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Ionization effect of solar particle GLE events in low and middle atmosphere

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Abstract

Using a new reconstruction of the solar proton energy spectra for 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 58 out of the 66 GLE events recorded by the world-wide neutron monitor network since 1956. The ionization computations are based on the numerical 3-D CRAC:CRII model. A table of the ionization effect caused by the GLE events at different atmospheric heights is provided. 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 ionization effect is important only in the polar atmosphere, where it can be dramatic in the middle and upper atmosphere (above 30 km) during major GLE events.

1 Introduction

Cosmic rays form an important source of ionization of the Earth's atmosphere and the main source in the troposphere and stratosphere. Most important for ionization in the troposphere-stratosphere are galactic cosmic rays (GCR) that possess high energies and produce a complicated cascade of secondary particles in the atmosphere, leading to permanent ionization of the ambient air. While the net energy brought by cosmic rays is small and the caused ionization rate is not high, it can affect physical and chemical properties of the atmosphere. The process of cosmic ray induced ionization (CRII) in the lower atmosphere is well known and can be properly modelled using Monte-Carlo numerical models (see a review by Bazilevskaya et al., 2008). The upper atmosphere (above a few g/cm^2) is affected mostly by solar electromagnetic radiation and by lower energy particles of magnetospheric origin, which is also quite well modelled using straightforward analytical ionization models.

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The GCR energy spectrum changes on different time scales, with the most apparent being a 11-yr solar cycle, so that GCR flux is higher around solar minima. While the intensity of high energy GCR (above several tens of GeV) changes little, the lower part of the spectrum may change quite a bit – the difference in 100 MeV particles flux can be an order of magnitude or more between the periods of solar minima and maxima. This variation is caused by the related changes in the heliospheric properties, such as polarity, strength and turbulence level of the interplanetary magnetic field, density and speed of solar wind, which are ultimately driven by the solar surface magnetic activity. This cyclic change in the GCR intensity is broadly called heliospheric modulation of cosmic rays and reaches 25% magnitude between maximum and minimum, as recorded by a ground-based polar neutron monitor (NM). The corresponding variations in CRII are also cyclic but their magnitude depends on the altitude and location (Bazilevskaya et al., 2008). On the other hand, solar-heliospheric transient phenomena, such as coronal mass ejections (CME) interplanetary shocks, corotating interaction regions, magnetic clouds may lead to strong but relatively short suppressions of the GCR intensity near Earth. Such suppressions are called Forbush decreases (Cane, 2000) which can be as strong as 25–30% in a polar NM count rate. The suppression itself develops quickly (within several hours up to one day), and the recovery may take days to weeks.

In addition to the permanently operating ionization process due to GCR, there are additional instantaneous atmospheric effects during relatively short periods of SEP (solar energetic particle) events, potentially affecting the Earth's environment (Miroshnichenko, 2008; Vainio et al., 2009). A typical SEP event is characterized by enhanced (sometimes by many orders of magnitude) flux of low energy (<100 MeV for protons) SEPs, which may last for several days (e.g., Cane et al., 1988; Reames et al., 1996; Lario and Simnett, 2004; Klecker et al., 2006). Because of low energy, such SEPs are not able to initiate atmospheric cascade and are stopped due to ionization losses, and their ionization effect is limited to the upper polar atmosphere. This is usually modelled using analytical approximation of direct ionization (e.g., Vitt and Jackman, 1996). There are numerous studies of the effects caused by magnetospheric and solar

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energetic particles but they are usually limited to the upper atmosphere above 30 km (e.g., Jackman et al., 2008, 2009; Damiani et al., 2008; Seppälä et al., 2008). However, there is a special class of SEP events, called Ground Level Enhancement (GLE) events, which are characterized by higher energy of solar particles that can extend up to ∼1–10 GeV (e.g., Duggal, 1979; Stoker, 1994). These energies are high enough to induce cascades of secondary particles in the atmosphere, similar to GCR. Accordingly, an increase of the nucleonic component of the cascade can be measured at the ground level by NMs, which is a standard tool to record cosmic-ray intensities. Therefore, the ionizing atmospheric effect of GLE events is expected to be noticeable in the lower atmosphere. Phenomenological studies performed for the extremely large GLE event of January 20, 2005 suggest that an increase of ionization due to SEPs can be significant in the polar low and middle atmosphere (Mironova et al., 2008). However, to the best of our knowledge, to date there have been no proper systematic computations of lower atmosphere ionization effects caused by GLE events. Estimates based on analytical or truncated numerical models of the atmospheric ionization that neglect development of the atmospheric cascade lead to potentially large errors in the lower-atmosphere ionization (Usoskin et al., 2010).

Here we straightforwardly compute, using the Monte-Carlo CRAC:CRII model (Usoskin and Kovaltsov, 2006; Usoskin et al., 2004, 2010), ionization of lower and middle atmosphere during 58 out of the 66 GLE events of the last five solar cycles, using new reconstructions of the energy spectra of SEP protons (Tylka and Dietrich, 2009). (The remaining GLE events were too small or had too little data for spectral analysis.) We note that GLE events often occur on the background Frobush decrease, that can overcompensate the ionization enhancement due to SEPs, leading to the negative (reduced ionization) net atmospheric effect, contrary to naive expectations. Here we systematically evaluate the summary ionization effect of both GCR and SEP in the low and middle atmosphere. We discuss in full detail the ionization effect of the GLE event of 20 January 2005, and for other events we briefly summarize the results.

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2 Cosmic ray induced ionization

Nucleonic-muon-electromagnetic cascades initiated by energetic cosmic rays in the Earth's atmosphere lead to ionization of the ambient air at different altitudes. Generally the CRII rate (number of ion pairs produced in one gram of the ambient air per second) at a given residual atmospheric depth[1] h can be represented as follows (Bazilevskaya et al., 2008):

$$I(h,P_c,t) = \sum_i \int_{T_{c,i}}^{\infty} S_i(T,t) \cdot Y_i(h,T)\, dT, \quad (1)$$

where the summation is performed over different i-th species of primary CR (protons, α-particles, heavier nuclei), $Y_i(h,T)$ is the ionization yield function (the number of ion pairs produced at the atmospheric depth h in the atmosphere by the unit flux of CR particles of the i-th type with kinetic energy T), $S_i(T,t)$ is the differential energy spectrum (in units of $[\mathrm{cm^2\,sr\,GeV\,s}]^{-1}$) of galactic or solar cosmic rays. The integration is performed above $T_{c,i}$, which is the kinetic energy of a particle of i-th type, corresponding to the local vertical geomagnetic cutoff rigidity P_c, which is the minimum rigidity (momentum per unit charge) that a charged particle must possess to overcome the shielding effect of the geomagnetic field and reach the given location (Cooke et al., 1991) in Earth's atmosphere. The value of P_c varies from zero (in polar regions) to 15 GV at equatorial regions. Full details of the CRII computations by the CRAC:CRII model, used here, are given in references (Usoskin and Kovaltsov, 2006; Usoskin et al., 2010). This model

[1] Here we operate with the concept residual atmospheric depth, which is the amount of matter (air) overburden above a given point in the atmosphere. The top of the atmosphere is 0 g/cm^2, and the mean sea-level corresponds to h=1033 g/cm^2. This concept is naturally related to the development of the cascade and to the ionization. The atmospheric depth h in [g/cm^2] is linearly related to the static barometric pressure p in mb (or hPa) as h=1.0195·p. Conversion into the atmospheric height is not straightforward and depends on the exact vertical density profile.

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has been validated by comparisons with the observations (Bazilevskaya et al., 2008) and with other models (e.g., Usoskin et al., 2009; Velinov et al., 2009; Atri et al., 2010). 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 in Usoskin and Kovaltsov, 2006; Usoskin et al., 2010), geographical location via the geomagnetic cutoff rigidity P_c (integration limits), and time via the integrand GCR 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 is often approximated in the framework of the force-field approach by fitting the measured data from the world-wide NM network (see Usoskin et al., 2005, for full details). In this framework, the GCR spectrum is parameterized via a single time-variable parameter, called the modulation potential ϕ. The GCR-induced ionization rate was computed in this way for each of the days with GLE events analyzed here and also for the entire solar cycle 23 (1996–2008).

In order to compute the SEP-induced ion production during GLE events one needs to know the event-integrated energy spectrum of SEPs. Here we use event-integrated solar proton spectra derived by the method described in Tylka and Dietrich (2009); Tylka et al. (2010). The method begins by extracting the solar proton spectrum above 1 GV rigidity (430 MeV kinetic energy) from the world-wide NM network using the NM yield function of Clem and Dorman (2000). Since a NM is sensitive to cosmic particles with energy above a few hundred MeV, it cannot provide data to reconstruct a lower energy part of the energy spectrum. Accordingly, satellite measurements in the ∼10–700 MeV energy range from GOES, IMP8, and SAMPEX spacecrafts were used in combination with NM-based results. The validity of the analysis is confirmed by comparing the NM and satellite fluence measurements at nearly overlapping energies (Tylka and Dietrich, 2009) and by comparison with previously published studies of individual GLEs. 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 (Band et al., 1993), with point-to-point residuals on the order of ∼10% at satellite energies and of ∼30% at NM energies, which are relevant for the low and middle atmosphere.

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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.

Let us express rigidity R in GV and kinetic energy T in GeV. Then the integral omnidirectional event-integrated fluence (in protons/cm^2) of SEP is represented using the Band function:

$$J(>R) = J_0 \cdot R^{-\gamma_1} \exp\left(-R/R_0\right), \quad \text{for } R \le (\gamma_2-\gamma_1)R_0,$$
$$J(>R) = J_0 \cdot A \cdot R^{-\gamma_2}, \quad \text{for } R > (\gamma_2-\gamma_1)R_0, \tag{2}$$

where

$$A = \left[(\gamma_2-\gamma_1)R_0\right]^{(\gamma_2-\gamma_1)} \exp(\gamma_1-\gamma_2),$$
$$R = \sqrt{T^2+2T_0 \cdot T} \tag{3}$$

T_0=0.938 GeV is the proton's rest-mass energy. These equations correspond to the event-integrated differential spectrum in kinetic energy event-integrated spectrum (in protons/(cm^2 sr GeV)):

$$S = \frac{1}{4\pi} J_0 \cdot R^{-\gamma_1} \exp(-R/R_0) \frac{(\gamma_1 R_0 + R)(T+T_0)}{R^2 R_0}, \qquad \text{for } R \le (\gamma_2-\gamma_1)R_0,$$
$$S = \frac{1}{4\pi} J_0 \cdot A \cdot \gamma_2 \cdot R^{-\gamma_2} \frac{T+T_0}{R^2}, \qquad \text{for } R > (\gamma_2-\gamma_1)R_0. \tag{4}$$

In this study we neglect α-particles and heavier species of SEP, since their contribution is minor (Tylka et al., 1999, 2006). However, heavier species were considered in full extent when calculating CRII from GCR where they play a role (Webber and Higbie, 2003; Usoskin and Kovaltsov, 2006). Since we are interested in the event-integrated effect, we also average over the initial SEP anisotropy, which is typically large only for a comparatively short period of time in SEP events (e.g., Plainaki et al., 2007).

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3 SEP event of 20 January 2005

In this Section we discuss in detail the ionization effect of the GLE event of 20 January 2005. This event was the second strongest ever observed by the ground-based NMs with an increase exceeding 20-fold in 5-min data (54-fold in 1-min data) of the South Pole NM (Mewaldt, 2006; Plainaki et al., 2007; Belov et al., 2010). It was characterized by a short-lasting anisotropic component with a very hard spectrum followed by prolonged isotropic emission of SEPs with a softer spectrum (McCracken et al., 2008). The first anisotropic injection led to a strong but very short ionization pulse only in the South polar region but the event-integrated atmospheric ionization was fairly symmetric in both polar regions (Bütikofer et al., 2008).

The time profile of the polar Oulu NM count rate is shown in Fig. 1. Note that the relatively quiet first period, before 17 January, was followed by a strong 15% Forbush decrease caused by an interplanetary disturbance (Papaioannou et al., 2010). The GLE of 20 January 2005 occurred at the early recovery phase of the Forbush decrease when the background suppression of the NM count rate was about 10%. During the following two days, an additional suppression of the CR intensity occurred, making the overall time profile even more complicated.

The energy spectrum and intensity of cosmic rays varied quite a bit from day to day in January 2005. Figure 2a shows the SEP event-integrated spectrum computed using Eq. (4), along with the GCR proton fluence for the day of 20 January 2005 (including the effect of the Forbush decrease). The value of the modulation potential, computed from the NM network data using the approach of Usoskin et al. (2005), for that day is ϕ_d=1188 MV. The average GCR intensity for the whole month of January 2005 corresponded to the value of ϕ=788 MV. The corresponding average daily GCR proton fluence for January 2005 is also shown for comparison. One can see that for the day of 20 January SEPs heavily dominated below 1 GeV, but the effects quickly decreased 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

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was an interplay between an enhancement due to SEPs and the reduction due to the Forbush decrease.

In order to study the ionization effect in full detail, we computed the daily averaged CRII rate in the polar region separately from SEPs and GCRs (Fig. 2b), using daily spectra shown in Fig. 2a. In all cases we assumed that the major ionization effect occurred within the 24 h following the onset of GLE. This assumption is well validated for SEP with energy of SEP above 100 MeV and for ionization at the atmospheric depths larger than 100 g/cm^2 that are considered here; however, it may lead to somewhat overestimated SEP ionization effect in the upper atmosphere for strongest SEP events, e.g., GLE #42 (29 September 1989) and #69 (20 January 2005). For GLEs like 19 October 1989 (#43) and 4 November 2001 (#62), with a strong secondary particle increase associated with the CME-driven shock's arrival at Earth, this secondary increase was not included in the ionization calculations. Effects in the upper atmosphere (at depths with less than 10 g/cm^2) are beyond the scope of this study. 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. The SEP ionization effect vanishes already at geomagnetic latitude of about 53° ($P_c\approx 2$ GV), even in the upper atmosphere.

Let us now define the absolute C and relative c CRII effect (at fixed altitude h and location P_c) of a SEP event as follows:

$$C(h,P_c) = \frac{I_{SEP} + I_{GCR}}{\langle I \rangle}, \qquad c = (C-1)\cdot 100\% \tag{5}$$

where I_{SEP} and I_{GCR} are daily CRII production rates by SEP and GCR separately for the very day of event, and $\langle I \rangle$ is the averaged daily CRII for the whole month. A 2-D (altitude vs. geomagnetic latitude) chart of the thus defined effect C is shown in Fig. 3 for the event of 20 January 2005. The effect is a reduction (i.e. $C<1$) in the major part of the atmosphere because of the Forbush decrease of GCR. Less energetic SEPs are effectively rejected from lower altitudes and latitudes because of the geomagnetic and atmospheric cutoffs. Note that the overall effect is small in equatorial regions, being only a few percent. The increase (C>1) is observed only in the polar upper atmosphere (P_c<2 GV, h<700 g/cm^2). In order to illustrate this, we have plotted in Fig. 4 the computed temporal variability of CRII (as the ionization effect C) during the month of January 2005 at two atmospheric depths, roughly 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 P_c. One can see the main feature – a flattish profile before 17 January and after 25 January with a fractured dip during January 17–24. 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. 1), 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. Therefore, even for such a severe GLE, the ionization effect was negative and small in the major part of the atmosphere and positive only in the middle and upper polar atmosphere.

4 Results for other GLEs

Here we summarize the results for all the GLE events for the last five solar cycles (1956–2006), for which it is possible to evaluate the SEP spectrum. We note that each GLE has an official number given by the International cosmic ray community (Shea et al., 1987), and presently there are 70 GLE events recorded since 1942 (see http://data.aad.gov.au/aadc/gle/). GLE events #1 through 4 were recorded by ion chambers before the NM era and no spectrum parametrization is possible. Thus, one analysis starts with GLE #5 (23 February 1956) which was the strongest among all and covers the whole range until GLE #70 (13 December 2006). However, GLE #6, 14, 15, 18, 20,

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33, and 34 were not considered, since they were too weak in NM count rates (Duggal, 1979; Stoker, 1994; Belov et al., 2010), to support reliable spectrum reconstruction. A weak GLE #16 and stronger GLE #17 occurred on the same day and were merged together.

The events analyzed are listed in Table 1 together with the estimated effects at different altitudes in the polar atmosphere. Here we show the mean daily ionization due to SEPs only at the day of the GLE at two atmospheric depths, 100 g/cm^2 (≈16 km altitude) and 300 g/cm^2 (≈9 km), denoted as I_{100} and I_{300}, respectively. We also show the relative ionization effect c (Eq. 5) at four atmospheric levels of 100, 300, 500 and 700 g/cm^2 corresponding to about 16 km, 9 km, 5.5 km, and 3 km altitudes, respectively. The Table is sorted according to the SEP-induced ionization in the lower stratosphere I_{100}.

5 Discussion and conclusions

One can see from Table 1 that the extreme event (the strongest GLE with a 90-fold increase at Leeds NM) of 23 February 1956 led (in the framework of the available data on SEP event-integrated spectrum) to a 33-fold increase of the daily ionization rate in the stratosphere and to a tripling in the lower troposphere. On the other hand, the second strongest GLE event (a 54-fold increase at South Pole NM) of 20 January 2005 is only number 7 in the strength of stratospheric ionization effect. As the strength of GLE we consider here the maximum increase of count rate among all ground-based NMs in the world network (see Table 1). The formal correlation between the GLE strength and the stratospheric effect c_{100} in Table 1 is r=0.83±0.05, but it is totally defined by the two severe GLE events #5 and 69. However, the other 56 points depict wider scatter and poorer correlation r=0.53±0.11 (see Fig. 5). Although this correlation is statistically significant, the strength of the GLE event is not a particularly reliable indicator of the overall ionization effect of the event. This result is not unexpected, in that the peak count rate of a polar NM during GLE event is often caused by a highly

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anisotropic short impulsive phase of the event with a hard spectrum, while the main isotropic phase may have a softer spectrum and lower intensity, as was in the case of the event of 20 January 2005. Thus, the use of the formal GLE strength as a proxy for the possible ionization effect in the polar atmosphere may be misleading.

A strong correlation ($r>0.97$) exists between the SEP-induced ionization I_{100} and the relative ionization effect c_{100} in the stratosphere, even if the seven strongest events ($I_{100}>5\times10^4$ g^{-1} s^{-1}) are removed. There is no correlation between GLE strength and ionization in the lower troposphere – the overall correlation between I_{100} and the effect in the low troposphere c_{700} is strong enough ($r\approx0.8$) but it is totally defined by the strongest events. Removal of the seven strong events leads to a formally negative correlation $r=-0.25\pm0.12$. This indicates that the ionization of the troposphere is defined not by the additional SEP flux but rather by the variability of the GCR flux, in particular by the Forbush decrease. The range of variations of the daily GCR-induced ionization rate, within a month, varies between –32 and 10%, –25 and 7%, –20 and 5%, and –15 and 4% for the atmospheric depths of 100, 300, 500 and 700 g/cm^2, respectively. Accordingly, the ionization of the lower troposphere during a day of GLE is largely defined (except for a few extremely strong events) mostly by the GCR background.

As an example of interplay between GCR- and SEP-induced variability of CRII, we show on Fig. 6 temporal profile of the ionization rate in the polar region at two atmospheric depths, 100 and 300 g/cm^2, during the solar cycle 23. A few spikes correspond to the GLE events (as denoted at the top panel), while the long-term variation is due to GCR modulation. The effect of SEP, visible at h=100 g/cm^2, diminished already at 300 g/cm^{2}m with only the event of 20 January 2005 producing a small observable increase.

In conclusion, we have calculated the atmospheric ionization effect from nearly all of the GLE events since 1956. The results are presented in Table 1 for the polar atmosphere. There is no ionization effect at mid- or low-latitudes, even for the strongest events. We show that there is no straightforward relation between the strength of GLE (as measured by neutron monitors) and the ionization effect in polar atmosphere. The

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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 analysis 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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Table 1. Computed ionization effect of GLE events, ordered according to their ionization effect I_{100} at 100 g/cm^2. The official GLE number, the date, and the strength (maximum increase in % of NM count rate – see Duggal, 1979; Belov et al., 2010) of the events are given in the first three columns. Daily mean ionization due to SEP only at 100 and 300 g/cm^2 atmospheric depths is given in 10^4 (g s)$^{-1}$ as I_{100} and I_{300}, respectively. Relative CRII effect c in % (Eq. 5) at different depths h is shown in columns #6–9. All the values are given for the polar atmosphere.

Date	GLE No.	NM increase	I_{100}	I_{300}	c_{100}	c_{300}	c_{500}	c_{700}
23 Feb 1956	5	9000	681	44.1	3370	680	365	196
12 Nov 1960	10	100	135	7.26	940	140	67	31
29 Sep 1989	42	404	84.7	5.81	653	125	64	34
15 Nov 1960	11	150	71.8	3.8	476	58	22	7
24 Oct 1989	45	162	60	3.47	479	67	30	12
19 Oct 1989	43	92	59.9	3.16	448	68	31	14
20 Jan 2005	69	5400	51.8	2.92	285	35	13	3
17 Jul 1959	7	5	25.6	1.48	179	9	−5	−9
14 Jul 2000	59	59	23.8	1.36	168	20	5	0
15 Apr 2001	60	237	20.4	1.16	130	16	6	1
22 Oct 1989	44	193	19.7	1.13	140	9	−3	−6
01 Sep 1971	23	16	17.1	0.892	86	16	9	5
04 Aug 1972	24	15	13.4	0.751	68	10	2	1
28 Jan 1967	16+17	20	13	0.761	68	12	6	3
29 Oct 2003	66	35	12.8	0.71	53	−11	−14	−13
13 Dec 2006	70	92	10.2	0.588	40	4	1	−4
18 Jul 1961	13	24	9.97	0.575	61	7	2	0
28 Oct 2003	65	47	9.67	0.557	57	8	2	0
16 Aug 1989	41	24	8.69	0.504	58	6	1	−4
11 Jun 1991	51	12	8.63	0.527	75	−1	−6	−7
15 Jun 1991	52	42	7.75	0.442	62	−5	−9	−9
06 Nov 1997	55	19	7.11	0.426	33	7	4	2
24 May 1990	48	52	5.59	0.352	44	5	1	0
22 Nov 1977	30	55	5.28	0.311	23	4	2	1
24 Jan 1971	22	29	5.12	0.287	23	1	−1	−1
07 Aug 1972	25	8	4.96	0.281	16	−3	−4	−3
30 Mar 1969	21	5	4.83	0.337	32	8	5	1
23 Sep 1978	32	13	4.79	0.281	27	7	4	3
21 May 1990	47	24	4.23	0.296	31	2	0	−1
20 Nov 1960	12	7	4.2	0.255	21	−1	−2	−2
24 Sep 1977	29	11	4.06	0.24	12	−1	−2	−2
26 May 1990	49	13	3.66	0.208	28	2	0	−1
08 Dec 1982	38	56	3.62	0.231	38	12	8	5
02 Nov 1992	54	6.5	3.57	0.206	16	1	0	−1
04 Nov 2001	62	8	3.32	0.191	28	8	5	3
12 Oct 1981	36	18	3.04	0.186	22	4	2	1
18 Apr 2001	61	26	2.82	0.175	20	4	2	1
03 Sep 1960	9	4	2.76	0.163	18	3	1	0
04 May 1960	8	175	2.71	0.201	16	2	0	0
18 Nov 1968	19	13	2.56	0.142	17	2	1	0
28 May 1990	50	6	2.3	0.144	16	0	−1	−1
17 Jan 2005	68	3.5	2.29	0.133	16	4	2	1
02 Nov 2003	67	39	2.22	0.122	−5	−13	−12	−9
26 Dec 2001	63	13	1.89	0.103	15	4	3	2
07 May 1978	31	214	1.65	0.128	0	−4	−3	−3
16 Feb 1984	39	212	1.53	0.0949	11	3	2	1
26 Nov 1982	37	6	1.32	0.084	10	2	1	0
24 Aug 2002	64	14	1.29	0.0714	9	2	1	0
30 Apr 1976	27	4	1.21	0.0677	7	2	1	1
19 Sep 1977	28	3	1.19	0.063	5	0	0	0
02 May 1998	56	7	1.08	0.0592	−6	−7	−6	−4
25 Jun 1992	53	7	1	0.0562	6	1	0	0
25 Jul 1989	40	8	0.988	0.0527	13	5	4	3
24 Aug 1998	58	4	0.889	0.0549	−2	−3	−3	−2
15 Nov 1989	46	12	0.756	0.0438	6	0	0	0
29 Apr 1973	26	3	0.649	0.0442	5	2	1	1
10 May 1981	35	3	0.562	0.0317	11	5	4	3
06 May 1998	57	4	0.243	0.0131	−5	−4	−3	−2

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Table 2. GLEs of cycle 23: Date (column #1) and 5-min peak percentage increase (column #2) in Oulu NM count rate; Parameters of the SEP (columns #3–6 – see Eq. 4) and GCR daily (column #7) and monthly (column #8) spectrum; Relative CRII effect ($c=(C-1)\cdot 100\%$, where C is defined by Eq. 5) at different depths h (columns #9–12) in the polar atmosphere.

GLE		Spectrum parameters						Effect (%) at h (g/cm^2)			
Date	NM %	J_o (cm^{-2})	γ_1	γ_2	R_o (GV)	ϕ_d (MV)	ϕ_M (MV)	c_{100}	c_{300}	c_{500}	c_{700}
06 Nov 1997	11	8.15 E+08	0.284	5.38	0.116	427	439	33	7	4	2
02 May 1998	7	8.98 E+06	1.306	6.51	0.196	714	572	−6	−7	−6	−4
06 May 1998	4	1.64 E+06	1.921	7.46	0.202	641	572	−5	−4	−3	−2
24 Aug 1998	3	2.1 E+05	2.977	5.27	0.677	644	568	−2	−3	−3	−2
14 Jul 2000	30	2.94 E+09	0.506	7.46	0.123	1407	1167	168	20	5	0
15 Apr 2001	57	5.22 E+07	1.388	5.69	0.26	1164	995	130	16	6	1
18 Apr 2001	5	8.39 E+06	1.852	5.02	0.237	978	995	20	4	2	1
04 Nov 2001	3	2.14 E+09	0.242	6.67	0.093	760	865	28	8	5	3
26 Dec 2001	5	2.17 E+07	1.806	7.86	0.18	777	833	15	4	3	2
24 Aug 2002	5	5.06 E+06	2.356	6.7	0.225	1053	1058	9	2	1	0
28 Oct 2003	5	8.44 E+09	0.01	6.48	0.088	1016	963	48	3	−1	−2
29 Oct 2003	N/A	7.62 E+07	2.044	6.86	0.206	1763	963	53	−11	−14	−13
02 Nov 2003	6	2.27 E+06	3.50	7.01	0.321	1830	1281	−3	−13	−12	−9
17 Jan 2005	3	3.51 E+07	2.65	8.29	0.162	751	788	16	4	2	1
20 Jan 2005	269	3.8 E+08	0.719	5.78	0.204	1188	788	285	35	13	3
13 Dec 2006	92	1.33 E+08	1.045	5.8	0.177	544	467	40	4	1	−4

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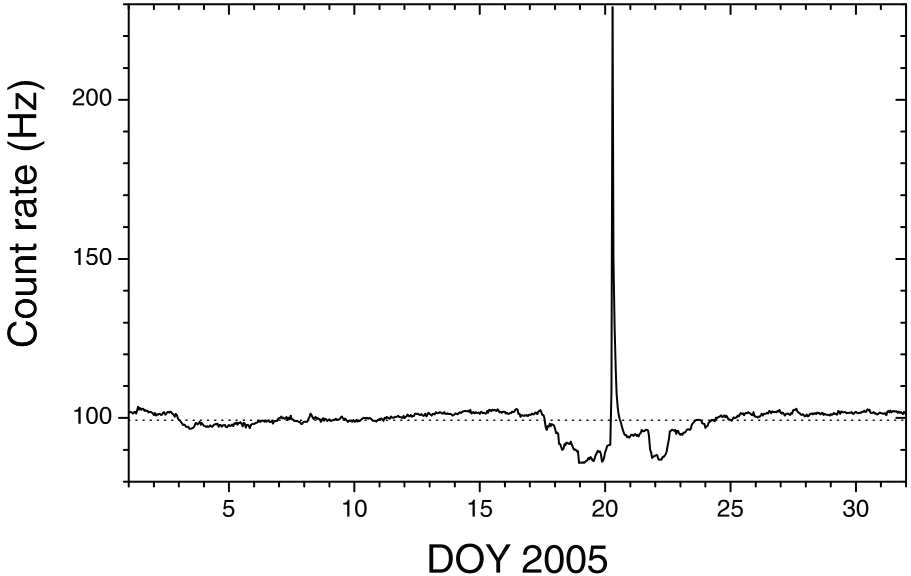

Fig. 1. Time profile of Oulu NM hourly averaged count rate for January 2005 (http://cosmicrays.oulu.fi). The dotted line represents the averaged monthly count rate for the month.

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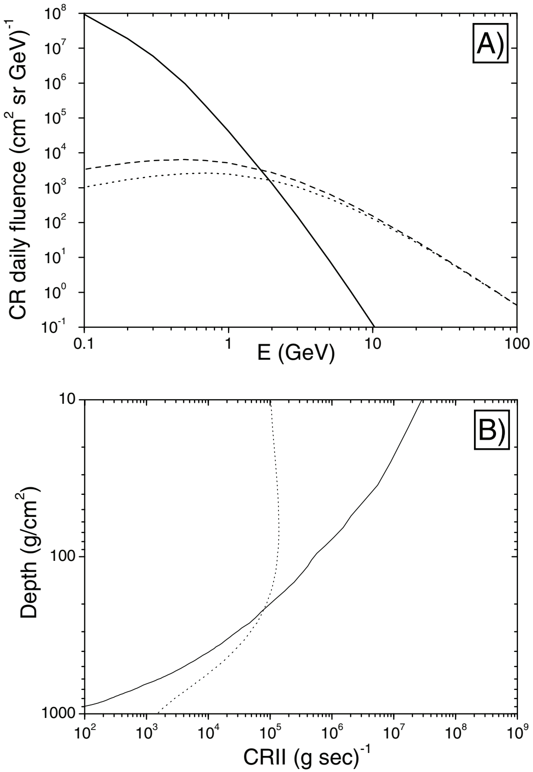

Fig. 2. Input proton spectra and the resulting atmospheric ionization for the event of 20 January 2005. **(A)** Differential fluence of solar protons from the 20 January 2005 event and the daily fluence of GCR protons for the day of 20 January 2005, including the effect of the Forbush decrease (dotted line). The dashed curve depicts the average GCR proton fluence for January 2005. **(B)** The vertical profile of the daily averaged CRII in the polar region from GCR (dotted curve) and SEP (solid curve) separately, for the day of 20 January 2005.

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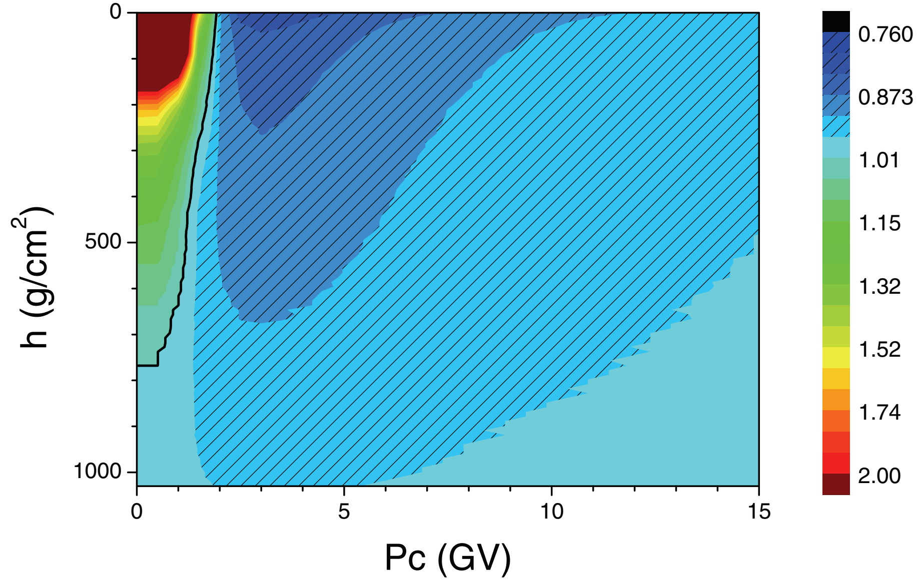

Fig. 3. The relative ionization effect C (see text for definition) of GLE 20 January 2005 as function of the geomagnetic cutoff rigidity P_c and atmospheric depth h. The region of suppression ($C<0.99$) effect is hatched, while the solid curve bounds enhancement ($C>1.01$) effect.

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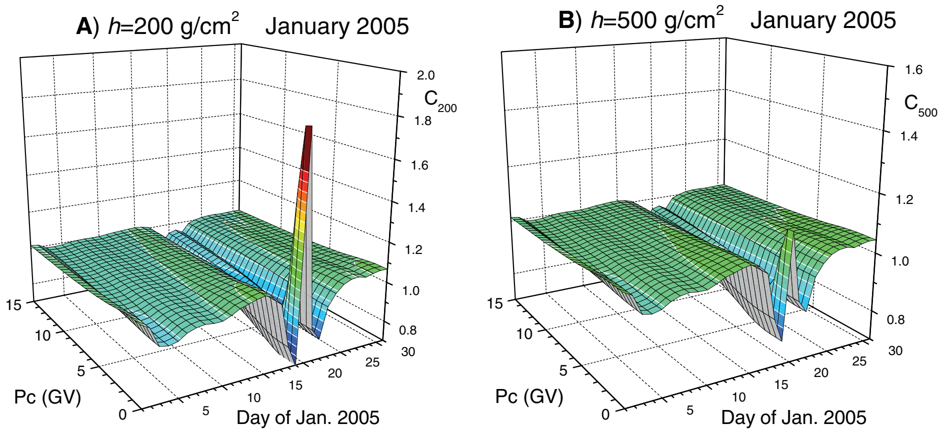

Fig. 4. The relative ionization *C* (normalized to the average ionization rate in January, 2005) as function of time and location (P_c) for two atmospheric depths, 200 g/cm^2 **(A)** and 500 g/cm^2 **(B)**.

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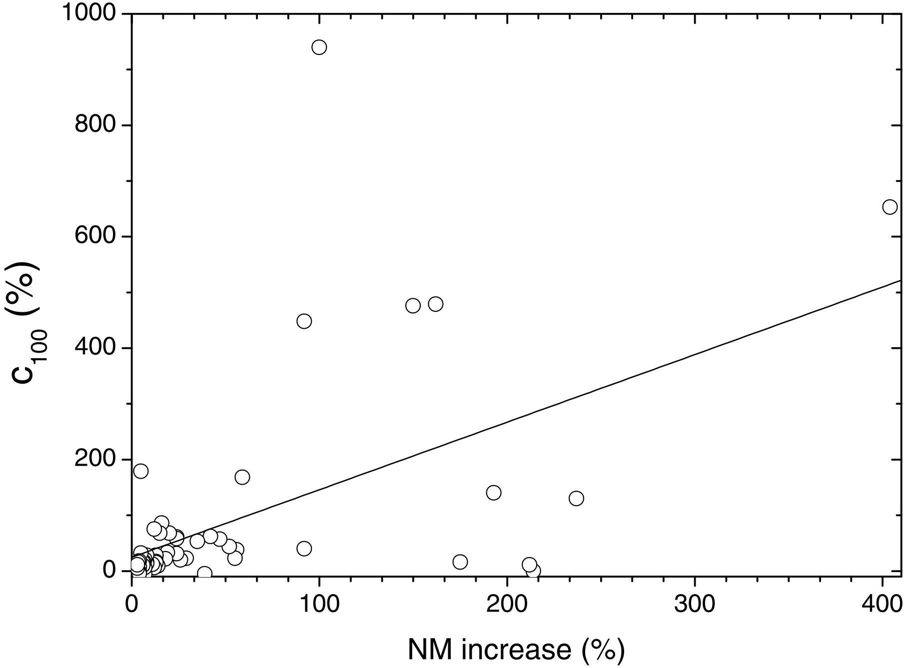

Fig. 5. Scatter plot of the relative CRII effect c_{100} vs. the GLE strength (NM increase) – see Table 1 along with the best fit regression line. The two strongest GLE events #5 (23 February 1956) and 69 (20 January 2005), whose NM increases are larger that these by more than an order of magnitude, are not included into the plot.

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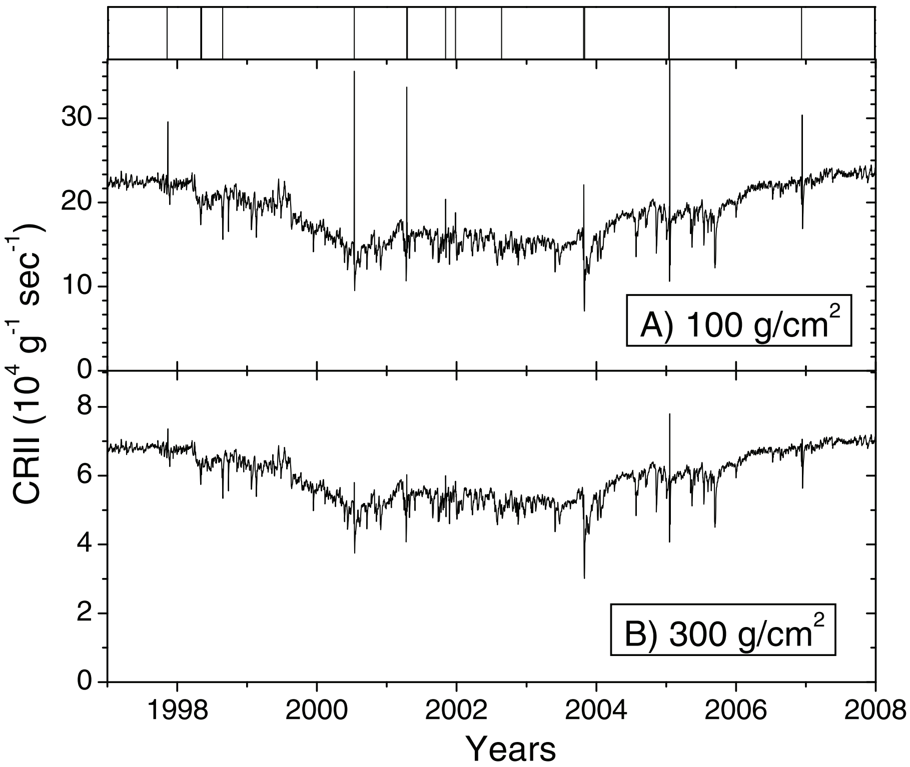

Fig. 6. Daily cosmic ray induced ionization at two atmospheric layers, 100 g/cm^2 **(A)** and 300 g/cm^2 **(B)**, during the solar cycle #23. Note that the CRII value for the day of 20 January 2005 goes far beyond the Y-scale of **(A)**. Dates of the GLE events #55 through 70 (see Table 1) are indicated in the top panel.

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