



Research

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The first four ground-level enhancements in the 1940s: investigation, digitization and analysis of forgotten data

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Intense solar eruptions occasionally accelerate solar energetic particles (SEPs) and trigger ground-level enhancements (GLEs). Among the 77 known GLEs, the first four #1–4, in the 1940s, took place before the advent of the standard neutron monitors (NMs) and were missing from the International GLE Database (IGLED). This data gap challenged their quantification. To overcome this difficulty, we systematically gathered, digitized and quantified contemporaneous cosmic-ray records pertaining to these GLEs. These data allow us to reconstruct the GLE temporal evolution with 1–15 minute resolutions and broaden their geographical coverage to a global scale. GLEs #1 and #3 exhibited gradual increases in their rise times, measured at 45 ± 15 and 105 ± 15 minutes, respectively. By contrast, GLEs #2 and #4 both exhibited abrupt increases of 15 ± 15 minutes. We also compared integral ionization increase on the standard ionization chambers (ICs) and their local geomagnetic cut-off rigidities

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P_c to qualitatively compare GLE spectral hardness: Our result indicates that their spectra are extremely hard for GLEs #2 and #4 and mildly hard for GLEs #1 and #3. GLE #3 showed the greatest integral ionizations for polar detectors among them.

This article is part of the Theo Murphy meeting issue 'Radiocarbon and cosmic radiation events'.

1. Introduction

Solar eruptive energy releases, such as flares and coronal mass ejections, can occasionally accelerate charged particles in the corona and interplanetary medium, forming solar energetic particles (SEPs), which can be detected in the vicinity of Earth [1–3]. Occasionally, the flux and energy of SEPs appear sufficiently high to be detected by ground-based cosmic-ray monitoring systems, mostly a network of standard neutron monitors (NMs). These phenomena are known as ground-level enhancements (GLEs) [4,5]. GLEs correspond to the strongest SEP events that are known from direct observations. They have the potential to elevate radiation exposure and produce technological hazards for spacecraft or aircraft [6–9]. Especially, intense GLEs may affect not only crew, passengers, and avionics on the flight altitude but also safety-critical industries such as nuclear power and autonomous vehicles on the ground level [7]. Moreover, analyses on the most intense GLEs may bridge the knowledge gap towards very rare once-in-a-millennium extreme solar particle events (ESPEs) known from cosmogenic isotopes [10–12].

At the time of writing, 77 GLEs have been registered by the network of ground-based instruments from their first confirmed detections in February 1942 [13,14] to the latest detections in the 2020s [15–20]. Most of these GLEs, particularly those following GLE #5 in February 1956, have been extensively recorded using the worldwide network of standard NMs [21–27] and catalogued in the International GLE Database (IGLED; <http://gle.oulu.fi>). This comprehensive compilation provides a crucial basis for scientific analyses [25], although additional research could potentially allow us to find some more GLEs or sub-GLEs (SEPs that cause cosmic-ray enhancements to polar high-altitude stations but do not cause cosmic-ray enhancements on the sea-level stations), especially for the period prior to the 1970s [28,29].

GLE #5, recorded on 23 February 1956, has been regarded as a reference event for the studies of ESPEs, owing to its characteristics of the greatest fluence and the hard spectrum [11,27,30,31]. This event has been used to model worst-case scenarios for radiation doses and assess potential technological effects at flight altitudes [7], as well as to analyse atmospheric effects of SEP events [32]. Furthermore, GLE #5 serves as a link between contemporary GLE observations and extreme solar events inferred from cosmogenic isotopes present in tree rings and ice cores [10,12,33–40].

Occasional qualitative assessments have compared GLE #5 with the earliest recorded GLEs of the 1940s [23,41,42]. However, there exists a notable scarcity of information and data regarding the original datasets associated with these early GLEs, as they occurred before the standard NM network started its operation [21,43]. The IGLED includes data only from GLE #5 in 1956 onward, without covering these early GLEs #1–4 that took place before the standard NM network was developed. They are difficult to assess quantitatively owing to uncertainties such as those in the cross-instrument calibrations between the contemporaneous detectors and standard NMs, atmospheric effects on the contemporaneous detectors or instrumental set-ups [25,27]. These GLEs were recorded through observations of such devices as ionization chambers (ICs), telescopes made of early Geiger–Müller (GM) tubes, electroscopes and a prototype NM. These detectors have some limitations, such as broad energy response, lower sensitivity, higher data noise and limited stability, e.g. drifts, compared to the standard NMs [44]. These difficulties may have caused these instruments to miss some of the early GLEs before 1956. In recent scientific discussions, Miroshnichenko [23] listed these GLEs among the most intense events in the observational history following the 15-minute peak intensities and normalization of Duggal [41]. Shea & Smart [45] highlighted their limited data availability, noting that only bi-hourly measurements from Carnegie ICs

in Cheltenham and Huancayo (figure 1) were readily accessible to the scientific community. They also reported the presence of original data traces archived at the US National Geophysical Data Centre, alongside hourly measurements done with Japanese ICs [46] (figure 2) and a prototype NM situated in Manchester, UK [47]. So far, none of their time series has been digitally available and thus suitable for analyses, despite such discussions.

Importantly, these GLEs were recorded using a variety of contemporary devices (e.g. figures 1 and 2), with data captured in diagrams and tables that served as contemporaneous scientific reports [48–50], apart from the bi-hourly datasets of the often-consulted Carnegie IC records. These diagrams potentially provide data at higher temporal resolutions, facilitate discussions on the intricate temporal evolution of GLEs and enhance geographic coverage. To accommodate that, we comprehensively surveyed contemporaneous reports and digitized the published diagrams and tables related to contemporaneous GLE measurements during the 1940s. Accordingly, we have produced machine-readable datasets for GLEs identified as #1–4. These datasets will be integrated into the IGLED in the standard GLE format to cover the complete observational history of GLEs (§2–5). We computed the geomagnetic cut-off rigidity for each station with GLE measurements. We then compared the distributions of the integral percentage increase at each site against its local cut-off rigidity for each of the early GLEs (§6). Based on these new datasets, we quantified the GLEs #1–4 at the best possible temporal resolutions, in their rise times, integral ionizations and spectral characteristics, revealing insights that were not discernible in the existing bi-hourly datasets (§7–9).

2. Material and methods

A comprehensive bibliographic survey was first conducted to identify and digitize diagrams that depict the temporal evolution of cosmic-ray measurements published in close temporal proximity to the GLEs #1–4. This initial step involved identifying relevant references by examining early reviews [48–50] and contemporary scientific journals. Following this, diagrams representing contemporaneous cosmic-ray measurements were cropped, and the data points were digitized directly with the tool WebPlotDigitizer, intentionally avoiding the digitization of curves to prevent the introduction of potentially misleading interpolations. For the majority of data given as relative increases in percentage units, we conservatively estimated the absolute digitization error as $\pm(0.1\text{--}0.3)$ percentage points varying for different plots owing to their quality. Exceptionally, the data for Ottawa, Resolute and Climax cosmic-ray detectors during GLE #4 have the highest digitization errors of about two percentage points, partially because of their high percentage increase. The data given in absolute units, e.g. count rates or voltage, have the digitization error of the same order of a per cent. We also conservatively estimated the timing error as ± 1 minute for records with a resolution of 5 minutes or less, around ± 3 minutes for 15-minute resolution series and up to ± 15 minutes for hourly and bi-hourly data. In addition, we tried some archival investigations, if not comprehensively. For GLE #4, an unexpected discovery was made at the University of Chicago Archives—a source table related to the work of Adams [47] that John Simpson received from Henry Braddick (figure 3). This finding emerged as a by-product of the surveys conducted in [27]. Therefore, instead of digitizing the diagram from [47], this source table was tabulated and compiled into our dataset.

In the summary table 1, essential details such as the name, geographical coordinates, altitude of each observing station, instrumental category and presence/absence of the measurement data for each GLE are documented. For acronyms, we use a six-character code, where the first four characters denote the location, and the last two denote the detector type. If multiple detectors of the same type were installed at one location, the final character indicates the detector number, and the part indicating the location is shortened to three characters. The geographical coordinates and altitudes of the individual stations were extracted from their respective source reports. In instances where geographical profiles were not provided, information was sourced from the observatory

Table 1. Cosmic-ray stations used in this work: station name; acronym; type of instrumentation—ionization chamber (IC), Geiger–Müller tube (GM), neutron monitor (NM) or electroscope (ES); geographical coordinates; mean altitude above sea level (m.a.s.l.) and data availability for the GLEs (signs ‘+’, ‘−’ and ‘x’ indicate the presence, absence and textual mention to non-detection, respectively, of records in the dataset). The lower-case ‘x’ in an acronym denotes the number of a specific detector in the location. Altitudes denoted by an asterisk were deduced from the station coordinates using OpenTopoMap. We show their values only if the altitude was not given in their source report or in [51].

station	acronym	instrument	location	altitude (m.a.s.l.)	GLE #1	#2	#3	#4
Amsterdam	AMSICx	IC	52°21′ N 4°57′ E	0	−	+	+	+
Azabu	AZABIC	IC	35°40′ N 139°44′ E	27*	x	+	−	−
Bargteheide	BARGMx	GM	53°44′ N 10°16′ E	52*	−	−	−	+
Cheltenham	CHLTIC	IC	38°44′ N 76°51′ W	72	+	+	+	+
Christchurch	CHRSIC	IC	43°32′ S 172°37′ E	8	+	+	−	+
Climax	CLMXIC	IC	39°24′ N 106°12′ W	3500	−	−	−	+
Freiburg	FREIGM	GM	47°55′ N 7°45′ E	1200	−	−	−	+
Friedrichshafen	FRHNGM	GM	47°39′ N 9°28′ E	403*	+	+	−	−
Godhavn	GODHIC	IC	69°15′ N 53°32′ W	9	+	+	+	+
Huancayo	HUANIC	IC	12°3′ S 75°20′ W	3350	+	+	+	+
Komagome	KOMAIC	IC	35°44′ N 139°44′ E	32*	x	+	−	−
London	LONDGM	GM	51°30′ N 0°11′ W	24*	+	+	−	−
Manchester	MANCGM	GM	53°28′ N 2°14′ W	42*	−	−	+	+
Manchester	MANCNM	NM	53°28′ N 2°14′ W	42*	−	−	−	+
Moscow	MOSCIC	IC	55°29′ N 37°19′ E	203	−	−	−	+
Mount Wilson	MTWLES	ES	34°14′ N 118°3′ W	1740	−	−	+	−
Norfolk	NORFIC	IC	36°52′ N 76°18′ W	8*	+	−	−	−
Ottawa	OTWGMx	GM	45°24′ N 75°36′ W	101	−	−	−	+
Predigtstuhl	PREDIC	IC	47°42′ N 12°53′ E	1614	−	−	−	+
Resolute	RSLGM3	GM	74°41′ N 94°55′ W	17	−	−	−	+
Teoloyucan	TEOLIC	IC	19°45′ N 99°11′ W	2285	+	−	−	−
Tokyo	TOKYGM	GM	35°44′ N 139°44′ E	32*	−	−	−	+
Thule	TULEES	ES	76°31′ N 68°42′ W	260	−	−	+	−
Weissenau	WEIGMx	GM	47°46′ N 9°36′ E	427	−	−	−	+
Yakutsk	YAKTIC	IC	62°1′ N 129°43′ E	108	−	−	−	+

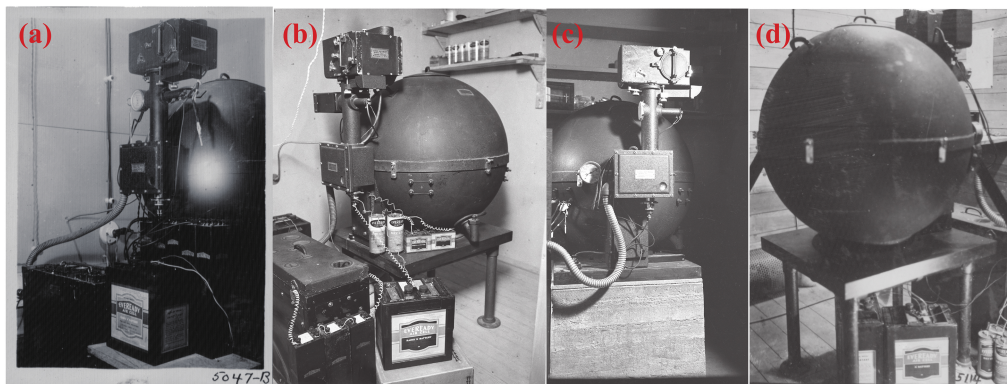


Figure 1. Examples of Forbush's ionization chambers: panel (a) Cheltenham observatory (5047B), panel (b) Teoluyucan observatory (5058), panel (c) Huancayo observatory (5080) and panel (d) Christchurch observatory (5114), as reproduced from the said archival photographs of Carnegie science collections.

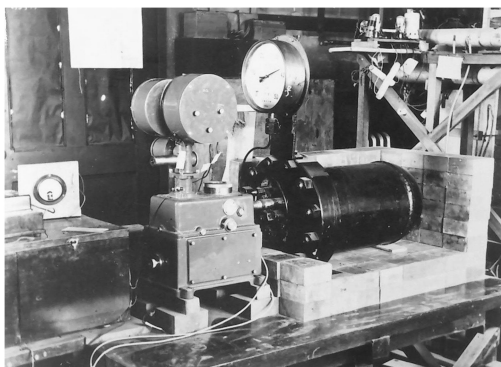


Figure 2. One of the Nishina-type ionization chambers that was operated in RIKEN and currently preserved in the Yoshio Nishina Memorial Room of RIKEN, as reproduced with courtesy to the Nishina Memorial Foundation.

catalogue maintained by the US Air Force Research Laboratory [51], or alternatively from up-to-date geographical data based on Google Earth Pro. For each location, we computed the geomagnetic cut-off rigidity at each GLE (figure 4) using the OTSO tool [52], the International Geomagnetic Reference Field model IGRF 14 [53] for the internal geomagnetosphere, Tsyganenko-89 model [54] for the external geomagnetosphere and geomagnetic Kp index values corresponding to the time of each GLE peak [55]. We have selected the Tsyganenko-89 model over later, more realistic Tsyganenko models, which require spacecraft measurements of the ambient solar wind conditions as input parameters, and such measurements were absent during GLEs #1–4. The Tsyganenko-89 model only requires geomagnetic data as the input for a given time; such data is readily available for GLEs #1–4. We note that the Tsyganenko-89 model is found adequate when computing cut-off rigidities under quiet to moderately disturbed geomagnetic conditions [56–59].

It is unclear whether the source datasets have been routinely corrected for barometric pressure variations, unless explicitly stated in their source documents. In the absence of pressure measurements for each detector, we did not correct our digitization with barometric pressure in our study. An accurate pressure correction method should be developed in future studies.

If the time stamps were recorded in local time, we corrected the time stamp according to the time-zone charts in the reprints of the Admiralty Navigation Manual of the United Kingdom

(1949)	(UT)	(Single Neutron Counts)	Data given are the times (UT) at which the impulse counters were photographed and the single neutron counts recorded between these times.
Nov.18	2358	572	
Nov.19	0058	608	
	0158	614	
	0258	620	
	0358	560	
	0458	554	
	0558	570	
	0658	610	
	0758	602	
	0858	406	Corresponds to 5.67 Per hour ✓
	0941	928	
	1058	3756	
	1158	4408	
	1323		
	1627	772	
	1658	1364	
	1758	1170	
	1858	1008	
	1958	896	
	2058	852	
	2158	786	
	2258	724	

$\frac{62}{77} \times 928 = 747$
 $\frac{6}{177}$

Figure 3. The source data table for the Manchester NM in Braddick’s correspondence to Simpson in Simpson Folder 216 Box 14, with a courtesy to the archives of Hanna Holborn Gray Special Collections Research Center, University of Chicago Library.

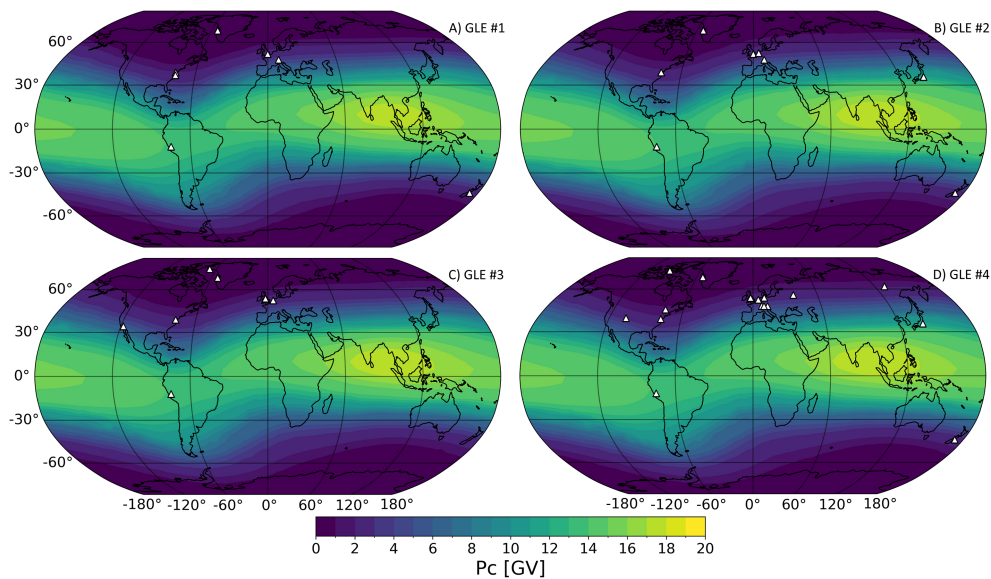


Figure 4. World map of geomagnetic cut-off rigidities P_c and stations from table 1 (triangles) for GLEs #1–#4 shown in panels (A)–(D), respectively. The values of P_c are calculated with OTSO [52] specifically for the dates of the GLEs.

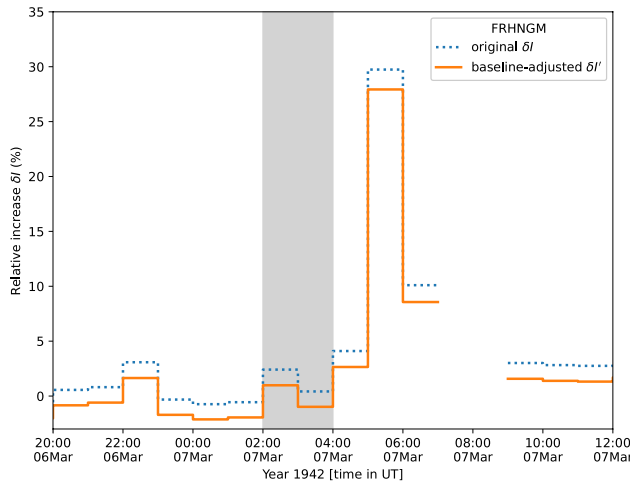


Figure 5. Example of the baseline adjustment applied to a relative increase series in this work. Specifically, the original δI and adjusted $\delta I'$ records from Friedrichshafen during GLE #2 are plotted as dotted blue and solid orange lines, respectively. The grey area indicates the period 02–04 UT, 7 March 1942, used for the calculation of the baseline δI_b .

Hydrographic Office [60]. Dates of measurements and tables were accessed from <http://www.worldtimezone.com>.

Many original data were given as increases in δI as a percentage relative to baselines defined with different approaches. In order to make the series comparable with each other, we adjusted the recorded data δI relative to a standard baseline and computed the standardized relative variation $\delta I'$. In most cases, the original baseline is given as 0% (figure 5). For its adjustment, we applied the following equation:

$$\delta I'[\%] = \frac{\delta I[\%] - \delta I_b[\%]}{\delta I_b[\%] + 100\%} \cdot 100\%. \quad (2.1)$$

For the rest of the records, when the original baseline was given as 100% or is absolute units (count rate, voltage, etc.), i.e. without data normalization, we used the equation

$$\delta I'[\%] = \frac{\delta I - \delta I_b}{\delta I_b} \cdot 100\%. \quad (2.2)$$

The standard baseline δI_b used in this work is defined based on the average of 2 hours of measurements before the onset of the GLE, following the practice of the database IGLED. Unfortunately, we could not enforce this uniformly for every series, because some of them have missing data points or time resolution that can be low or irregular. In those cases, we tried to use as much data as possible within 2 hours or slightly increase the 2-hour interval for calculating the baseline.

3. Ground-level enhancements #1 and #2 of February–March 1942

GLEs #1 and #2 occurred in close succession on 28 February and 7 March 1942, with their respective source flares recorded at approximately 12:00–13:00 UT on 28 February ([61], p. 318) and 04:14–06:20 UT on 7 March ([62], p. 202), as indicated by contemporaneous reports of geomagnetic crochets that served as indirect geomagnetic indicators of the solar flares [63]. We have collected, digitized and standardized the contemporaneous measurements in table 2 and figure 6 for GLE #1 and table 3 and figure 7 for GLE #2, respectively.

During this period, five of Forbush's ICs—Cheltenham, Godhavn, Christchurch, Teoloyucan (the latter operational solely for GLE #1) and Huancayo—were in operation. We digitized their

bi-hourly measurements presented in fig. 1 of [64]. GLE #1 demonstrated observable spikes in the bi-hourly IC measurements at Cheltenham, Godhavn and Christchurch; however, no spikes were evident at high-cut-off stations of Teoloyucan and Huancayo. By contrast, GLE #2 produced spikes across all bi-hourly IC measurements, including those from Huancayo.

To enhance our analysis, we derived 15-minute interval data for Cheltenham, Christchurch and Godhavn from fig. 6 of [64], which elucidates the intricate temporal structures associated with these events. GLE #1 began within the 12:00 to 12:15 UT interval at the aforementioned stations, peaking at approximately 12.8% at Cheltenham during the 13:00 to 13:15 UT interval, approximately 7.5% at Christchurch during the 12:45 to 13:00 UT interval and reaching approximately 15.4% at Godhavn from 13:00 to 13:15 UT. GLE #2 commenced between 05:00 and 05:15 UT at the respective monitoring stations, reaching a peak of approximately 13.8% at Cheltenham from 05:30 to 05:45 UT. Similarly, Christchurch recorded a peak of approximately 12.2% from 05:15 to 05:30 UT, while Godhavn observed a peak of approximately 9.1% within the same 05:15 to 05:30 UT window. Notably, Godhavn experienced a secondary peak reaching approximately 12.0% between 06:00 and 06:15 UT. These observations delineate the rise time of GLE #2 as 22.5 ± 22.5 minutes.

To create a comprehensive dataset, we integrated the GLE #1 bi-hourly data series from fig. 1 of [64] with the 15-minute data series from the same source (figure 6) for Cheltenham, Godhavn and Christchurch, making necessary adjustments to ensure consistency. Specifically, we validated the 15-minute series, comparing their bi-hourly averages to the published bi-hourly diagrams for their overlaps. A minor discrepancy of less than 1% was detected between the series. We consider the 15-minute series to be more reliable, given the superior quality of fig. 6 in [64] compared to the more generalized overview presented in figure 1, from which the bi-hourly series was derived.

In addition, we identified an IC record in Norfolk, USA, as detailed in the work of Berry & Hess [67]. We digitized fig. 4 from [67], extracted the hourly data, and adjusted the time stamps from the local time to Coordinated Universal Time (UTC). This process revealed a peak cosmic-ray intensity in Norfolk of approximately 7.4% occurring around 14:00 UTC during GLE #1.

We also analysed three ICs located in Amsterdam, as documented by Clay *et al.* [68]. These chambers included one unshielded IC (AMSIC6), one shielded with 12 cm of iron (AMSIC5) and another one shielded with 110 cm of iron (AMSIC8). The time resolution for the unshielded IC was bi-hourly, while the shielded ICs operated at an hourly resolution. Clay *et al.* [68] did not discuss GLE #1, aside from the subsequent Forbush decrease represented in their graph 11. Amsterdam ICs might have missed GLE #1. Elliot associated Amsterdam ICs with non-detection [48], while it is not clear what source he consulted. By contrast, we successfully identified and digitized their measurements corresponding to GLE #2, which are illustrated in their graph 12. The recorded peak intensities from these ICs were approximately 3.7% at 07:00 UTC for the unshielded AMSIC6, approximately 8.1% at 05:00 UTC for the 12 cm iron-shielded AMSIC6 and approximately 2.9% at 05:00 UTC for the 110 cm iron-shielded IC AMSIC8 for GLE #2.

Furthermore, in Japan, we located records from one underground IC located in Komagome and three ground-level ICs situated in Azabu [46,69]. These ICs did not observe any significant cosmic-ray increases during GLE #1 ([46], p. 3). By contrast, GLE #2 resulted in a substantial increase in cosmic-ray activity across all observed ICs. We digitized their approximately 5-minute variations from fig. 1 of [69]. The cosmic-ray levels recorded at Komagome and Azabu peaked at 4.5% at 05:06 UT and 9.3% at 05:14 UT, respectively. We prioritized the data from [69] over that from [46] because there was a significant contradiction between them, and the former comes from the actual measurers. Unfortunately, presently, it is impossible to resolve the cause of this contradiction, as the original Tokyo IC records were lost at least since 2017, when RIKEN shut down the storage at Itabashi.

We verified the functionality of two GM tube set-ups located in the UK and Germany during this period. In the UK, we sourced and digitized GM measurements from Imperial College London, as depicted in fig. 3 of [66], enabling us to compile bi-hourly data. This GM effectively detected both GLEs. The peak measurements for GLEs #1 and #2 in London were approximately 4.0% at 14:00 UT on 28 February and around 8.6% at 06:00 UT on 7 March, respectively.

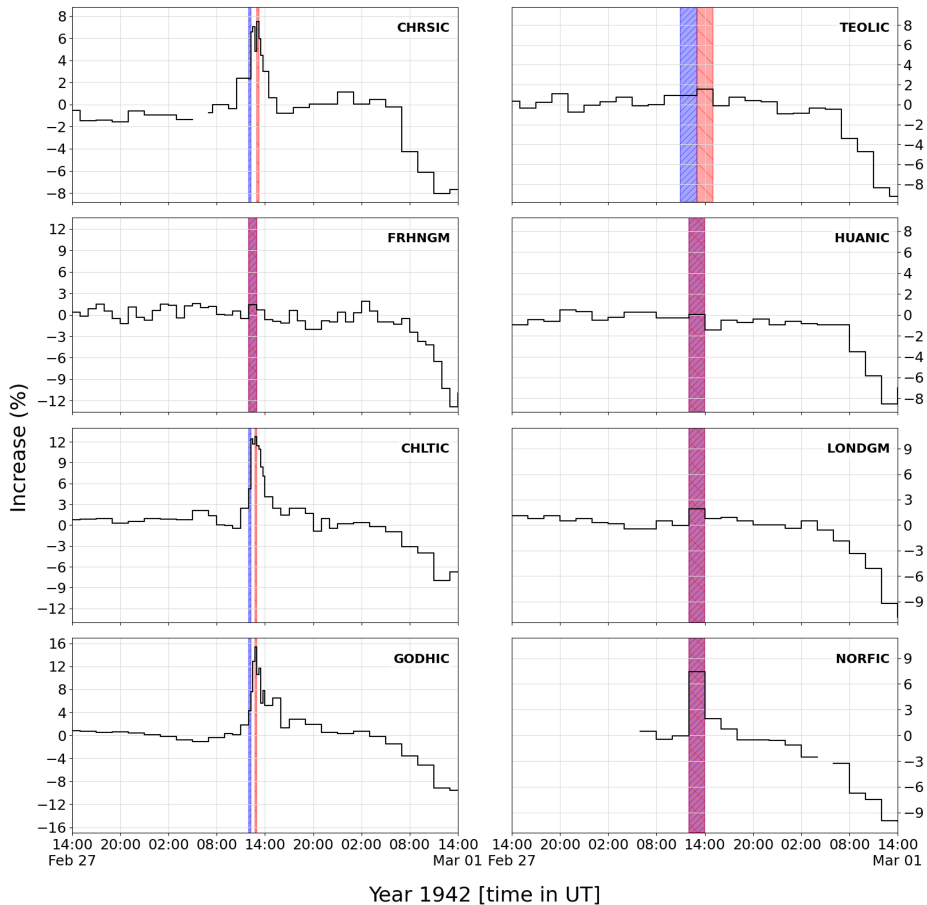


Figure 6. Standardized relative increases during GLE #1. The onset period for the GLE and GLE peak in the NM time resolution are denoted by the blue and red shaded regions, respectively. A purple region is used when the onset and peak increase overlap.

In addition, in Germany, we gathered and digitized GM readings from Friedrichshafen, illustrated in fig. 1 of [65], allowing us to derive hourly data. This GM also successfully detected both GLEs, with peak values for GLEs #1 and #2 measuring approximately 1.9% at 13:30 UT on 28 February and an impressive 28.0% at 05:30 UT on 7 March, respectively.

4. Ground-level enhancements #3 of July 1946

GLE #3 was recorded on 25 July 1946. According to contemporaneous H α flare patrols, the source flare peaked at 16:27 UT on 25 July 1946 [70]. This solar eruption triggered an intense and long-lasting GLE. We have collected, digitized and standardized the contemporaneous measurements in table 4 and figure 8 for GLE #3.

At that time, three of Forbush's ICs were operational: those located in Cheltenham, Godhavn and Huancayo. We have digitized fig. 1 of [75] to include the measurements from these three ICs, which were recorded at hourly intervals around the peak and at bi-hourly intervals thereafter. Notably, measurements at Cheltenham displayed marginal discrepancies when compared to Forbush's bi-hourly dataset for the same observatory, as depicted in fig. 1 of [14]. Among the ICs, those at Cheltenham and Godhavn successfully detected GLE #3, whereas the Huancayo IC showed no significant increase during the SEP event.

Furthermore, we have extracted 15-minute interval data for Cheltenham and Godhavn ICs from fig. 7 of [64], which provides a detail of the time structure of their measurements. These

Table 2. GLE #1 observed by different instruments. The geomagnetic apparent cut-off rigidities P_c are given specifically for the period of that GLE. The resolution corresponds to the interval around the GLE peak. Weak and insignificant peak increases are denoted with a dagger (†) mark. The integral ionization values are not provided for them. Integral ionizations from data, where there are gaps, are lower estimates and marked with an asterisk (*).

station	reference	P_c (GV)	peak increase (%)	best resolution (min)	integral ionizations (%-h)
CHLTIC	[13,14,64]	1.63	12.75	15	38.6
CHRSIC	[64]	2.28	7.49	15	16.7
FRHNGM	[65]	4.63	1.38 †	60	–
GODHIC	[64]	0.00	15.4	15	39.5
HUANIC	[13,64]	14.29	0.03 †	120	–
LONDGM	[66]	2.29	1.93	120	7.2
NORFIC	[67]	2.02	7.44	120	20.2
TEOLIC	[64]	10.13	0.9 †	120	–

Table 3. GLE #2 observed by different instruments. The geomagnetic apparent cut-off P_c rigidities are given specifically for the period of that GLE. The resolution corresponds to the interval around the GLE peak. Integral ionizations from data, where there are gaps, are lower estimates and marked with an asterisk (*).

station	reference	P_c (GV)	peak increase (%)	best resolution (min)	integral ionizations (%-h)
AMSIC5 (12 cm iron shield)	[68]	2.58	8.11	60	21.0
AMSIC6 (unshielded)	[68]	2.58	3.67	120	20.8
AMSIC8 (110 cm iron shield)	[68]	2.58	2.86	60	7.6
AZABIC	[69]	12.22	9.27	4	4.7
CHLTIC	[13,14,64]	1.92	13.78	15	25.1
CHRSIC	[64]	2.59	12.19	15	19.4*
FRHMGM	[65]	4.78	27.93	60	39.1*
GODHIC	[64]	0	11.97	15	29.8
HUANIC	[13,64]	14.42	3.02	120	5.9
KOMAIC	[46,69]	12.22	4.89	4	4.4
LONDGM	[66]	2.58	8.58	120	25.5

measurements reveal notable increases of approximately 21.8% for Cheltenham and around 16.4% for Godhavn, which were gradually rising for approximately 120 and 150 minutes for Cheltenham and Godhavn, respectively. Such a long rise time is typical for the gradual component of strong GLE events, e.g. GLE #42 (29 September 1989) or GLE #77 (11 November 2025).

In addition to the Forbush ICs, we also digitized the hourly measurements from two electroscopes that recorded GLE #3: one at Thule in Greenland [74] and the other at the Mt. Wilson Observatory in California [73]. The Thule electroscop was protected by 11 cm of lead shielding, whereas

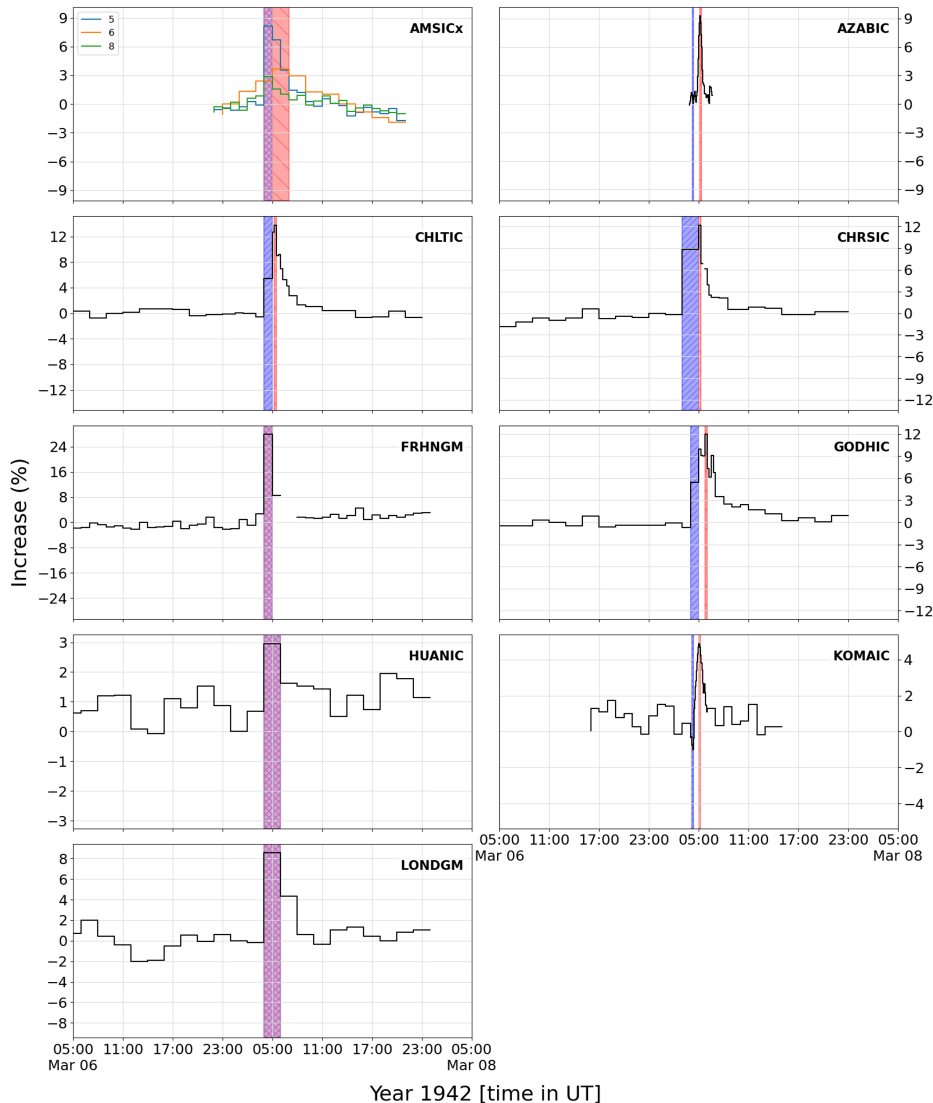


Figure 7. Standardized relative increases during GLE #2. Shaded regions for the GLE onset, GLE peak and any overlapping regions follow the same colour scheme as figure 6. The GLE peak region for locations with multiple detectors covers the peaks of all detectors at said location.

the electroscope at Mt. Wilson was unshielded. Specifically, for Mt. Wilson, Neher & Roesch [73] reported a 2.2-hour chronological offset between the source flare and the GLE peak. This long duration is probably instrumental. Their original measurements were taken at 15-minute resolution [73], although they plotted the data at only hourly resolution.

In England, Dolbear & Elliot [72] operated a GM tube located in Manchester. We digitized their hourly measurements from their figure. At least two additional recorders were operated in Manchester at that time [72], while their data have neither been presented in [72] nor in subsequent related research. The hourly recordings from Manchester indicate a peak associated with the GLE of approximately 13.3%. Moreover, Dolbear & Elliot [72] synthesized data from three distinct recorders to locate the GLE peak occurring between 18:00 and 18:30 UTC, with a peak value nearing 17% over this half-hour time frame, although the original source data for this analysis were not explicitly disclosed.

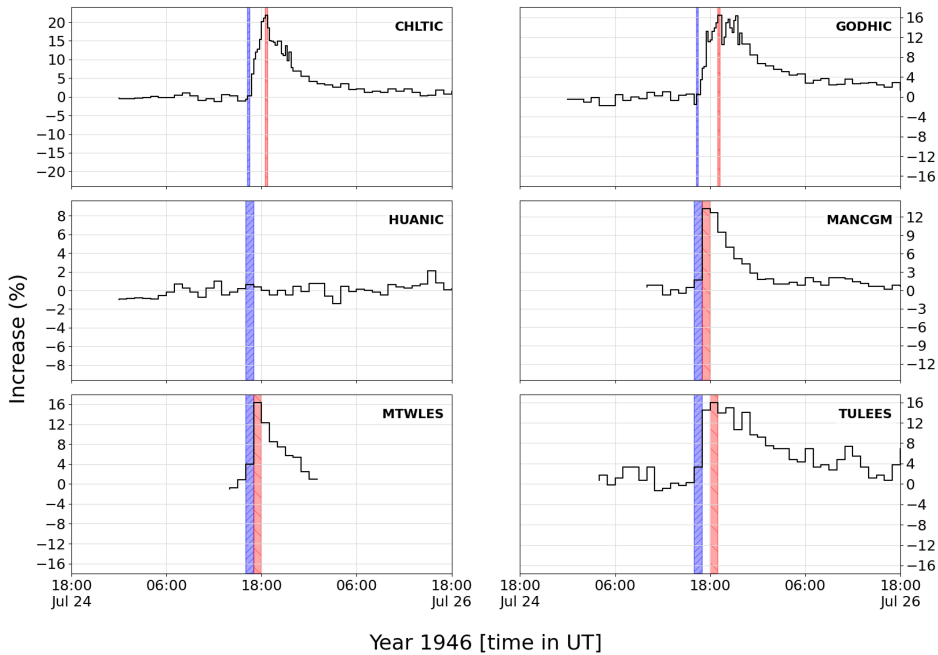


Figure 8. Standardized relative increases during GLE #3. Shaded regions for the GLE onset, GLE peak and any overlapping regions follow the same colour scheme as figure 6. The GLE peak region for locations with multiple detectors covers the peaks of all detectors at said location. We did not include the AMSICx dataset, which is contaminated by noise of unknown origin and should not be used in further analysis.

In Amsterdam, four ICs (AMSIC5–8) filled with argon gas at varying pressures of 40, 40, 97 and 58 atmospheres, respectively, were operated. We successfully located and digitized their records, illustrated in graph 2 of [76]. All measurements were presented hourly. Of these, two chambers (AMSIC5 and AMSIC6) were unshielded, while the other two chambers (AMSIC7 and AMSIC8) were covered with 110 cm of iron shielding. We note that the configuration of ICs in Amsterdam during observation of GLE #3 was different from that during GLE #2. These ICs seem to have detected GLE #3, although the open ICs exhibited notable deviations in measurements even before the onset of GLE #3. Each of the four ICs recorded another peak immediately following GLE #3, with the peak magnitudes that varied among the instruments. It remains ambiguous to what extent these ICs were sensitive to external noise. There is no documentation suggesting any cause of this enhancement even before GLE #3. Unless we determine the actual cause, it is wiser to refrain from using the AMSIC for any future analyses on GLE #3. Therefore, we included the AMSIC dataset neither in table 4 nor in figure 8.

5. Ground-level enhancements #4 of November 1949

GLE #4 took place on 19 November 1949. According to contemporaneous optical observations [77], the source flare peaked at 10:32 UT on 19 November 1949. We have collected, digitized and standardized the contemporaneous measurements in table 5 and figure 9 for GLE #4.

During this period, five of the Forbush ICs were actively in operation: those located in Cheltenham, Godhavn, Christchurch, Climax and Huancayo. We digitized the hourly IC measurements from Cheltenham and Huancayo, as depicted in fig. 4 of [64], along with the 15-minute IC measurements from Climax. Furthermore, we digitized fig. 7 of [64], which presents the 15-minute IC measurements for Cheltenham, Christchurch and Godhavn. Notably, the Huancayo IC

Table 4. GLE #3 observed by different instruments. The geomagnetic apparent cut-off rigidities P_c are given specifically for the period of that GLE. The resolution corresponds to the interval around the GLE peak. Weak and insignificant peak increases are denoted with a dagger (†) mark. The integral ionization values are not provided for them.

station	reference	P_c (GV)	peak increase (%)	best resolution (min)	integral ionizations (%-h)
CHLTIC	[14,64,71]	1.95	21.84	15	110.0
GODHIC	[64,71]	0	16.44	15	126.6
HUANIC	[64,71]	14.35	2.09 †	60	–
MANCGM	[72]	2	13.27	60	63.5
MTWLES	[73]	5.54	16.37	60	62.2
TULEES	[74]	0	15.99	60	200.5

recorded a modest GLE spike of approximately 1.9% between 11:00 and 12:00 UT. By contrast, the Climax IC and the Christchurch IC recorded significant cosmic-ray intensity peaks of around 181% at approximately 11:00 UT and approximately 24.2% during the interval from 11:00 to 11:15 UT, respectively. In addition, the Cheltenham and Godhavn ICs were saturated from 11:15–11:45 UT and 11:00–12:00 UT, respectively, after attaining cosmic-ray intensities of approximately 40.3% and 26.5%. We showed these intervals as gaps in the respective plots.

This GLE is unique as it marks the inaugural observation of a GLE using a prototype NM [47,83]. We have successfully located and digitized the source table for this measurement at the University of Manchester, alongside correspondence from Henry Braddick, preserved within John Simpson's Box 216 Folder 14, which John Simpson received in 1957 (figure 3). This documentation allowed us to determine that the peak cosmic-ray intensity registered by the Manchester NM reached approximately 542.9% during the period from 10:58 to 11:58 UT. The NM was constructed using boron-trifluoride-filled proportional counters, which were integrated into a 'Pile' made of high-purity graphite. As reported by Adams ([47], p. 504), this configuration demonstrated a detection efficiency for incoming neutrons with energy levels spanning from thermal up to approximately 10 MeV, with optimal sensitivity concentrated between 3 and 5 MeV. This is because Adams was aware of possible barometric pressure effects on the count rate of the instrument, but the registered variation of the pressure during the reported period of the GLE was within ± 0.1 inches Hg (± 3.4 mb), which would lead to a minor ($\mp 2.5\%$) variation of the count rate. Moreover, the University of Manchester conducted a separate cosmic-ray measurement using a GM counter, oriented in a north–south direction at a 45° angle relative to the local horizon, following the McDonald Elliott configuration ([47], p. 503). This measurement documented an increase in cosmic-ray activity of approximately 12% during the time frame of 11:00 to 12:00 UT [47]. We located and digitized a plot for this GM measurement in ([49], p. 351) to confirm a cosmic-ray increase of 11.5% at 11:30 UT at a 15-minute resolution.

In Japan, we successfully located and digitized cosmic-ray measurements obtained from a counter telescope in Tokyo (identical to a GM detector), as documented by Miyazaki *et al.* [81]. These measurements displayed remarkable temporal resolution. Following the onset of the event at 10:48 UT, the cosmic-ray levels reached a notable peak of approximately 5.9% between 11:03 and 11:04 UT. This observed value surpasses the peak reported in the running average by Miyazaki *et al.* [81], which was approximately 4%. A similar spike in cosmic rays was corroborated by data from a local IC, which was equipped with a 10 cm thick lead shield beneath a 30-cm-thick concrete roof [81]. However, it is regrettable that Miyazaki *et al.* [81] did not provide any published plots or tables detailing the measurements from the IC.

In the Netherlands, we identified and digitized three IC measurements from Amsterdam, as depicted in fig. 1 of [78]. These ICs, filled with argon at a pressure of 60 atmospheres, yielded bi-hourly measurements from one unshielded chamber AMSIC6 and hourly measurements from two shielded chambers—one with a 12 cm iron shield (AMSIC5) and the other with a 110 cm iron shield (AMSIC8). The data indicated that the shielded ICs experienced a peak around 11:00 UT, while the unshielded chamber peaked later, around 12:00 UT. This discrepancy is probably attributable to the less frequent bi-hourly time resolution associated with the unshielded IC. Furthermore, the unshielded AMSIC6 exhibited a significant amount of variability prior to the GLE on 18 November, warranting caution in the interpretation of its data.

In Germany, we located and digitized GM measurements at Predigtstuhl (10-minute resolution), Bargtheide with two devices (5 minutes) and Freiburg (hourly), as depicted in figs. 3, 5 and 6 of [79]. A 20-minute GM measurement conducted at Weissenau is illustrated in their fig. 4; however, the data from this measurement reveals a notable gap surrounding the peak. The records indicate that peak cosmic-ray intensity occurred at approximately 11:40–12:00 UT in Predigtstuhl, 11:55–12:00 UT in Bargtheide I1, 11:45–11:50 UT in Bargtheide I2 and 10:00–11:00 UT in Freiburg.

In France, an IC measurement was recorded at Bagnères (42°55' N 0°11' E, altitude 550 m.a.s.l.) as referenced in [84]. This particular instrument was characterized by a large IC fabricated from aluminium–magnesium alloy, having a volume of 120 l and filled with argon at a pressure of 10 atm. Although Dauvillier's article [84] does not include a graphical representation of the measurement allowing us to digitize their data, it does document a linear rise in cosmic-ray intensity that started around 11:30 UT, reached a maximum of 3.6% at approximately 12:00 UT, and subsequently decayed until around 15:00 UT.

In the Soviet Union, two IC measurements were performed in Yakutsk and Moscow. The IC measurements from Yakutsk are summarized in table 1 of [82], where the instrument used was a small S-2 IC, with a volume of 20 l filled with pure argon. This IC detected a cosmic-ray level peak at approximately 11:30–12:30 UT. We digitized the Moscow IC measurements illustrated in fig. 206 of [49], which revealed a peak occurring between 11:30 and 12:30 UT. This digitization might be improved if we manage to locate the source IC records.

In Canada, we located five GM measurements from Ottawa (OTWGM1, OTWGM3, OTWGM4, and coincidence counts between detectors GM1–GM2 and GM1–GM3) and three from Resolute (RSLGM3, and coincidence counts between GM1–GM2 and GM1–GM3), as depicted in figs. 2 and 3 of [80]. The captions accompanying these figures indicate that the measurements were conducted at higher time resolutions, specifically from 10:30 to 13:30 UT. Notably, the GM measurements from Ottawa exhibited inconsistent intervals. To enhance the reliability of our data analysis, we recommend substituting these datasets with tabulated original measurements, provided that the source records are retained in Canadian institutions. Although the original data were plotted as relative increases over the background radiation, as summarized in table 1 of [80], which outlines the average count rates before the GLE, we successfully reconstructed the actual count rates from these relative values. In this work, we decided to omit the coincidence counts data and present only the GM data series. In the records, GLE peaks were observed around 11:00 UT. Conversely, the GM measurements from Resolute employed 20-minute intervals, with peak occurrences noted approximately between 11:30 and 12:30 UT. The peak intensities recorded ranged from 155% to 192% in Ottawa and from 112% to 122% in Resolute, as detailed in table 1 of [80]. These data provide compelling evidence for a significant anisotropic effect during GLE #4.

6. Geomagnetic cut-off rigidity of the observational sites

In table 1, we list a comprehensive summary of the data recovery based on contemporaneous measurements, and we illustrate their geographical distributions in figure 4.

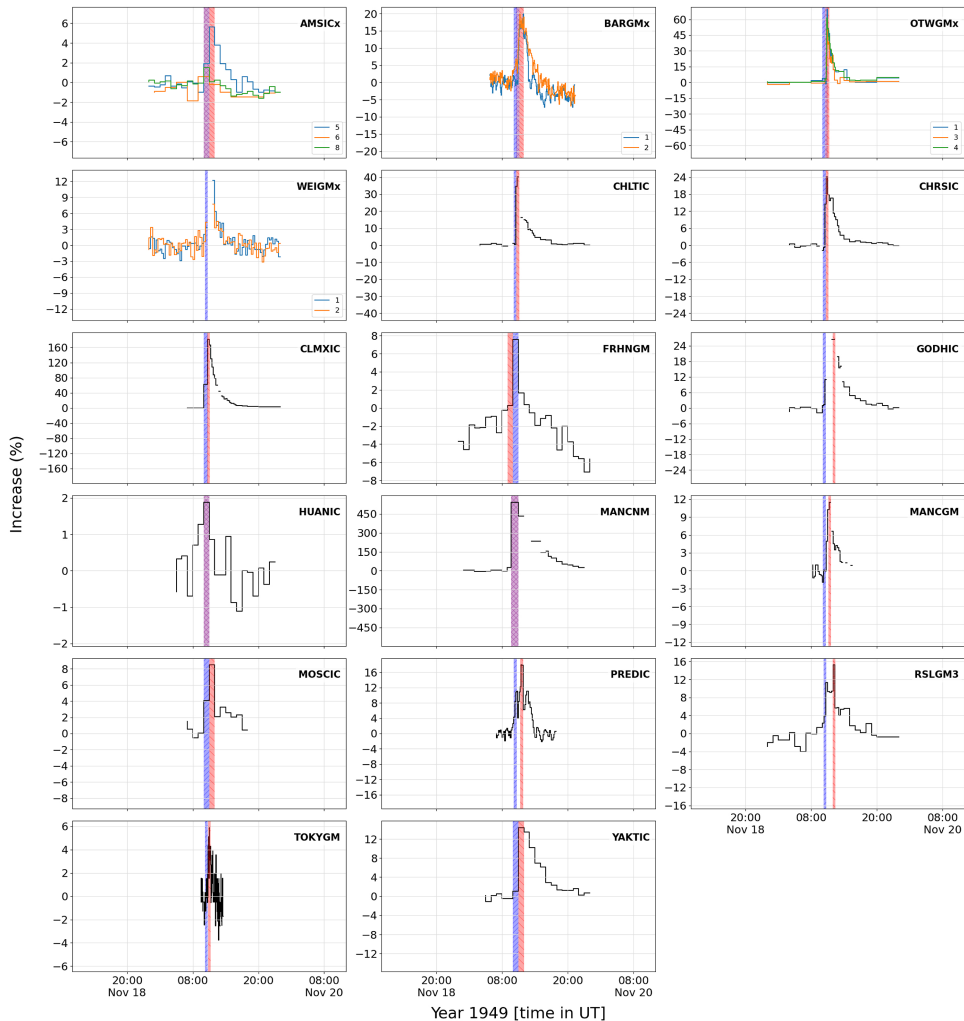


Figure 9. Standardized relative increases during GLE #4. Shaded regions for the GLE onset, GLE peak and any overlapping regions follow the same colour scheme as figure 6. The GLE peak region for locations with multiple detectors covers the peaks of all detectors at said location.

Geographical coordinates of these stations (table 1) allow us to compute an effective geomagnetic cut-off rigidity at each site (figure 4), using the OTSO package [52] for the geomagnetic conditions during these GLE, the IGRF 14 model [53] for the internal geomagnetosphere and the Tsyganenko-89 model [54] for the external geomagnetosphere. The Tsyganenko-89 model uses the Kp index as an input. The Kp-index values (rounded to the nearest integer) for GLEs #1–4 were 6, 2, 4 and 3, respectively [55].

7. Barometric corrections

The majority of the records analysed reflect a percentage increase in relation to the background galactic cosmic-ray (GCR) levels. However, the specific baseline measurements employed are inadequately documented in most of the original reports. The majority of these records did not clarify whether these values were corrected against the barometric pressures. In some cases, it remains ambiguous whether adjustments for barometric pressure were implemented. Contemporary literature offers only partial descriptions, hindering the ability to verify the application of barometric

Table 5. GLE #4 observed by different instruments. The geomagnetic apparent cut-off rigidities P_c are given specifically for the period of that GLE. The resolution corresponds to the interval around the GLE peak. Weak and insignificant peak increases are denoted with a dagger (†) mark. Integral ionizations are not provided for them. Integral ionizations from data, where there are gaps, are lower estimates and marked with an asterisk (*).

station	reference	P_c (GV)	peak increase (%)	best resolution (min)	integral ionizations (%·h)
AMSIC5 (12 cm iron shield)	[78]	2.64	5.64	60	14.5
AMSIC6 (unshielded)	[78]	2.64	0.59 †	120	—
AMSIC8 (110 cm iron shield)	[78]	2.64	2.94 †	60	—
BARGM1	[79]	2.36	19.84	5	26.2
BARGM2	[79]	2.36	19.91	5	43.3
CHLTIC	[64]	1.97	40.27	15	59.6*
CHRSIC	[64]	2.55	24.17	15	43.0*
CLMXIC	[64]	3	180.9	15	301.5*
FREIGM	[79]	4	7.57	60	9.2
GODHIC	[64]	0	26.47	15	67.74*
HUANIC	[64]	14.31	1.88 †	60	—
MANCGM	[49]	2.1	11.5	15	13.2*
MANCNM	(this work, figure 3)	2.1	542.87	60	1743.1*
MOSCIC	[49]	2.34	8.48	60	24.8
OTWGM1	[80]	0.98	69.74	2	85.7
OTWGM3	[80]	0.98	69.74	2	47.8
OTWGM4	[80]	0.98	69.74	2	89.6
PREDGM	[79]	4.25	17.88	10	32.4
RSLGM3	[80]	0	15.23	20	39.9
TOKYGM	[81]	12.26	5.88	1	2.0
WEIGM1	[79]	4.13	12.16	20	12.5*
WEIGM2	[79]	4.13	7.75	20	9.6*
YAKTIC	[49,82]	1.43	14.35	60	52.2

pressure corrections in bi-hourly Carnegie IC records ([64], p. 502) and certain Dutch ICs ([78], p. 909). This contrasts with the clear absence of such corrections in the Canadian GM measurements ([80], p. 232) and the Manchester NM data ([47], p. 504). Consequently, further investigations on the original unpublished manuscripts are imperative to determine whether barometric pressure corrections were indeed made to these measurements.

On this basis, it is desired to provide a conservative estimate of the additional uncertainty related to the possible lack of the barometric correction in our dataset. The estimate is based on the

fact that a typical barometric sensitivity of an NM is approximately $0.7\% \text{ mb}^{-1}$, while that for the ionization is approximately $0.4\% \text{ mb}^{-1}$ for detectors at mid to low latitudes with low altitudes under moderately modulated GCR [85,86]. Considering that the barometric pressure changes would not normally exceed a few mb during the event duration, we conservatively estimate the related uncertainties as 1% and 5% h for the peak and integral intensities, respectively. An accidental coincidence of such independent processes as a GLE and a weather storm is unlikely. An explicit account for specific barometric correction of SEPs is not routinely made and is beyond the scope of this work.

8. Temporal evolutions

Our data recovery efforts have facilitated a thorough analysis of the temporal evolution of these GLEs with 15-minute resolutions for the Carnegie ICs. In addition, we obtained high temporal resolution data, i.e. approximately 5 minutes for GLE #2 and approximately 1 minute for GLE #4. These advancements have significantly contributed to the documentation of the temporal dynamics of early GLEs during the 1940s. For these GLEs, the Carnegie ICs commonly offer measurements at 15-minute resolutions, as portrayed in figs. 6 and 7 in [64], although their measurements in Cheltenham and Godhavn were saturated near the peak of GLE #4. The IC measurements were employed to determine the shortest rise times to the first peak for GLEs. Specifically, their shortest rise times can be reconstructed as follows: 45 ± 15 minutes (Christchurch) for GLE #1, 15 ± 15 minutes (both Christchurch and Climax) for GLE #2, 105 ± 15 minutes (Cheltenham) for GLE #3 and 15 ± 15 minutes (Christchurch and Climax) for GLE #4. Our results critically contrast GLEs #2 and #4, both of which were characterized by a prompt rise, with GLEs #1 and #3, which displayed a comparatively gradual rise.

Significantly, for GLEs #2 and #4, we obtained high-time-resolution measurements from Tokyo, Japan, yielding measurement intervals of approximately 5 minutes and approximately 1 minutes, respectively. These datasets refined measurements allowed us to adjust the shortest rise times for GLE #2 and GLE #4 to 32 ± 4 minutes and 35 ± 1 minute, respectively. These high-time-resolution datasets revealed saturation of the measurements, in contrast to the existing bi-hourly data or the existing 15 minute peak values from the Forbush ICs. Certain Carnegie IC measurements exhibited saturation during GLE #4 within the 15-minute dataset, shown as gaps in the respective plots; however, such saturation effects were absent in the bi-hourly data. These saturation issues pose significant challenges in efforts to compare the early GLEs with the contemporary events.

The temporal variations observed in these measurements emphasize the difficulties inherent in quantifying GLEs and accurately determining the peak cosmic-ray increases across different time resolutions. The distinctions among short-rise GLEs become increasingly significant, particularly for GLEs #2 and #4. This pronounced difference is probably attributable to the limited duration of their rise, which proves insufficient for accurate assessments within a bi-hourly time window. Therefore, it is crucial to exercise caution when comparing peak values recorded at different measurement stations, as these stations operate under varying temporal resolutions.

9. Integral ionization increases

Expanding the geographical data coverage, our datasets involve richer datasets for detector responses from different P_c ranges (tables 2–5). On this basis, our results indicate the energy caps of these GLEs on the basis of their highest cut-off rigidities at GLE stations with signal detections, alongside the lowest cut-off rigidities at stations that did not detect GLE signals.

We first examine data from all the detectors to determine whether they detected the said GLEs or not. We determine a rigidity cap P_{cap} , a boundary for the local detectability for each GLE. For example, when a certain GLE is detected at Tokyo but not detected at Huancayo, the rigidity cap is located between the cut-off rigidity values of Tokyo and Huancayo. According to our datasets,

GLE #1 and GLE #3 were not detected in the Huancayo IC. GLE #1 was detected only up to Friedrichshafen station (4.63 GV) but was not detected in Tokyo (11.50 GV). GLE #3 was registered only up to Mt. Wilson (5.54 GV) and was similarly not observed in Huancayo, which had a threshold of 14.35 GV. These observations allow us to narrow down the rigidity cap for GLE #1 and GLE #3 to 4.63–11.50 GV and 5.54–14.35 GV in P_{cap} for the GLE detections, respectively. For the specific case of solar protons, one can use the following equation to convert rigidity P_{cap} to energy:

$$E_{\text{cap}} = \sqrt{P_{\text{cap}}^2 + E_0^2} - E_0, \quad (9.1)$$

where E_{cap} is the energy in GeV, P_{cap} is the rigidity in GV and $E_0 = 0.938$ GeV is the rest energy of a proton. Doing so for the found rigidity caps allows us to narrow down the energy caps, an energy threshold for the detections of cosmic-ray precipitations on the ground-based instruments, to $3.8 \text{ GeV} \leq \text{GLE \#1} \leq 10.6 \text{ GeV}$ and $4.7 \text{ GeV} \leq \text{GLE \#3} \leq 13.4 \text{ GeV}$, respectively.

It is highly marginal whether GLE #2 and GLE #4 were detected in Huancayo, while they were robustly detected in Tokyo. Even in the history of the NM measurements, GLEs have been recorded in Huancayo no more than 10 times since 1951. ICs or GM counters detected GLEs considerably less frequently than NMs, because the former's energy sensitivity is shifted to higher energies of SEP and GCR with respect to NMs. Contemporary ICs and GM counters also had higher noise levels. Overall, this resulted in the fact that ICs and GM counters registered only the highest-energy and intensity SEP events, much more energetic in comparison to most GLEs registered with NMs.

On this basis, Tokyo detectors at least put an energy cap of about $11.3 \text{ GeV} \leq \text{GLE \#2}$ and $11.4 \text{ GeV} \leq \text{GLE \#4}$. If we conservatively regard Huancayo data as a non-detection, we can further constrain the range of their rigidity caps as $12.22 \text{ GV} \leq \text{GLE \#2} \leq 14.42 \text{ GV}$ and $12.26 \text{ GV} \leq \text{GLE \#4} \leq 14.35 \text{ GV}$ for the GLE detections, respectively. These rigidity caps allow us to narrow down the energy caps as $11.3 \text{ GeV} \leq \text{GLE \#2} \leq 13.5 \text{ GeV}$ and $11.4 \text{ GeV} \leq \text{GLE \#4} \leq 13.4 \text{ GeV}$, respectively. This is more probably the case.

Based on these results, it is desired to qualitatively compare the intensity of these GLEs not merely by the peak ionization values at each site, but rather through the integral percentage ionizations observed at each site. To this end, we calculated the integral percentage ionization in cosmic-ray levels relative to the background GCR, based on the summary data listed in [tables 2–5](#) and illustrated in [figures 6–9](#).

It is straightforward to define the duration of each GLE at each station. We set the GLE onset after the flare onset documented in the contemporaneous optical observations or after the onset of the geomagnetic crochets, that is, after 12:00 on 28 February 1942 for GLE #1 [61], 04:14 on 7 March 1942 for GLE #2 [62], 16:20 on 25 July 1946 for GLE #3 [70] and 10:30 on 19 November 1949 for GLE #4 [77].

Similarly, we defined the peak time as the time when the count rate reached the highest enhancement in our target period after the GLE onset at each site. We defined the interval between the GLE onset and the GLE peak as a GLE rise time. We have taken the uncertainty range between the lower limits and upper limits, expecting the most extreme scenarios where the GLE onset started at the end of the onset time-stamp range and the beginning of the peak time-stamp range (a lower limit) and where the GLE onset started at the beginning of the onset time-stamp range and the end of the peak time-stamp range (an upper limit).

However, it is trickier to quantitatively compare the integrated ionizations at each station for each of these GLEs. This is partly because most of the data that we digitized are from contemporary instruments and require further in-depth analyses for their metadata for standardization. For example, the Manchester NM predated the International Geophysical Year (IGY) NMs. It is not immediately clear how to calibrate this NM with the IGY NMs. Adams's contemporaneous reports do not provide too many details for this issue either [47,83]. Obviously,

this NM was much more efficient at detecting cosmic-ray increases in comparison with ICs. The Manchester NM has an exceptionally high peak value (approx. 542.9%) and would require substantial rescaling when compared to the Manchester GM readings (approx. 11.5%). Each instrument may have different energy sensitivity to cosmic rays. This highlights the necessity for recalibrations in future studies to ensure accuracy and consistency in measurements across different detection systems. Recent archival investigations have revealed substantial amounts of unpublished records for contemporary-device measurements of GLE #5, as a by-product of our previous survey [27]. Their in-depth studies will hint at how to calibrate such early measurements with the modern NM measurements and develop estimates on their absolute magnitudes beyond some preliminary attempts [41,42]. Keeping these caveats in mind, we focused our analyses on measurements from the standardized instruments (Forbush ICs and Nishina ICs; figures 1 and 2), against their cut-off rigidity for each GLE in figure 4, to avoid the unwanted uncertainty of the cross-instrumental comparison. These detectors are at least theoretically standardized. In reality, it is known that their measurements drift on a longer time scale [87], while this probably does not affect their short-term responses.

Qualitatively, these data indicate that GLEs #2 and #4 had extremely hard spectra and GLEs #1 and #3 had marginally hard spectra. As we discussed above, GLEs #2 and #4 were detected at least up to Tokyo ICs (12.22 GV for GLE #2 and 12.26 GV for GLE #4). Their detections in Huancayo (14.42 GV for GLE #2 and 14.35 GeV for GLE #4) are at best marginal. Their local integral ionization should be used as an upper limit for GLEs #2 and #4. Among the Forbush ICs and Nishina ICs, we confirm detections of GLEs #1 and #3 down to Chetltenham and Christchurch, respectively.

These GLEs were all detected in Forbush ICs at Godhavn and Cheltenham. In particular, Godhavn's P_c is calculated as 0 GV for each GLE. While we need to consider shielding of the Godhavn IC, in reality we can, anyway, consider Godhavn as a benchmark for the lowest P_c reference. At Godhavn, the integrated ionizations were 39.5% h for GLE #1, 29.8% h for GLE #2, 126.6% h for GLE #3 and more than 67.7% h for GLE #4, respectively. In combination with the energy caps that we discussed above, these data show marginally steep increases for GLE #1 and GLE #3 and gradual increases for GLE #2 and GLE #4. Qualitatively, speaking, they also indicate extremely hard spectra for GLE #2 and GLE #4 and marginally hard spectra for GLE #1 and GLE #3. The integrated ionizations at Godhavn are the most enhanced in GLE #3. This is followed by GLE #4, GLE #1 and GLE #2. This indicates that GLE #3 had the largest fluence among them, GLE #4 had the second largest fluence and GLEs #1 and #2 were comparable in their fluence, while further intensive studies are needed on how to quantitatively estimate their fluence from integrated ionizations. Finally, further analyses are needed to support this simple analysis and to reconstruct their SEP spectra quantitatively.

10. Conclusions

In this study, we compiled contemporary cosmic-ray records and measurements related to GLEs from the 1940s. We meticulously organized the source data and digitized the corresponding measurement plots. We constructed time series for eight stations at GLE #1, nine stations at GLE #2, seven stations at GLE #3 and 17 stations at GLE #4. These datasets significantly enhance global data coverage. Moreover, we managed to derive the datasets for the contemporaneous local measurements of the early GLEs in the resolutions of 1–15 minutes. This improvement allows us to resolve the detailed time structure and integral percentage ionizations of these early GLEs, in contrast with the previous studies that used bi-hourly data from the Forbush ICs of Cheltenham IC and Huancayo [45,88] and in the existing 15-minute peak values from the Forbush ICs [23]. These datasets considerably improve the temporal resolution of these events, offering data at 15-minute intervals for GLEs #1 and #3, 5-minute intervals for GLE #2 and 1-minute intervals for GLE #4. This increased resolution has enabled us to ascertain the shortest rise times recorded for these

GLEs. Specifically, our findings indicate that GLEs #1 and #3 exhibit gradual rise times of 45 ± 15 minutes and 105 ± 15 minutes, respectively, in contrast to the abrupt rise times of GLEs #2 and #4, both of which occurred within 15 ± 15 minutes.

The expanded geographical coverage allows for a more comprehensive analysis of the GLE spectra by leveraging the terrestrial magnetic field as a natural spectrometer. Our data allow us to qualitatively compare their integral ionizations and spectra with one another, showing hard spectra for GLE #2 and GLE #4, and somewhat softer spectra for GLE #1 and GLE #3. Among them, GLE #3 had the greatest enhancements for the integral ionizations.

Our data tables refine the energy caps of these GLEs on the basis of their highest cut-off rigidities at GLE stations with signal detections, alongside the lowest cut-off rigidities at stations that did not detect GLE signals. Notably, GLE #1 was observed in Friedrichshafen, whereas it was not detected in Tokyo. This locates the energy cap of GLE #1 as $3.8 \text{ GeV} \leq \text{GLE \#1} \leq 10.6 \text{ GeV}$; GLE #2 was observed in Tokyo but was not detected in Huancayo, indicating its energy to be within the range of $11.3 \text{ GeV} \leq \text{GLE \#2} \leq 13.5 \text{ GeV}$. Similarly, GLE #3 was observed in Mt. Wilson, but not in Huancayo, resulting in locating the energy cap in the range of $4.7 \text{ GeV} \leq \text{GLE \#3} \leq 13.4 \text{ GeV}$; GLE #4 was recorded in Tokyo, also absent in Huancayo, locating its energy cap in a range of $11.4 \text{ GeV} \leq \text{GLE \#4} \leq 13.4 \text{ GeV}$.

These findings effectively fill the existing data gap for IGLED concerning the initial four GLEs from the 1940s. The compiled data files will enable the quantification of their temporal evolution, the reconstruction of their spectral characteristics and ionizations, and their contextualization with the greatest historical events. Further in-depth analyses are needed on the simultaneous measurements of these non-standard contemporary devices and the standard NMs, especially in the 1950s, to determine how to calibrate them with the modern datasets.

Data accessibility. This article has no additional data.

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. H.H.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, resources, supervision, visualization, writing—original draft; S.P.: formal analysis, methodology, resources, software, validation, visualization, writing—original draft, writing—review and editing; S.K.: formal analysis, investigation, resources, software, validation, visualization, writing—original draft, writing—review and editing; A.M.: formal analysis, investigation, supervision, validation, visualization, writing—review and editing; N.L.: formal analysis, resources, software, validation, visualization, writing—review and editing; I.U.: data curation, writing—review and editing; I.U.: supervision, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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