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GLE and Sub-GLE Redefinition in the Light of High-Altitude Polar Neutron Monitors

S.V. Poluianov[1,2] · **I.G. Usoskin**[1,2] ·
A.L. Mishev[1,2] · **M.A. Shea**[3] · **D.F. Smart**[3]

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Abstract The conventional definition of ground-level enhancement (GLE) events requires a detection of solar energetic particles (SEP) by at least two differently located neutron monitors. Some places are exceptionally well suitable for ground-based detection of SEP – high-elevation polar regions with negligible geomagnetic and reduced atmospheric energy/rigidity cutoffs. At present, there are two neutron-monitor stations in such locations on the Antarctic plateau: SOPO/SOPB (at Amundsen–Scott station, 2835 m elevation), and DOMC/DOMB (at Concordia station, 3233 m elevation). Since 2015, when the DOMC/DOMB station started continuous operation, a relatively weak SEP event that was not detected by sea-level neutron-monitor stations was registered by both SOPO/SOPB and DOMC/DOMB, and it was accordingly classified as a GLE. This would lead to a distortion of the homogeneity of the historic GLE list and the corresponding statistics. To address this issue, we propose to modify the GLE definition so that it maintains the homogeneity: A GLE event is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located neutron monitors, including at least one neutron monitor near sea level and a corresponding enhancement in the proton flux measured by a space-borne instrument(s). Relatively weak SEP events registered only by high-altitude polar neutron monitors, but with no response from cosmic-ray stations at sea level, can be classified as sub-GLEs.

Keywords Energetic particles

1. Introduction

A nearly simultaneous enhancement of the count rates of several ground-based cosmic-ray detectors, neutron monitors (NM) or ionization chambers (*e.g.* Forbush, 1946; Simpson,

✉ S.V. Poluianov
stepan.poluianov@oulu.fi

1 Space Climate Research Unit, University of Oulu, Oulu, Finland

2 Sodankylä Geophysical Observatory, University of Oulu, Oulu, Finland

3 SSSRC, 100 Tennyson Avenue, Nashua, NH 03062, USA

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1990) that is caused by solar energetic particles (SEP) is known as a ground-level enhancement (GLE) event. Observations of GLEs provide key information about the high-energy portion (above several hundred MeV nuc^{-1}) of strong SEP events, which cannot be continuously monitored by space-borne instruments (Tylka and Dietrich, 2009). We note that the modern space-borne particle spectrometers such as the alpha magnetic spectrometer AMS-02 (Aguilar *et al.*, 2015) and payload for antimatter–matter exploration and light-nuclei astrophysics (PAMELA: Picozza *et al.*, 2007) are not well suited to study SEP events because in low orbits they spend most of the time in regions with high geomagnetic cutoff.

The GLE dataset spans high-energy SEP events over almost seven solar cycles, providing a sufficient basis for statistical studies (*e.g.* Gopalswamy *et al.*, 2014; Raukunen *et al.*, 2017; Vainio *et al.*, 2017). Since the beginning of systematic ground-based measurements of cosmic rays, over 70 GLEs have been "officially" registered so far (see the International GLE Database gle.oulu.fi). However, in 2015, there was an SEP event that was clearly observed by the South Pole (SOPO/SOPB) and Dome C (DOMC/DOMB) stations, but it was hardly distinguishable in the count rates of other NMs. Based on the current GLE definition, it would have been identified as a GLE, but on the other hand, it would not if the DOMC/DOMB station had not been operational. Accordingly, this can compromise the homogeneity of the GLE dataset and introduce a bias in the statistics. Here we propose a revision of the GLE definition to keep the GLE dataset homogeneous.

2. The Present GLE Definition and Its Limitation

The definition of a GLE was proposed by the cosmic-ray community in the 1970s and is commonly understood as the following:

> *A GLE event is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located NMs.*

We note that previously, there was only one high-latitude high-altitude NM station, the South Pole, and an SEP event must have been recorded at sea-level to be identified as a GLE. However, with the installation of DOMC/DOMB, the situation has changed significantly. The sensitivity of an NM to cosmic rays depends on the rigidity/energy threshold of detectable particles, which is defined by the geomagnetic- and atmospheric-shielding effects. The geomagnetic shielding is quantified in terms of the geomagnetic cutoff rigidity, which varies from almost zero in the polar region to 15 – 17 GV at the geomagnetic Equator (*e.g.* Smart and Shea, 2009; Nevalainen, Usoskin, and Mishev, 2013). In addition, there is the atmospheric cutoff, implying that a primary particle must possess some minimum energy to be able to initiate the atmospheric cascade and be registered on the ground. It depends on the thickness of the atmosphere above the location, which is greatest (≈ 430 MeV nuc^{-1}, see Grieder, 2001; Dorman, 2004) at sea level and decreases with altitude. The atmospheric cutoff dominates shielding in the polar regions, and elevation of a cosmic-ray detector above sea level significantly reduces the atmospheric attenuation of cosmic-ray cascades. Accordingly, cosmic-ray detectors located at high altitude in the polar region possess higher sensitivity to low-energy cosmic rays than those located near sea level and/or at non-polar locations.

There are two regions with these properties in the world: the top of the Greenland ice sheet (3205 m above the sea level (asl)), and the Antarctic plateau (average elevation of about 3000 m asl). Although there is no high-altitude cosmic-ray station in Greenland, two NMs are located on the Antarctic plateau: at South Pole and at Dome C (Figure 1).

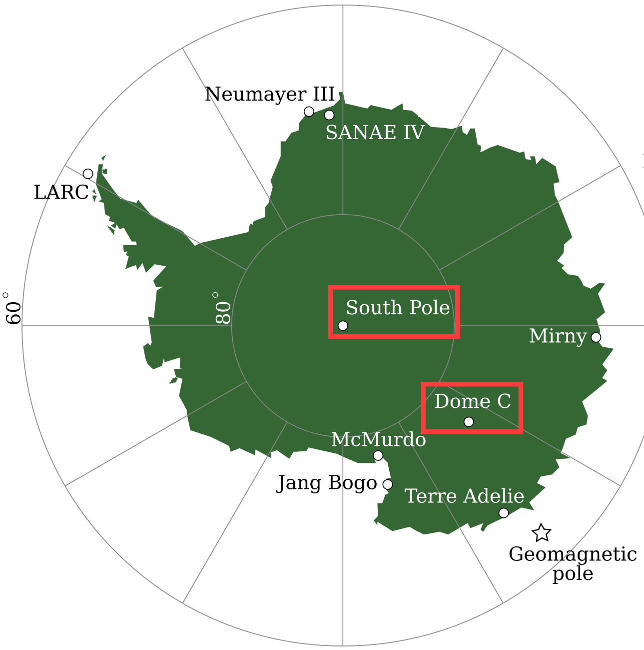

Figure 1 Antarctic neutron-monitor stations operational in 2017. *Red boxes* indicate the high-altitude stations. The map is adopted from ©Gringer/Wikimedia Commons/GFDL.

The Amundsen–Scott US research station at the geographical South Pole (90°S, elevation of 2835 m asl, the nominal barometric pressure 690 hPa) has had a neutron monitor in operation since 1964 (Evenson *et al.*, 2011: nmdb.eu). The setup consists of two types of cosmic-ray detectors: a standard NM-64 instrument with a lead layer for multiplication of neutrons, and a so-called "bare" or lead-free NM without the lead layer (*e.g.* Vashenyuk, Balabin, and Stoker, 2007). The South Pole standard and bare NMs are denoted as SOPO and SOPB, respectively.

A more recent neutron monitor, called "Dome C", is located at the Franco–Italian research station Concordia (75°06′S, 123°23′E, 3233 m asl, 650 hPa). It is also equipped with the two types of neutron monitors denoted as DOMC (standard) and DOMB (bare). The Dome C cosmic-ray station started operation in early 2015 (Poluianov *et al.*, 2015).

Before 2015, the global NM network had only one high-altitude polar station (SOPO/SOPB). All GLEs were registered by instruments that included at least one located near sea level, implying that SEP events causing GLEs had a sufficiently high flux of particles with energy above the full atmospheric cutoff of ≈ 1 GV (≈ 430 MeV nuc^{-1}). The installation of the DOMC/DOMB detector in 2015 has led to a situation when an SEP event with much lower flux of energetic particles can be formally classified as a GLE. Several SEP events have been registered already by only these instruments and were confirmed by data from spacecraft, but these events have not been detected by other NMs at near sea-level elevations. One example is an event of 29 October 2015, which took place around 02:40 UT, as shown in Figure 2. A distinguishable signal was recorded only by SOPO/SOPB and DOMC/DOMB (left panel), while other polar sea-level NMs did not register any significant response. Thus, when the commonly used GLE definition is applied, this event might have been considered as a GLE, while it is obvious that it would not have been counted

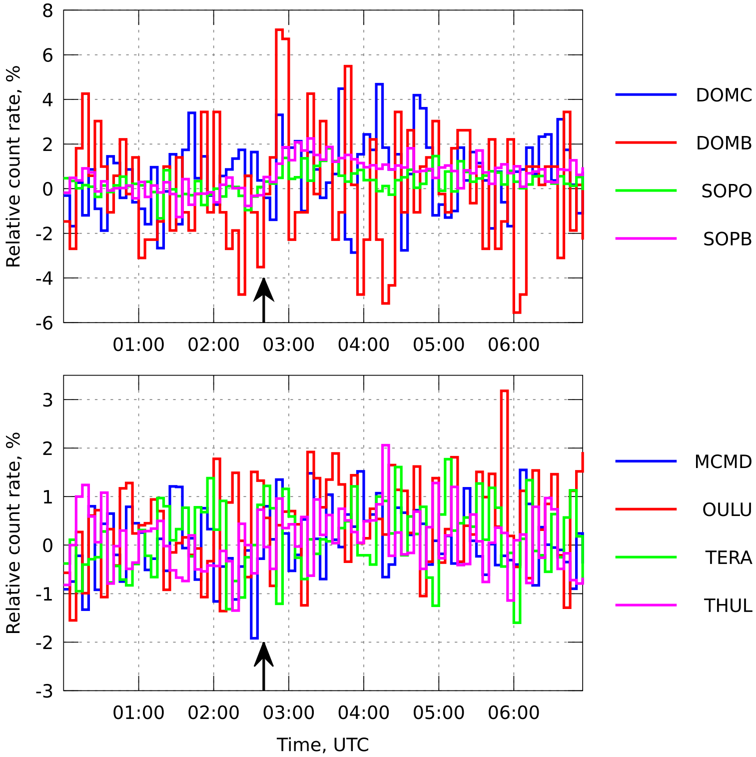

Figure 2 Solar energetic particle event on 29 October 2015 in neutron-monitor data (see the *color legends*). Dome C (DOMC, DOMB) and South Pole (SOPO, SOPB) NMs are shown in the *upper panel*, while McMurdo (MCMD), Oulu (OULU), Terre Adelie (TERA), and Thule (THUL) NMs are plotted in the *lower panel*. *Arrows* indicate the onset of the event. Data are from the International GLE Database (gle.oulu.fi).

earlier, without DOMC/DOMB data. The SEP event on 29 October 2015 is different from other GLE events because of its lower intensity and much softer spectrum compared with a weak "official" GLE (Mishev, Poluianov, and Usoskin, 2017). The ratio of SEP peak fluxes, computed based on five-minute NM data during the maximum phase of the event using spectrum reconstructions by Mishev, Kocharov, and Usoskin (2014), Mishev and Usoskin (2016) for this event relative to the weak GLE on 17 May 2012 is 0.25, 0.13, and 0.05 for the energy ranges > 200, > 300, and > 500 MeV, respectively. The event of 29 October 2015 clearly was not only weaker, but also much softer than the GLE on 17 May 2012. It was also below the alert threshold of the GLE alert system (Souvatzoglou *et al.*, 2009). This introduces a bias to the definition of a GLE, since the NM network is more sensitive to GLE now than it has been before, and therefore some of the events observed today would not have been recorded if they had occurred in the past. Accordingly, we believe that applying the "classical" GLE definition now can significantly distort the homogeneity of the existing list.

When a small increase is measured in a high-altitude polar NM, it is normal to look for a corresponding increase in sea-level NMs; however, when investigating what might initially appear to be a small increase in the counting rate of a sea level NM, care must be taken to differentiate between the normal daily variation, random fluctuation, and an increase from solar particles. In addition, we acknowledge the uncertainty in exact timing of GLE detection that is caused by the different magnetic connection of NM stations during the initial highly anisotropic phase of a particle event.

3. Proposed Definitions of GLE and Sub-GLE

To address the issue described above, we suggest modifying the GLE definition, namely, to fix the condition that the event should be detected near sea level, implying that the corresponding SEP event has sufficient flux of particles with an energy exceeding the full atmospheric cutoff.

We propose to formulate the revised GLE definition as follows:

> *A GLE event is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located neutron monitors including at least one neutron monitor near sea level and a corresponding enhancement in the proton flux measured by a space-borne instrument(s).*

By the term "near sea level", we mean an altitude not higher than approximately a quarter of the mean attenuation length of the nucleonic component of the cosmic-ray cascade (*e.g.* Grieder, 2001; Dorman, 2004) above the sea level, *viz.* $\approx 30\ \mathrm{g\,cm^{-2}}$. This corresponds to $\approx 1000\ \mathrm{g\,cm^{-2}}$ in total atmospheric depth or ≈ 300 m asl in altitude. NMs located at higher altitudes possess a notably different response function because of the cascade attenuation effects (Clem and Dorman, 2000; Flückiger *et al.*, 2008). It is important to note that the proposed definition does not affect the existing list of "classic" GLEs, because all of them have been detected by at least one sea-level NM (or ionization chambers for the four events before 1950, Forbush, Stinchcomb, and Schein, 1950).

However, it would be incorrect to completely ignore SEP events that are registered by only high-altitude polar NMs, without a significant response from the near sea-level NMs. Such events (such as the event of 29 October 2015 discussed above) can be called sub-GLEs. Although this term is not very precise, it is already used in the literature (*e.g.* Atwell *et al.*, 2015; Vainio *et al.*, 2017) to classify events with a reduced, opposed to a "classic" GLE, proton energy range. For sub-GLE, we propose the following definition:

> *A sub-GLE event is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located high-elevation neutron monitors and a corresponding enhancement in the proton flux measured by a space-borne instrument(s), but no statistically significant enhancement in the count rates of neutron monitors near sea level.*

We note that this definition does not contradict the definition proposed by Atwell *et al.* (2015).

4. Summary

The installation of the second high-altitude polar cosmic-ray station DOMC/DOMB, in addition to the long-existing South Pole SOPO/SOPB station, has improved the sensitivity of the global NM network, so that now it can detect SEP events below the full atmospheric cutoff, which would not have been recorded previously and would not have been classified as GLEs. This distorts the homogeneity of the list of GLE and may affect studies based on the GLE long-term occurrence rate. In order to address this issue, we have suggested modifying the GLE definition by requiring that at least one of the NMs recording the event should be located near sea level. The new definition does not affect the list of already registered events, but rejects some weaker SEP events of Cycle 24 as being GLEs. SEP events detected by only high-altitude polar NMs, with no significant response of NMs near sea level, can be called sub-GLEs. The corresponding formal definition of such events is proposed.

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