrease (dotted line). The dashed curve depicts the average GCR proton fluence for January 2005.

world-wide NM network using the NM yield function of [12]. The NM results are combined with satellite measurements at $\sim$ 10-700 MeV from GOES, IMP8, and SAMPEX. The validity of the analysis is confirmed by comparing the NM and satellite fluence measurements at nearly overlapping energies. Together the NM and satellite fluences are represented as an integral spectrum in rigidity. This combined integral spectrum is generally well fit to the Band functional form [10], with point-to-point residuals on the order of $\sim$10-20%. The Band function smoothly rolls one power-law into another, keeping both the function and its first derivative continuous. This Band function is a convenient starting point for atmospheric-ionization and other radiation-effect calculations, since it can be readily transformed into a differential spectrum in kinetic energy.

In this study we neglect α-particles and heavier species of SEP, since their contribution is minor [7]. Since we are interested in the event-integrated effect, we also average over the initial SEP anisotropy, which is typically large for only a comparatively short period of time in each SEP event, e.g. [8].

III. SEP Event of 2005-Jan-20

The time profile of a polar Oulu NM count rate is shown in Fig. 1. Note that the relatively quiet first period, before 2005-Jan-17, was followed by a strong Forbush decrease. The GLE of 2005-Jan-20 occurred at the early recover phase of the decrease. During next two days, an additional suppression of the CR intensity occurred, making the overall time profile even more complicated.

The energy spectrum and intensity of protons varied quite a bit from day to day in January 2005. Figure 2 shows the event-integrated proton spectrum of the 2005-Jan-20 GLE as an integral function of rigidity. Figure 3 shows that spectrum converted to differential in energy, along with the GCR proton fluence for the day of 2005-Jan-20 (including the effect of the Forbush decrease). The average daily GCR proton fluence for the whole month of January 2005 is also shown for comparison. One can see that SEP dominate below 1 GeV, but the effects quickly decreases with energy. On the other hand, the reduction of GCR fluence due to the Forbush decrease was significant in this energy range. Therefore, the CRII during January 2005 was an interplay between an enhancement due to SEPs and the reduction due to the Forbush decrease.

In order to study these effects in detail, we computed the daily averaged CRII rate in polar regions separately from SEPs and GCRs (Fig. 4). One can see that the SEP-induced ionization is significant above $h \approx 200$ g/cm^2 (about 12 km altitude), but is subtle in the troposphere ($h \approx 500$ g/cm^2, or 5.5 km altitude). However, these ionization rates quickly become smaller with decreasing geomagnetic latitude. Let us now define the CRII effect

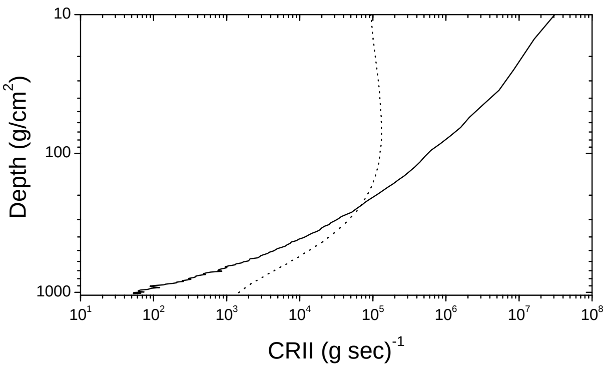

Fig. 4: The daily averaged CRII in the polar region from GCR (dotted curve) and SEP (solid curve) separately, for the day of 2005-Jan-20.

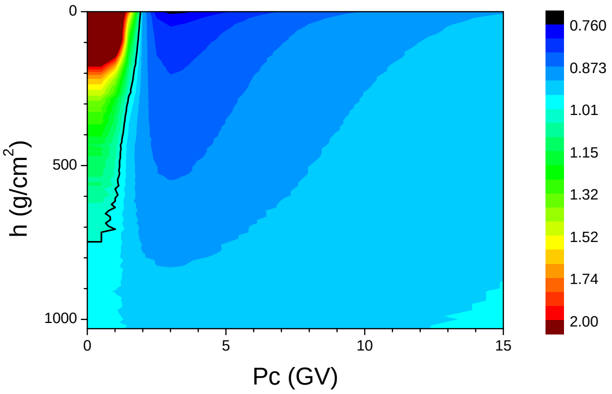

Fig. 5: The relative ionization effect C (see text for definition) of GLE 2005-Jan-20 as function of the geomagnetic cutoff rigidity P_c and atmospheric depth h. The solid curve bounds positive (enhancement) and negative (suppression) effects.

(at fixed altitude h and location P_c) of a SEP event as follows:

$$C(h, P_c) = \frac{I_{\rm SEP} + I_{\rm GCR}}{\langle I \rangle} \qquad (2)$$

where $I_{\rm SEP}$ and $I_{\rm GCR}$ are daily CRII productions by SEP and GCR separately, respectively, for the very day of event, and $\langle I \rangle$ is the averaged daily CRII for the whole month. A 2D (altitude vs. geomagnetic latitude) chart of the thus defined effect C is shown in Fig. 5 for the event of 2005-Jan-20. The effect is a reduction (i.e. $C < 1$) in the major part of the atmosphere, because of the Forbush decrease. The increase ($C > 1$) is observed only in polar upper atmosphere ($P_c < 2$ GV, $h < 700\,{\rm g/cm}^2$). Note that the overall effect is small in equatorial regions, being only a few percent.

In order to illustrate this, we have plotted the computed temporal variability of CRII during the month of January 2005 at two atmospheric depths, corresponding to the tropopause ($h = 200$ g/cm^2) and middle troposphere ($h = 500$ g/cm^2), as a function of the local geomagnetic cutoff. For convenience, all CRII values have been normalized to the mean (during that month)

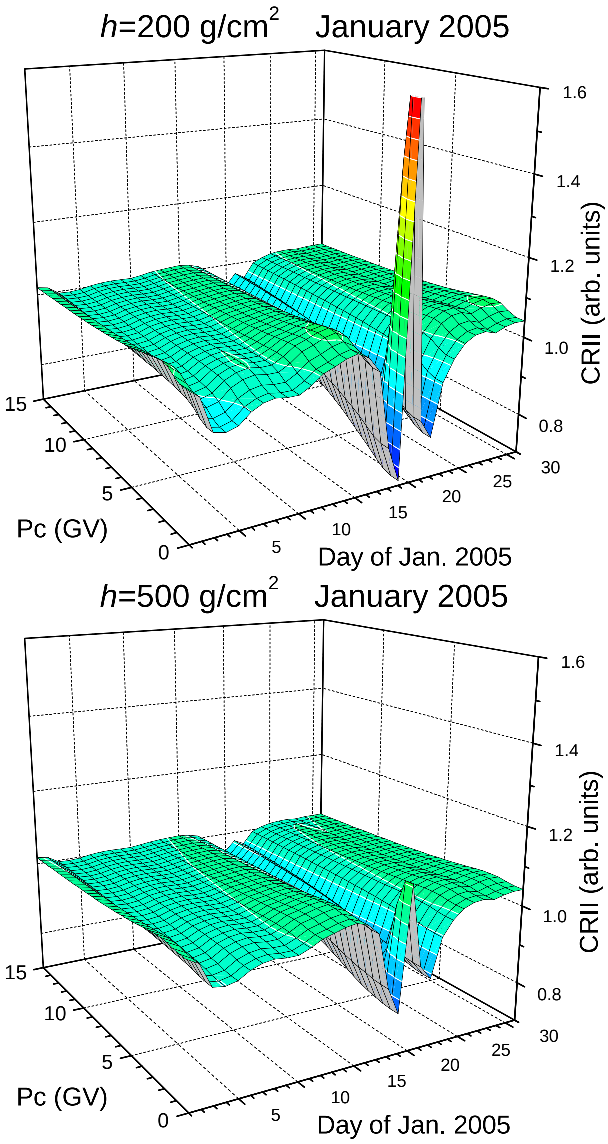

Fig. 6: The relative ionization (normalized to the average ionization rate in January, 2005) as function of time and location (P_c) for two atmospheric depths (200 g/cm^2 and 500 g/cm^2).

CRII at each location P_c (Fig. 6). One can see the main feature – flattish profile before Jan. 17-th and after 25-th with a fractured dip during 17–24 January. The fracture (seeming increase) in the middle of the dip was caused not by the GLE itself, but rather by the complicated CR intensity time profile (Fig. 4), when the recovery phase of the Forbush decrease was interrupted by another suppression during 21–22 January. We note that the GLE per se was able to compensate the effect of the Forbush decrease only in the high-latitude region with $P_c < 2$ GV. Note that the enhancement of the daily ionization due to GLE was subtle in the polar troposphere but significant in the stratosphere and higher (doubling and more). Therefore, even for such a severe GLE, the ionization effect was negative and small in the

TABLE I: GLEs of cycle 23 (Date and 5-min peak percentage increase in Oulu NM count rate), and relative CRII effect (% to the average of January, 2005) at different depths in the polar atmosphere.

GLE		effect at given height (g/cm^2)			
Date	NM %	100	300	500	700
1997-Nov-06	11	13	2	1	1
1998-May-02	7	-8	-7	-6	-4.5
1998-May-06	4	-6	-4.5	-4	-3
1998-Aug-24	3	-5	-5	-4	-3
2000-Jul-14	30	67	2	-1	-3
2001-Apr-15	57	98	8	2	0.5
2001-Apr-18	5	15	4	3	2
2001-Nov-04	3	17	6	5	3
2001-Dec-26	5	9	3	2	1
2002-Aug-24	5	5	1	0	0
2003-Oct-28	5	28	3	2	1
2003-Nov-02	6	-8	-11	-10	-7
2005-Jan-17	3	10	4	3	2
2005-Jan-20	269	217	18	5	0
2006-Dec-13	92	25	3	1	0.5

major part of the atmosphere and positive only in the middle and upper polar atmosphere.

IV. Results for other GLEs

We performed a similar analysis for the other major GLEs of solar cycle 23. The events are listed in Table I, including the date and the peak increase in 5-min count rate of a polar neutron monitor (http://cosmicrays.oulu.fi), in columns 1 and 2, respectively. Three events exceeded 50% increase in NM count rate, while most of them were of only several percent. The relative GLE effect in the atmospheric ionization, computed in the same way (Eq. 2) as above, is summarized in Table I for the polar atmosphere. The effect is shown for four different altitude levels corresponding to about 16 km, 9 km, 5.5 km, and 3 km, respectively in columns 3 through 6. There is a strong correlation between the GLE magnitude (in NM %) and the ionization effect in the stratosphere ($h = 100$ g/cm^2) – all strong GLEs led to a more than 10% enhancement of CRII in the polar region. There is still some weak relation in the upper troposphere ($h = 300$ g/cm^2) – all strong GLEs lead to a slight positive ionization effect. On the other hand, other weak GLEs (e.g., 2001-Apr-18) may produce similar or stronger effect if not accompanied by a Forbush decrease. There is no correlation between GLE strength and ionization in the lower troposphere – the effect is not driven by the additional SEP flux but is rather determined by the variability of the GCR flux.

V. Conclusions

The effect of an extreme SEP event of 2005-Jan-20 in cosmic ray induced ionization of the atmosphere has been discussed in detail. It is shown that SEP play a role in the ionization only in the upper-middle polar atmosphere. In all other regions the ionization is suppressed due to the accompanying Forbush decrease. We have also calculated the ionization effect from other GLEs of cycle 23 (1997–2006). The results are presented in Table I for the polar atmosphere. There is no ionization effect at mid- or low-latitudes, even for the strongest events. It is clear from Table I that there is no straightforward relation between the strength of GLE (as measured by neutron monitors) and the ionization effect in polar atmosphere. The net atmospheric ionization effect is defined by an interplay between the SEP event itself and a Forbush decrease, which often accompanying it. This interplay makes it difficult to utilize regression or superposed epoch analyses in statistical studies of these effects. Accordingly, the atmospheric effect of SEP events should be studied individually, based on detailed information of the exact solar, heliospheric, and geospace conditions around the event.

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