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Radiation dose of aircrews during a solar proton event without ground-level enhancement

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Abstract. A significant enhancement of radiation doses is expected for aircrews during ground-level enhancement (GLE) events, while the possible radiation hazard remains an open question during non-GLE solar energetic particle (SEP) events. Using a new air-shower simulation driven by the proton flux data obtained from GOES satellites, we show the possibility of significant enhancement of the effective dose rate of up to $4.5\,\mu\text{Sv}\,\text{h}^{-1}$ at a conventional flight altitude of 12 km during the largest SEP event that did not cause a GLE. As a result, a new GOES-driven model is proposed to give an estimate of the contribution from the isotropic component of the radiation dose in the stratosphere during non-GLE SEP events.

1 Introduction

Solar energetic particles (SEPs) are sometimes energetic enough and the flux is high enough to cause air showers in the stratosphere and in the troposphere, which are an important ionization source in the atmosphere. The most energetic events can be observed even at ground-based neutron monitors, and are called ground-level enhancements (GLE) (Forbush, 1946). Recently, Matthia et al. (2009a) reported that the effective dose rate at a conventional flight altitude of 40 kft (~ 12 km) reached $1.0\,\text{mSv}\,\text{h}^{-1}$ during the largest GLE-69 during solar cycle 23. The total effective dose at flight altitude has been estimated for all of the GLE events during so-

lar cycle 23, and ranged from $2.0\,\mu\text{Sv}$ to 0.3 mSv (Shea and Smart, 2012).

Kataoka et al. (2014) recently developed a forecast model called WASAVIES (Warning System of AVIation exposure to SEP) to give the time profile of effective dose rate at flight altitude during GLEs, using a new air-shower simulation developed by Sato et al. (2014). Based on the air-shower simulation, it was pointed out that SEP events may also contribute to aircrews' exposure; i.e., the flux of low-energy protons of an order of a few 100 MeV can be large enough to cause a radiation dose at conventional flight altitude, even though the low-energy protons do not cause a GLE. The purpose of this study is to evaluate the effective dose rate at conventional flight altitude during such non-GLE SEP events, using the new air-shower simulation and proton flux data obtained from GOES satellites.

2 Method of analysis

According to the NOAA SEP list (http://umbra.nascom.nasa.gov/SEP/), there were only four non-GLE SEP events that exceeded 10^4 pfu (particles $\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$) at ≥ 10 MeV protons, that did not cause GLEs. The SEP event on 9 November 2000, which was associated with an M7.4 flare, had the largest flux (~ 70 pfu) at 80–165 MeV protons among these top-four events (only 1.5 pfu on 24 March 1991, 0.3 pfu on 25 September 2001, and 0.06 pfu on 24 November 2001), and we focus on the 9 November 2000 non-GLE SEP event as the most plausible candidate for causing a significant radiation dose at conventional flight altitude. The well-known
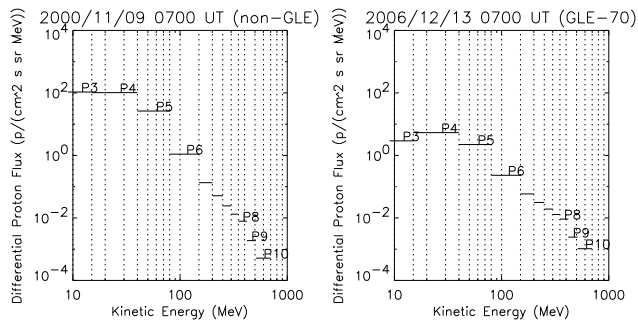
Figure 1. Examples of 5 min averaged proton spectra for the non-GLE SEP event (left) and the GLE-70 event (right). Dotted lines show the energy of the pre-calculated mono-energetic protons by Sato et al. (2014).
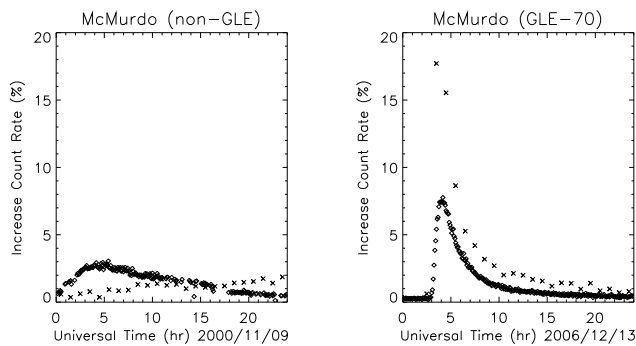

Figure 2. Simulated (diamonds) and observed (crosses) increase count rate at the McMurdo neutron monitor during the non-GLE SEP event (left) and during the GLE-70 event (right).

GLE-70 of 13 December 2006, which was the third-largest GLE event during solar cycle 23 (Shea and Smart, 2012), is also evaluated as a reference.

We use the simulation method developed by Sato et al. (2014), in which the radiation dose is calculated by using the response function generated for mono-energetic protons on the basis of an air-shower simulation performed with PHITS (Particle and Heavy Ion Transport code System) version 2.52 (Sato et al., 2013). INCL (The Liege Intranuclear Cascade model) version 4.6 (Boudard et al., 2013) is employed as the default nuclear reaction model for intermediate-energy neutrons in PHITS 2.52. The simulation method of Sato et al. (2014) is capable of quantitatively evaluating the altitude-dependent effective dose rate as well as the increase count rate at ground-based neutron monitors for both GLE events and for non-GLE events by preparing the input data as the proton spectra at the top of the atmosphere (TOA) of 86 km in altitude.

The proton spectra at TOA are calculated from the GOES-11 proton flux data obtained at geosynchronous orbit (GEO) as follows. We assume that the ratio of proton fluxes at GEO and at TOA in the polar region as 0.4 as a common value for all of the energy ranges; i.e., we used the cor-
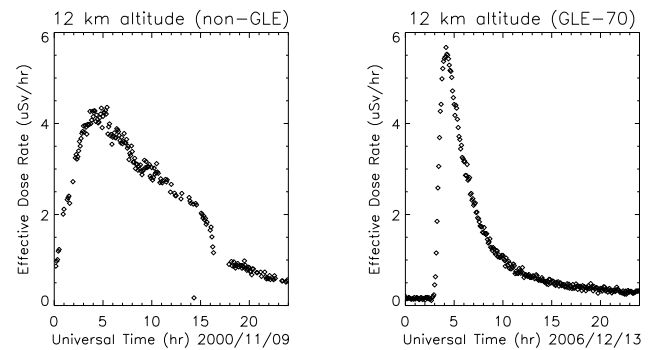

Figure 3. Simulated effective dose rate at 12 km altitude at the polar region during the non-GLE SEP event (left) and during the GLE-70 event (right).

rected proton flux of GOES-EPS P4 (15–44 MeV), P5 (40–80 MeV), and P6 (80–165 MeV) channels as the proton flux at TOA by simply multiplying the "penetration factor" of 0.4. The GOES-EPS P7 (165–500 MeV) channel is not employed because the assumption of constant flux for this relatively broad energy range may induce an inaccuracy in the calculation. Instead, we use the proton flux of the GOES-HEPAD P8 (350–420 MeV), P9 (420–510 MeV), and P10 (510–700 MeV) channels with the same penetration factor, and linearly interpolate the proton flux between the P6 and P8 channels on a log–log scale. The GOES-HEPAD P11 (> 700 MeV) channel is omitted because its upper limit energy is not specified. Examples of proton spectra at TOA for the non-GLE SEP event and the GLE-70 event are shown in Fig. 1. Note that the results shown in this paper can be used for a different penetration factor by linear scaling.

The assumed penetration factor of 0.4 is selected in this paper by finding the largest value not to cause a simulated GLE in the non-GLE SEP event on 9 November 2000, and to cause a simulated GLE in the GLE-70 event. In reality, however, the proton fluxes at GEO and at TOA do not have such a simple relationship (Bornebusch et al., 2010), and further careful investigations are needed to understand the actual balance between the mirroring and geometrical focusing of energetic protons in the complex geomagnetic field. Also, it has been shown that GLEs have an anisotropic component in their initial phase, and the dose rates at certain locations are expected to have been much higher than what is calculated in this work (see Matthia et al., 2009b; Meier and Matthia, 2014). It is therefore important to note that using the data from GOES alone cannot give a complete picture of the event and its impact over all longitudes and latitudes, and our method is limited to estimating the contribution from the isotropic component.
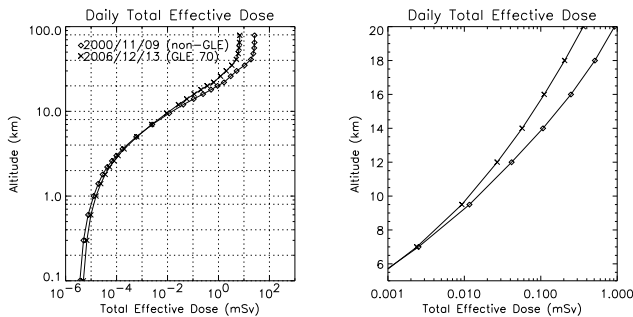
Figure 4. Simulated total effective dose at various altitudes during the non-GLE event (diamonds) and during the GLE-70 event (crosses) for 24 h.

3 Results

Figure 2 shows the result of the comparison between simulated and observed increase count rates during the non-GLE SEP event on 9 November 2000 and the GLE-70 event on 13 December 2006 at McMurdo station. The increase count rate is defined in this paper as the neutron monitor count rate above the mean value of the previous day. The simulated increase count rate is an order of the approximate noise level of 100 cph for the non-GLE SEP event. For the GLE-70 event, the increase count rate significantly exceeds the noise level, but it is lower than that of observed values, which is reasonable considering that we omitted the expected additional counts from very energetic particles of greater than 700 MeV for this particular GLE-70 event.

Figure 3 shows the result of a simulated effective dose rate at 12 km altitude in the polar region during the non-GLE SEP and GLE-70 events. It is found that the effective dose rate during the non-GLE SEP event can be up to 4.5 μSv h^{-1}. This value is comparable to the maximum effective dose rate during the GLE-70 event, approximately 5.8 μSv h^{-1}, instead of the large difference in the increase count rates between the two events as shown in Fig. 2. As a reference value, it is also worthwhile to note that the ambient dose equivalent rate during solar minimum (2006–2008) was ~ 9 uSv h^{-1} in the polar region at 41 K feet altitude (Meier et al., 2009).

Figure 4 shows 24 h integrated total effective doses during the non-GLE SEP and GLE-70 events. In order to consider the additional shielding due to airframe, we assume that the thickness of the airframe is 10 g cm^{-2}, and we ignore the dose contribution from less than 100 MeV protons. The total effective dose largely changes depending on the altitude, especially at around the conventional flight altitude; e.g., an increase in flight altitudes from 9.5 to 14 km results in an increase in the total effective dose by nearly 1 order of magnitude. The total effective dose of the non-GLE SEP event is found to be up to 0.03 mSv at an altitude of 12 km. The total effective dose for the non-GLE SEP event is more enhanced against a GLE event at higher altitude.

During one flight, the aircraft is at high latitudes and high altitudes only for a couple of hours. The calculated dose is only a theoretical value, and is not the actual radiation exposure of an aircrew during such an event. In order to estimate the total dose for a flight, one needs to take into account the flight durations and flight profiles.

4 Summary and discussion

We showed the possibility of significant enhancement of the radiation dose at conventional flight altitude during the largest SEP event that did not cause a GLE. It is important to note, however, that the SEP event on 9 November 2000 is the only such event we found so far using the GOES data after 1976. Such powerful non-GLE SEP events are therefore very rare, and rarer than GLEs.

As a next step, we extend this study to find similar but significantly weaker SEP events, and to evaluate the possible total impact on the atmosphere that may show dynamical change over solar cycles. This attempt gives a plausible altitude-dependent energy deposition rate by solar protons in the stratosphere, and the realistic limitation would contribute to understanding the fundamental mechanism for connecting the space environment and the planetary atmosphere.

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