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Statistical analysis of the Thunderstorm Ground Enhancements (TGEs) detected on Mt. Aragats

A. Chilingarian, T. Karapetyan *, L. Melkumyan

Yerevan Physics Institute, Alikhanyan Brothers 2, Yerevan 0036, Armenia

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Abstract

Starting from 2008 experimental facilities of the Aragats Space Environmental Center (ASEC) routinely measure time series of secondary cosmic ray fluxes. At these years of the minimum of solar activity we analyze the new high-energy phenomena in the terrestrial atmosphere. Namely, Thunderstorm Ground Enhancements (TGEs) and Extensive Cloud Showers (ECSs). Several new particle detectors were designed and fabricated having lower energy threshold to detect particle fluxes from the thunderclouds; some of them have possibility to distinguish charged and neutral fluxes. During 2008–2012 years ASEC detectors located at Aragats, Nor Amberd and Yerevan were detected ∼300 TGE enhancements. Amplitude of majority of them is less than 5%; however, 13 TGEs have amplitude exceeding 20%. The maximal value of observed enhancement was 271% (September 19, 2009). The paper summarizes five-years study of the TGEs on Aragats. The statistical analysis revealing the month and day-of-time distributions of TGE events, as well as the amplitude and event duration diagrams are presented.

Keywords: Cosmic rays; Thunderstorm activity; TGE

1. Introduction

Sudden boost of the secondary cosmic ray flux correlated with thunderstorm activity, so called Thunderstorm Ground Enhancements (TGEs, Chilingarian et al., 2010, 2011) is the manifestation of the high-energy processes in the terrestrial atmosphere (Dwyer et al., 2012a) Origin of TGE is strong electrical field in the thundercloud, giving rise to rather complicated physical phenomenon, including several physical processes:

1. Relativistic Runaway Electron Avalanches (RREA, Wilson, 1925; Gurevich et al., 1992; Babich et al., 1998; Dwyer, 2003; Khaerdinov et al., 2005);
2. Modification of the Secondary cosmic ray (electrons, muons, protons and charged mesons) energy spectra (MOS, Dorman and Dorman, 2005; Muraki et al., 2004);
3. Photonuclear reactions of the RREA gamma rays (Chilingarian et al., 2012a,b; Tsuchiya et al., 2012; Babich et al., 2013);
4. Roentgen and gamma radiation from the lightning (Dwyer et al., 2012b);

Surface detections of the TGE process, although have long history, are discrepant and rare. The first attempts to observe the runaway electrons on the earth surface were carried out by Wilson's co-workers Schonland, Viljoen and Halliday in South Africa with cloud chambers. However, due to low sensitivity of cloud chambers to low energy gamma rays (the majority of particles reaching the earth surface from the electron–photon avalanches unleashed by runaway electrons in the thunderclouds are few MeV gamma rays) the results of these experiments were

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* Corresponding author. Tel.: +374 98102505.
E-mail address: ktigran79@yerphi.am (T. Karapetyan).

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discouraging. Looking for the electrons with energies up to 5 GeV subsequently returning to the earth surface following the force lines of geomagnetic field (at the great distance from the thundercloud which had produced them) surely could not give positive outcome (see Halliday, 1941). However, the observation of the runaway electron phenomena and distinguishing it from the modification of energy spectra turns to be rather difficult. “In summary and as introduction to the present set of experiments, after 70 years of repeated theoretical and experimental investigations, it is still not clear whether or not the runaway electron acceleration mechanisms operates in a significant manner in either thunderstorms or lightning” (Suszcynsky et al., 1996). In last 2 decades there were significant progress in detection of the particles (mostly gamma rays) from thunderclouds (Aglietta et al., 1989; Eack et al., 2000; Brunetti et al., 2000; Alexeenko et al., 2002; Torii et al., 2002, 2011; Lidvansky, 2003; Tsuchiya et al., 2007, 2011). Detailed historical reviews of TGE detection are presented in Chilingarian et al. (2010), Dwyer et al. (2012a,b). The idea of C.T.R. Wilson that accelerated in the thunderclouds electrons can reach the atmosphere found its proof after the launch of the orbiting gamma ray observatories. Numerous Terrestrial Gamma Flashes (TGFs) are routinely observed at 500 km above the Earth in correlation with strong equatorial thunderstorms (Fishman et al., 1994; Smith et al., 2005; Bucik et al., 2006). The origin of TGFs is believed to be the runaway electrons accelerated by the upper dipole as Wilson suggested in 1925.

Starting from 2008 experimental facilities of the Aragats Space Environmental Center (ASEC) (Chilingarian et al., 2003, 2005a,b) routinely measure time series of secondary cosmic ray fluxes. During these years several new particle detectors were designed and fabricated having lower energy threshold and possibility to distinguish charged and neutral fluxes (Arakelyan et al., 2013; Chilingarian et al., 2013). Variety of ASEC particle detectors allows for the first time detect RREA process in the atmosphere (Chilingarian et al., 2011), recover both the electron and gamma ray energy spectra of largest TGEs (the sum of multiple RREA) and develop the model of the TGE phenomena (Chilingarian, Mailyan et al., 2012).

16 by 1 m^2 area scintillators previously belonging to the stopped in 2007 MAKET surface array (Chilingarian et al., 2007), registering Extensive Air Showers (EAS) were distributed on the surface of $\sim$1000 m^2. If signals from the first 8 scintillators covering $\sim$ 400 m^2 area coincide within the trigger time of 400 nanoseconds the amplitudes of all photomultiplier pulses (proportional to the number of particles hitting each scintillator) are stored. At fair weather the surface array registered EAS events initiated mostly by the primary protons with energies above $\sim$50 TeV (25 EAS per minute, 8-fold coincidences) and 100 TeV (8 EAS per minute, 16-fold coincidences).

At 19 September 2009 the ASEC detectors measure the largest TGE ever measured at Aragats. The significance of detection at energies of 10 MeV exceeds 200σ. Measuring electron flux with different thresholds allows recovering for the first time the electron integral energy and estimate the height of thundercloud above detectors. The time series of the surface array triggers also demonstrate huge enhancement. During 7 min of the TGE $\sim$200 additional triggers were registered; the count rate at 22:47, 19 September 2009 was enhanced $\sim$8 times for the 16-fold coincidences and 5 times for the 8-fold coincidences. The statistical analysis of detected showers reveals their systematic difference from the EAS events (see for details Chilingarian et al., 2011): the density was much lower and spatial spread of the electrons was much more uniform (EAS spatial distribution have characteristic bell-like form). Therefore, the particle showers from the thunderclouds constitute different from EAS physical phenomena and were named – Cloud Extensive Showers (CESs). A CES phenomenon is very rare: only 3 largest TGEs from 300 were accompanied by CES observation. CESs originated from individual runaway electrons accelerated in the cloud just above the detector. Like multiple EASs from the primary cosmic rays are sustaining stable flux of secondary cosmic rays, multiple CESs are sustaining transient enhancement of the TGEs lasting minutes. Due to global character of primary cosmic ray flux the secondary cosmic ray flux did not change significantly; CES phenomenon is very local and depends on the height of cloud above detector and on the strength of electric field in it. Both parameters are fast changing and only during several minutes cascades from runaway electrons can be developed enough to cover several thousand square meters of surface. Only very suitable location and large sizes of the scintillators allows detect CES on Aragats and for the first time prove existence of RREA phenomena.

During 2008–2012 ASEC detectors at Aragats (3200 m above sea level, geographical coordinates 40°28′N, 44°10′E) were operated 24 h, 12 months uninterruptedly, gathering rich harvest of TGE events (totally 277 TGE events in 5 years, see Tables 1–5). Much less TGE events (20, see Table 6) were detected in the same period at Nor Amberd station, on the slopes of Aragats (2000 m above sea level, geographical coordinates 40°22′N, 44°15′E). And only one TGE by 3.8% amplitude was detected in Yerevan (1000 m above sea level, geographical coordinates 40°20′N, 44°49′E), (see Table 7, measurements in Yerevan started in 2011).

34 of 277 TGE events were registered in 2008, 46 TGEs in 2009, 88 TGEs in 2010, 67 TGEs in 2011 and 42 TGEs in 2012 years. 190 TGEs from 277 have amplitude less than 5%, 55 TGEs have amplitude between 5% and 10% and 32 TGEs have amplitude greater than 10%. Only 13 TGEs have amplitude exceeding 20%. The maximal value of observed enhancements was 271% (September 19, 2009) and the minimal registered −0.8%. In the observed years the most productive months were: May and June in 2008, May–July in 2009. The maximum number of TGE events was detected in October 2010.

Table 1
Characteristics of TGEs registered at Aragats in 2008.

Date, time 2008	Detector	Duration (min)	Number of peaks	Percent of enhancement (%)
1 May, 12:23	MAKET	10	1	6.2
2 May, 17:31	MAKET	10	1	3.1
3 May, 15:13	MAKET	20	1	3.4
4 May, 10:32	MAKET	24	1	12
5 May, 21:34	MAKET	5	1	4.6
9 May, 5:38	MAKET	4	1	2.7
11 May, 10:10	MAKET	13	2	5.5
13:02		16		4.2
12 May, 13:23	MAKET	26	2	5.4
21:57		6		5.5
16 May, 7:05	MAKET	15	4	5.9
11:56		18		3.5
12:18		7		2.8
15:27		18		2
17 May, 17:30	MAKET	12	1	3
29 May, 11:43	MAKET	11	2	7.8
15:13		6		10
9 June, 1:39	MAKET	8	2	4.3
3:33		4		22.3
10 June, 17:16	MAKET	3	1	2.1
12 June, 11:05	MAKET	3	1	1.9
16 June, 13:35	MAKET	15	1	2.6
17 June, 23:38	MAKET	14	1	5.1
21 June, 17:30	MAKET	12	3	3.8
20:19		15		3.5
21:43		3		2.3
22 June, 3:18	MAKET	14	1	4.7
7 July, 14:46	MAKET	9	1	4.8
8 July, 11:05	MAKET	21	1	5.5
9 July, 23:52	MAKET	4	1	2.9
10 September, 15:53	MAKET	5	1	2.1
16 September, 21:41	MAKET	9	1	2.9
9 October, 12:29	MAKET	6	1	2.8
21 October, 20:44	MAKET	9	1	11.5

Detailed information about all events, as well as, description of detectors and forewarning/alert services are available from the site of Cosmic Ray Division (CRD) of Yerevan physics institute http://crd.yerphi.am. On-line access to database containing multiyear monitoring of secondary cosmic rays with more than 200 measuring channels is enabled by the multivariate visualization program ADEI (http://adei.crd.yerphi.am/adei/).

The paper presents statistics of the five-years study of the TGEs on Aragats. The analysis considers the number of TGEs as function of time of a day, month, duration, size of enhancement and other.

2. Brief description of ASEC particle detectors

The Aragats Space-Environmental Center provides monitoring of different species of secondary cosmic rays at three altitudes. The ASEC consists of two high altitude stations located on the slope of Mt. Aragats (3200 m, 2000 m) and a detector assembly in Yerevan headquarters of Cosmic Ray Division of Yerevan Physics Institute (1000 m). Two detectors, MAKET (Chilingarian et al., 2007) and Aragats Multidirectional Muon Monitor (AMMM, Chilingarian and Reymers, 2007) are in operation from late 90-ths with main goal to investigate the energy spectra of the primary cosmic rays in the “knee” region. Both detectors uses the same particle detection techniques to determine the density of electrons belonging to Extensive Air Showers (EAS) and infer the energy and type of a primary particle.

MAKET array consists of four 60 cm thick scintillators and 12 of 5 cm thick ones from which 3 are located outside of the main building. Maket array provides following information:

- 1 min count rates of all 16 channels independently;
- Coincidences of signals from 8 channels from 16, within 400 nanoseconds.

Count rate of the 60 cm detectors is ~34,000 counts per minute and variance ~240. Count rate of each 5 cm scintillators is ~22,000 counts per minute and variance ~190. The energy threshold of 5cm scintillators is ~9 MeV and 60 cm ~15 MeV.

Table 2
Characteristics of TGEs registered at Aragats in 2009.

Date, time 2009	Detector	Duration (min)	Number of peaks	Percent of enhancement (%)
30 April, 22:19	AMMM	5	1	7.2
1 May, 0:22	AMMM	7	1	6
3 May, 9:37	AMMM	12	2	7.2
9:43				7.6
8 May, 16:52	AMMM	13	1	14.9
21 May, 17:09	AMMM	20	2	19.3
17:15				30.7
26 May, 0:13	AMMM	21	4	9
8:26		11		4.3
12:16		11		3.5
12:45		12		11.5
27 May, 22:53	AMMM	6	1	8
2 June, 14:16	AMMM	7	1	4.7
3 June, 16:14	AMMM	10	2	10.5
17:07	AMMM	5		4.1
6 June, 16:04	SEVAN	13	1	2.1
8 June, 8:00	SEVAN	20	1	2.6
17 June, 19:22	SEVAN	23	1	1.8
20 June, 10:43	SEVAN	13	2	2.5
10:56		13		2.3
26 June, 17:00	MAKET	7	1	4.8
28 June, 11:56	MAKET	2	1	2.8
3 July, 18:21	MAKET	10	1	2.7
9 July, 3:54	MAKET	4	3	28.7
3:56		4		44.7
21:26		4		2.3
23 July, 19:06	MAKET	11	1	4
27 July, 10:05	MAKET	23	1	3.6
28 July, 16:55	MAKET	21	1	4.8
1 August, 17:34	MAKET	6	1	2
2 August, 13:13	MAKET	11	2	2.6
13:33		6		3.3
8 August, 16:39	MAKET	8	2	2.1
17:16		6		2.1
8 September, 4:48	MAKET	7	1	7.7
September, 11:59	MAKET	4	3	3.3
12:43		11		5.8
13:25		4		4.4
19 September, 22:47	MAKET	6	1	270.9
22 September, 3:18	MAKET	13	1	5.2
7 October, 9:58	MAKET	12	2	2.6
11:15		17		5.5
9 October, 20:43	MAKET	14	1	3.1
2 November, 13:27	MAKET	7	1	5.8
3 November, 2:27	MAKET	3	1	2.5
15 November, 22:31	MAKET	10	1	4.1

The AMMM detector consists of 5 cm thick 1 m^2 area plastic scintillators located outdoors and in underground hall beneath 14 m of concrete and soil. Upper layer is composed of 29 scintillators; underground detector consists of 90 scintillators of the same type. Count rate of the upper detectors is ~28,000 counts per minute and variance ~170. Count rate of each of 1 m^2 scintillator in the underground hall (for registering high energy muons with energy threshold 5 GeV) is ~3000 counts per minute and variance ~55.

Two standard neutron monitor (NM) of 18NM-64 type consisting of 18 boron-filled proportional chambers, located below 5 cm of lead (producer) and 10 cm of polyethylene (moderator) are operating at Aragats and Nor Amberd research stations.

The new particle detector system, named SEVAN (Space Environmental Viewing and Analysis Network, Chilingarian et al., 2009), simultaneously measures fluxes of most species of secondary cosmic rays, thus representing an integrated device used for the exploration of the solar modulation effects. In Armenia SEVAN modules are installed at all 3 locations, in Yerevan, Nor-Amberd and top of Aragats. The basic detecting unit of the SEVAN module consists from a "sandwich" of two plastic scintilla-

Table 3.1
Characteristics of TGEs registered at Aragats in 2010.

Date, time 2010	Detector	Duration (min)	Number of peaks	Percent of enhancement (%)
16 January, 7:43	MAKET	10	2	6.3
9:56		16		9
19 January, 2:32	MAKET	20	1	6.3
21 January, 9:04	MAKET	21	2	5.3
9:27		16		5.4
16 February, 21:57	MAKET	6	1	8.8
14 March, 22:00	MAKET	3	2	6.2
22:10		3		11
8 April, 9:41	MAKET	2	2	2.7
9:45		2		2.8
13 April, 7:23	MAKET	13	1	3.6
21 April, 16:26	MAKET	11	2	3.5
20:05		12		5.9
22 April, 15:11	MAKET	13	2	3.3
16:21		30		5.8
26 April, 12:19	MAKET	10	2	2.6
12:35		9		3.6
8 May, 17:28	MAKET	5	1	2.5
21 May, 4:15	MAKET	8	2	3.1
13:15		12		4.2
22 May, 6:07	MAKET	9	3	4.8
8:30		6		14.1
11:26		5		2.5
23 May, 0:50	MAKET	26	1	7
25 May, 6:43	MAKET	7	2	3.4
10:55		22		2.5
28 May, 4:45	MAKET	8	1	3.4
7 June, 1:04	MAKET	13	3	3.6
5:20		10		2.5
10:29		15		3
8 June, 14:35	MAKET	14	1	3
19 June, 8:34	MAKET	4	1	4.2
15 July, 16:42	MAKET	19	1	2.4
19 July, 14:02	MAKET	18	1	2.4
22 July, 18:28	MAKET	12	1	3.1
23 July, 14:06	MAKET	10	6	3.7
14:16		10		2.5
16:28		7		3.1
16:44		7		2.4
17:54		10		3.1
18:11		2		2
24 July, 17:37	MAKET	19	3	2.1
17:59		12		1.1
18:32		11		2.5
16 August, 7:00	MAKET	5	2	2
8:47		6		1.7
23 August,17:13	MAKET	10	2	1.7
17:39	MAKET	3		3.1
24 August, 15:34	MAKET	8	1	2.1
26 August, 9:55	MAKET	10	2	2.8
10:50		7		6.3
18 September, 10:53	MAKET	6	3	2
11:15		9		2.8
11:33		17		3.1
25 September, 19:11	MAKET	9	1	2.1

tors of 1 m^2 area and 5 cm thick with a 20 cm thick and 0.25 m^2 area scintillator in between. A scintillator light capture cone and photomultiplier tubes are located on the top, bottom, and inter-mediate layers of the detector. Incoming neutral particles undergo nuclear reactions in the thick 20 cm plastic scintillator and produce protons and other charged particles. In the upper 5-cm thick scintillator, charged particles are registered very effectively; however, for the nuclear or photonuclear interactions of neutral particles there is not enough substance. When a neutral

Table 3.2
Characteristics of TGEs registered at Aragats in 2010.

Date, time 2010	Detector	Duration (min)	Number of peaks	Percent of enhancement (%)
1 October, 0:54	MAKET	8	2	2.3
12:31		3		1.9
3 October, 4:17	MAKET	7	3	2.3
4:28		11		3.7
4:41		11		3.4
4 October, 5:50	MAKET	11	9	2.1
6:32		5		3.9
8:33		5		2
11:48		13		2.7
11:57		5		2.3
18:22		7		98.1
20:28		12		2.3
22:23		3		1.2
22:45		13		4.9
5 October, 1:18	MAKET	8	8	2.3
3:07		8		3.3
8:26		6		3.5
13:34		11		4.9
14:57		4		2.4
16:04		10		2.3
16:14		10		3.1
16:39		5		2.6
6 October, 7:48	MAKET	23	3	5.8
9:46		6		3.9
14:34		8		3.2
10 October, 10:19	MAKET	10	1	14.3
15 October, 12:07	MAKET	12	2	3.6
13:40		11		4.7
16 October, 8:42	MAKET	8	1	2.7
17 October, 14:26	MAKET	12	3	5
14:40		6		5.2
14:45		10		4.2
12 December, 16:08	MAKET	12	1	10.2

particle traverses the top thin (5 cm) scintillator, usually no signal is produced. The absence of the signal in the upper scintillators, coinciding with the signal in the middle scintillator, points to neutral particle detection (gamma ray or neutron). The coincidence of signals from the top and bottom scintillators indicates the traversal of high-energy muons, traversing 10 cm of lead (minimal energy is about 250 MeV).

“STAND” detector (Arakelyan et al., 2013), exclusively designed for the TGE research comprise of three-layer assembly of 1 cm thick 1 m^2 sensitive area molded plastic scintillators one above the other and one 3 cm thick scintillator located aside. Outdoors location, 1-cm thickness and three-layer design allow to measure flux of TGE electrons with 3 different energy thresholds starting from 1.5 MeV and to recover integral spectrum of TGE electrons. Proper tuning of the detector provides 98-99% signal detection efficiency simultaneously suppressing electronic noise down to 1–2%. The DAQ electronics allows measuring and storing all coincidences of the detector channel operation. For instance, coincidence “1 1 1” means that all 3 layers register particle, minimal energy of charged particles giving signal in all 3 layers should be above 10 MeV; coincidence “100” means that only upper detector register particle – the energy threshold of this coincidence is equal ~1.5 MeV. The energy threshold of 3 cm thick scintillators is ~5 MeV.

The Nor Amberd multidirectional muon monitor (NAMMM) consists of two layers of plastic scintillators above and below two of the three sections of the Nor Amberd Neutron Monitor (NANM) 18NM64 (Carmichael, 1964). The lead (Pb) filter of NANM absorbs electrons and low energy muons. The distance between layers is ~1 m. Each layer consists of six detectors of 0.81 m^2 area. NAMMM is hybrid detector measuring neutral and charged CR fluxes. Upper layer of detector measures low energy charged particles, mostly electrons and muons. The energy threshold of the upper scintillators is approximately equal to 7 MeV. Neutron monitor is measuring the secondary neutrons of the cosmic ray flux. The lower layer of the scintillators of NAMMM is sensitive to high-energy muons, since the lead filter absorbs low energy muons and electrons. The energy threshold of the lower scintillators is equal approximately to 250 MeV.

The amplitude of TGE was measured at maximal flux minute relative to the mean value of detector minutely count rate before TGE event started. The enhancement was accepted as genuine TGE only if it was observed by as minimum with 3 independent detectors and the amplitude of signal in each of detectors exceeds 3 standard deviations. Additional necessary condition is large disturbance of the near-surface electrical field.

However, as was discussed in Dwyer et al. (2012a), measurements based solely upon count rates of signals above some discriminator threshold should be viewed with caution, since it is not obvious what is being counted, pulses from energetic particles or, for instance, RF noise from atmospheric discharge processes. To answer if the enhancements in particle detector count rates (peaks in minutely time series) can be due to electromagnetic inferences, we performed in-depth analysis of the enhancements of the ASEC detectors and for each TGE collect evidence demonstrating the existence of the indisputable additional particle fluxes responsible for the detected peaks (see details in the appendix of Chilingarian et al., 2011):

- The distance between AMMM and MAKET detectors is 400 m, detectors operate with fully independent cabling and data acquisition electronics (DAQ), and demonstrate very similar time-coherent patterns of flux enhancements;
- Along with count rates the ASNT DAQ electronics also register energy deposit spectra of PM signals. The TGEs are concentrated only in the region of the small energy deposits. The large energy deposits due to cosmic rays remain unchanged;
- The ASNT detector measures also the incoming directions of the detected particles. The count rates of the near vertical and inclined particles are dramatically dif-

Table 4.1
Characteristics of TGEs registered at Aragats in 2011.

Date, Time2011	Detector	Duration (min)	Number of peaks	Percent of enhancement (%)
4 May, 14:27	MAKET	5	2	4.3
14:34		6		4.5
5 May, 4:43	MAKET	20	1	2.1
7 May, 15:1821:12	MAKET	20	2	4.2
		10		4.1
8 May, 1:47	MAKET	18	3	6.8
10:06		22		6.3
12:50		6		4.9
9 May, 7:44	MAKET	10	2	2.5
9:31		12		5.7
13 May, 10:10	MAKET	11	3	4.5
10:22		1		3.9
10:27		11		5.1
18 May, 22:11	MAKET	16	1	5.3
21 May, 11:57	MAKET	8	5	8.4
12:03		9		9.8
14:36		10		5
15:06		12		3.4
20:38		10		2.6
22 May, 15:15	MAKET	9	1	4.2
24 May, 13:31	MAKET	13	2	3.2
13:45		7		2.3
25 May, 19:07	MAKET	19	1	1.4
27 May, 13:14	MAKET	12	1	21
4 June, 1:45	MAKET	4	1	6.5
7 June, 14:24	MAKET	3	1	2.5
8 June, 11:55	MAKET	14	1	2
9 June, 15:49	MAKET	3	2	1.7
16:08		2		1.5
11 June, 11:54	MAKET	6	1	2.7
12 June, 10:03	MAKET	27	1	4.3
10 July, 22:12	MAKET	9	1	2.5
11 July, 7:46	MAKET	10	3	2.4
8:29		3		2.2
9:53		6		2.3
13 July, 1:09	MAKET	9	2	3.7
6:29		16		2.6
15 July, 21:29	MAKET	9	1	2.4
19 July, 20:11	MAKET	11	1	3.5
22 July, 6:37	MAKET	3	1	2.4
23 July, 13:31	MAKET	8	2	4.3
13:50		13		2.9
16 August, 15:49	MAKET	12	1	1.5
18 August, 15:20	MAKET	19	2	3.9
17:34		8		2.1
19 August, 12:20	MAKET	8	1	3.1
21 August, 11:31	MAKET	3	1	2.6
22 August, 22:19	MAKET	15	1	8.4
3 September, 15:52	MAKET	15	3	2.6
16:57		17		2.2
17:16		6		0.8
15 September, 16:01	MAKET	16	1	3.1

ferent. If we observe huge enhancement in the near vertical direction (expected arrival direction of the TGE particles), in the same time the same detector using the same DAQ electronics and analysis software do not measure any enhancement in the inclined particle flux;

- SEVAN particle detector measures 3 types of particle fluxes: low energy charged particles, neutral particles and high-energy muons ($E_{\mu} > 250$ MeV). During several TGEs we measure deficit of muons and huge peaks in time series of neutral particles and low energy charged particles. All 3 types of particle fluxes are detected by SEVAN detector with one and the same cabling and DAQ electronics.

Nonetheless, we detect some induced signals in a few from hundreds channels of the ASEC detectors. Some of

Table 4.2
Characteristics of TGEs registered at Aragats in 2011.

Date, time 2011	Detector	Duration (min)	Number of peaks	Percent of enhancement (%)
20 September, 9:08	STAND1 3 cm	15	3	2.9
10:28		11		3
13:58		22		5
24 September, 16:14	STAND1 3 cm	35	1	25.7
25 September, 11:37	STAND1 3 cm	24	1	8
28 September, 3:50	STAND1 3 cm	7	1	4.7
30 September, 13:00	STAND1 3 cm	15	2	6.6
13:26		8		5.7
3 October, 8:48	STAND1 3 cm	8	1	3.5
13 October, 5:24	STAND1 3 cm	4	3	2.7
5:30		6		2.5
11:37		16		22.4
16 October, 0:12	STAND1 3 cm	8	1	14.9
17 October, 13:55	STAND1 3 cm	20	1	6.9
19 October, 7:18	STAND1 3 cm	10	1	10.1

Table 5
Characteristics of TGEs registered at Aragats in 2012.

Date, time 2012	Detector	Duration (min)	Number of peaks	Percent of enhancement (%)
5 April, 20:53	MAKET	15	1	1.7
8 April, 0:51	STEND1 3 cm	12	1	2.6
9 April, 2:32	MAKET	15	2	2
3:01		22		1.6
19 April, 11:52	MAKET	16	4	3.1
11:56		5		2.1
13:00		11		1.3
13:16		9		2.3
28 April, 11:33	MAKET	20	2	1.6
12:16		8		1.3
29 April, 12:58	MAKET	15	2	5.2
14:02		12		1.5
11 May, 3:02	STEND1 3 cm	17	1	46.4
12 May, 18:33	STAND1 3 cm	8	1	17.1
13 May,19:22	STAND1 3 cm	22	1	19.1
20 May, 22:22	STAND1 3 cm	10	1	3.2
22 May, 7:26	STAND1 3cm	13	2	8.3
7:36		9		2.8
25 May, 2:32	STAND1 3 cm	11	1	30.3
26 May, 10:22	STAND1 3 cm	9	1	13.2
29 May, 13:56	STEND1 3 cm	9	2	1.9
14:03		7		3
29 June, 15:19	AMMM	14	1	2.6
30 June, 9:22	STAND1 3 cm	19	3	4.3
9:56		11		6
10:10		10		3.6
3 July, 16:44	STAND1 3 cm	32	1	12.8
8 July, 19:03	STAND1 3 cm	4	3	5.2
19:30		17		37.4
20:04		20		9.2
10 July, 1:43	STAND1 3 cm	17	2	3
2:59		9		4.2
4 October, 18:12	STAND1 3 cm	18	3	4.7
18:48		10		4.3
19:33		3		3.4
7 October, 14:12	STAND1 3 cm	17	2	10.8
15:09		15		27.7
8 October, 14:37	STAND1 3 cm	14	4	6.9
16:56		11		16
17:35		17		1.8
21:20		19		7.1
9 October, 11:36	STAND1 3 cm	11	1	4.6

Table 6
Characteristics of TGEs registered at Nor Amberd in 2008–2012.

Date, time (2008–2012)	Detector	Duration (min)	Number of peaks	Percent of enhancement
14 March, 2008, 12:42	NAMMM	4	1	2.97
09 May, 2008, 11:40	NAMMM	12	1	2.47
11 May, 2008, 13:08	NAMMM	4	1	1.33
24 February, 2009, 17:35	NAMMM	10	1	3.89
24 March, 2009, 10:40	NAMMM	2	1	3.25
28 March, 2009, 13:41	NAMMM	9	4	5.94
14:55		11		2.17
17:16		7		3.13
17:50		8		5.5
25 May, 2009, 12:15	NAMMM	13	1	3.57
09 June, 2009, 11:34	NAMMM	7	1	1.74
27 September, 2009, 22:30	NAMMM	7	2	1.76
23:00		17		2.59
25 January, 2010, 13:19	NAMMM	14	1	6.47
16 February, 2010, 22:15	NAMMM	8	1	5.35
22 February, 2010, 3:00	NAMMM	10	1	7.35
30 March, 2010, 19:41	NAMMM	23	1	5.24
20 May, 2010, 17:34	NAMMM	16	1	2.7
11 March, 2011, 15:50	NAMMM	12	1	3.28
10 June, 2011, 22:28	NAMMM	1	1	1.69

Table 7
Characteristics of TGE registered at Yerevan in 2013.

Date, time 2013	Detector	Duration (min)	Number of peaks	Percent of enhancement
8 January, 2013, 04:14	SEVAN	14	1	3.8

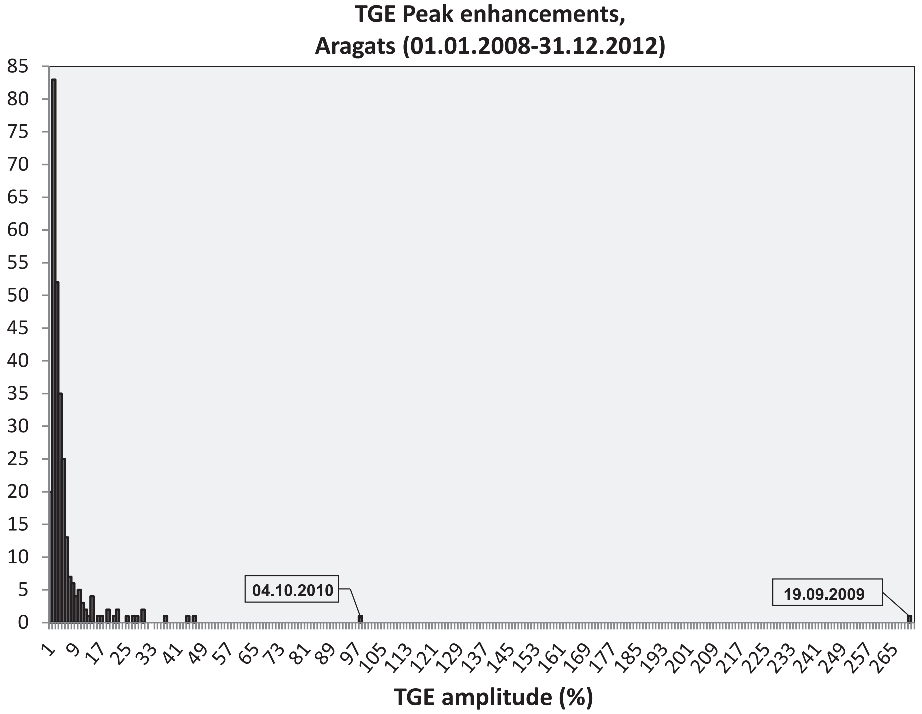

Fig. 1. The histogram of TGE amplitudes registered at Aragats in 2008–2012.

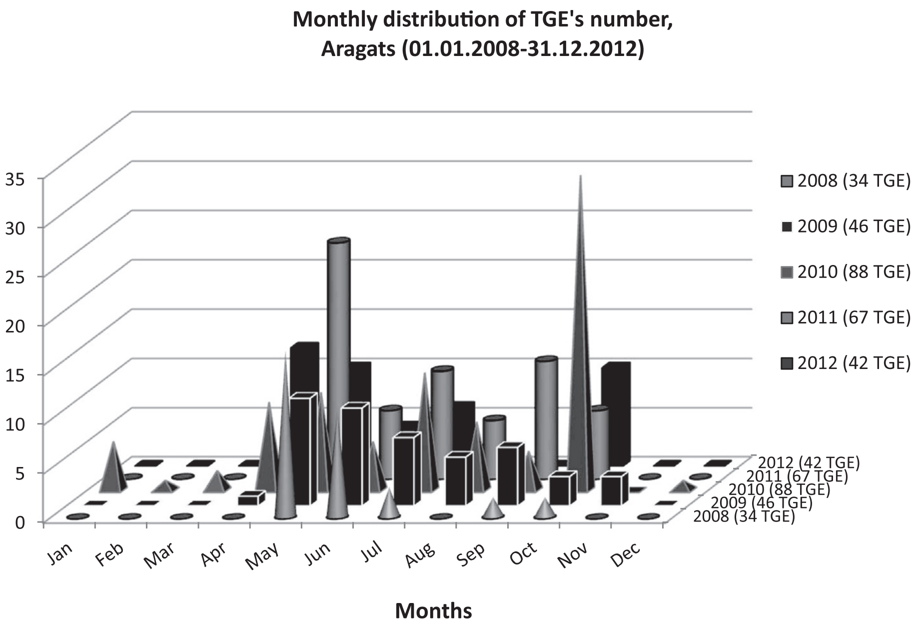

Fig. 2. The monthly distribution of TGE events registered at Aragats in 2008–2012.

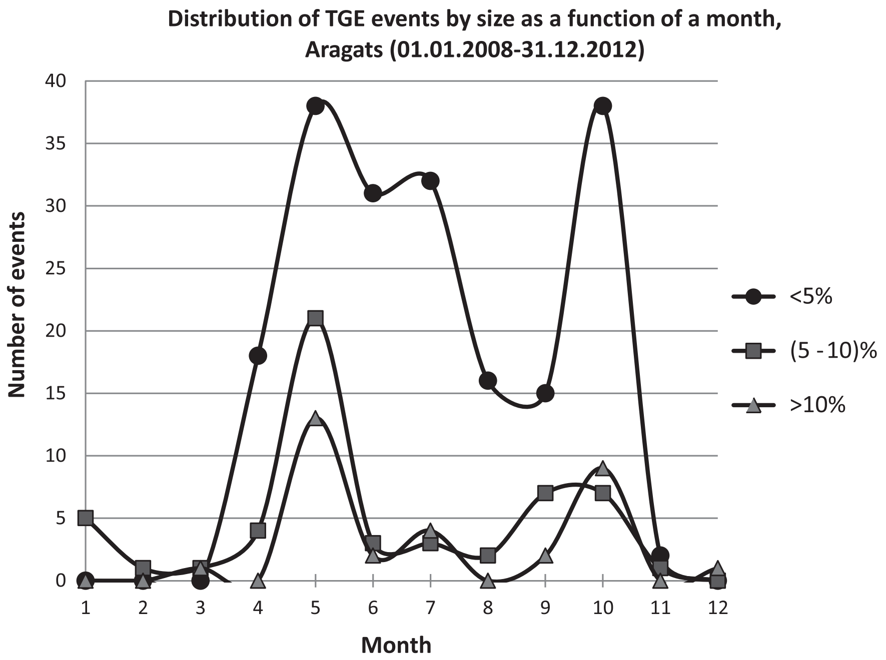

Fig. 3. Distribution of TGE events by enhancement size at Aragats in 2008–2012.

detectors were bad grounded, or some of cables had bad isolation and the radio signals from atmospheric discharges induced peaks in these channels. Lightning induced signals have very specific shape and fallow the pattern of the lightning activity, now also monitored by the BOLTEK company lightning detectors. Due to strictly different duration of TGEs (tens of minutes) and atmospheric discharges (hundreds of milliseconds) it is very easy to outline fake peaks in the time series of particle detectors. Moreover during TGEs the lightning activity strictly decreases and most powerful cloud-to-ground lightnings are suppressed (Chilingarian and Mkrtchyan, 2012).

3. Statistical analysis of the registered TGEs

In 2008–2012 at Aragats were registered 277 TGEs. For estimating the amplitude of TGEs we use identical 5 cm thick 1 m^2 area outdoor plastic scintillators of MAKET and AMMM detectors. In 2012 the data from 3 cm thick outdoor plastic scintillator was used due to failure of

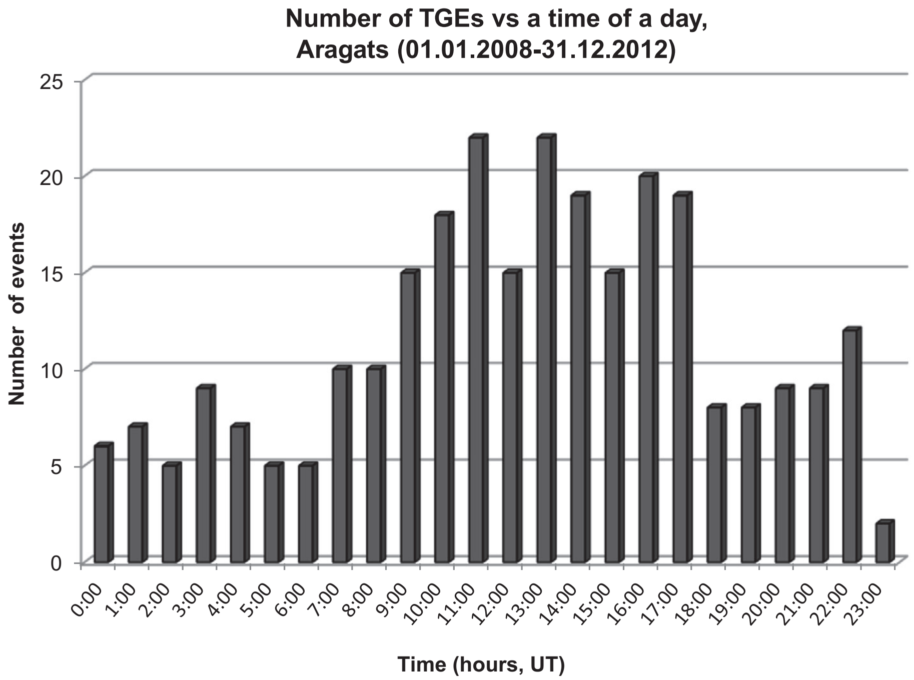

Fig. 4. Distribution of TGE events as a function of a time of a day at Aragats in 2008–2012.

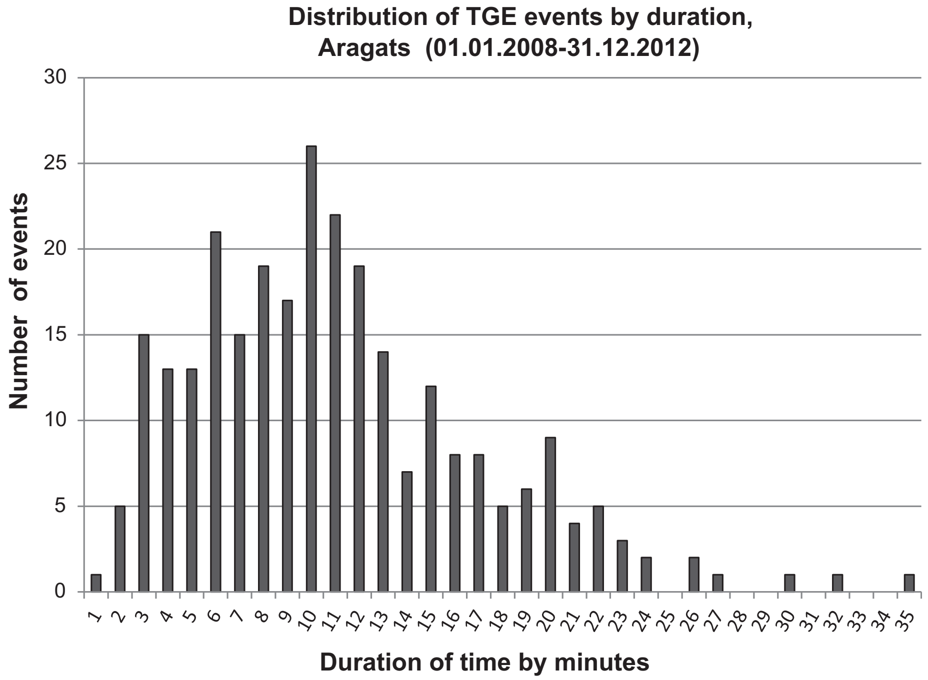

Fig. 5. Distribution of TGE events by duration at Aragats in 2008–2012.

MAKET and AMMM detectors after strong lightning. The flux enhancement is presented by percent relative to rather stable background of secondary cosmic rays. As we can see from Fig. 1 the majority of TGEs have amplitudes less than 10%. The dates of 2 largest TGE events are displayed as boxed text. The amplitude of TGE depends on many factors that are very difficult to measure or estimate. First of all it is structure and strength of electric field in the thundercloud. Starting from 2011 at all 3 sites the monitoring of the near surface electric field is performed with electric mills produced by the BOLTEK Company.[1] It allows outlining 4 patterns of electric field giving rise to TGEs (Chilingarian and Mkrtchyan, 2012). How-

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[1] BOLTEK's electrical mill EFM-100, measurement accuracy 5%, details in http://www.boltek.com/efm100.html.

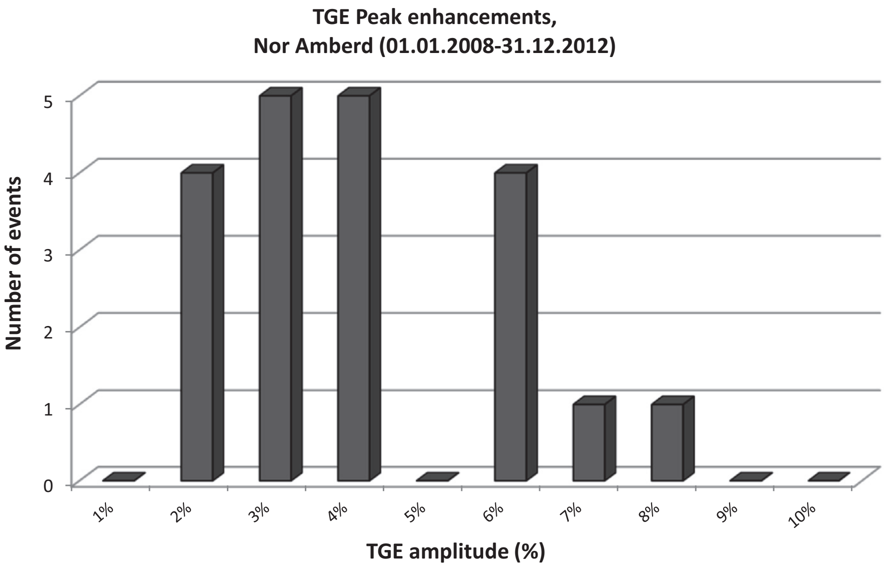

Fig. 6. The histogram of TGE amplitudes registered at Nor Amberd in 2008–2012.

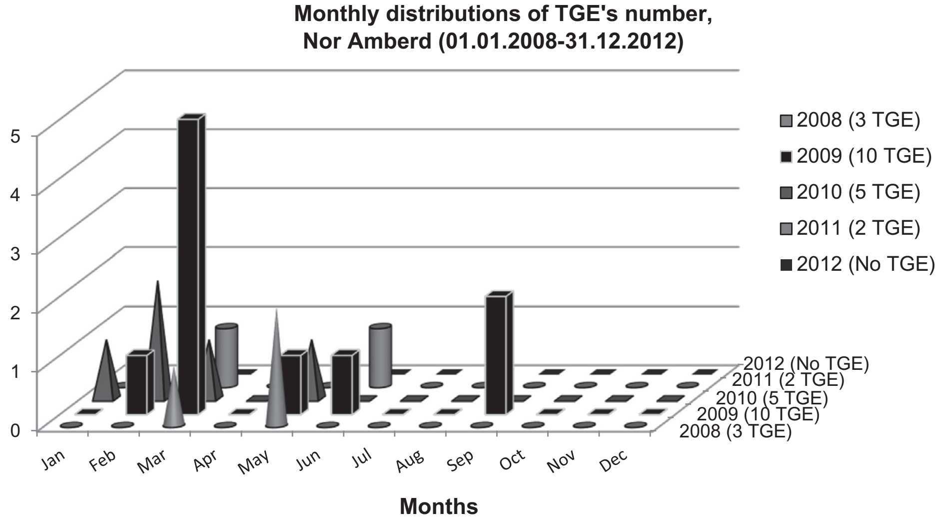

Fig. 7. The monthly distribution of TGE events registered at Nor Amberd in 2008–2012.

ever, although there should be a correlation between measured near-surface electric field and electric field in the thundercloud it is not possible to recover intracloud electric field by measurements of near surface field. Unknown parameters affecting the near surface electric field are the topology of electric field in the thundercloud and location of the cloud relative to detectors. We adopt the tripole structure of electric field with positive dipole between main negative charged layer in the middle of the thundercloud and smaller Lower Positive Charge Region (LPCR) sitting in the bottom of thundercloud. Lower dipole accelerates electrons downward, runaway electrons initiate cascades, and, if thundercloud low above the Earth's surface the particle detectors register enhancement of secondary cosmic rays above stable background initiated by the ambient flux of galactic cosmic rays incident on the terrestrial atmosphere.

In the Fig. 2 we can observe 2 high frequency clusters of events on April–May and October (especially in 2010). These months coincide with maximum of thunderstorm activity at Aragats. However, even in January there were detected particle fluxes from thunderclouds. The distribution of TGEs by amplitude also demonstrates maximums in April–May and October (see Fig. 3); however, the largest events were detected in September 2009 and October 2010.

In the Fig. 4 we can see that TGEs mostly happen in day-evening time: from 9 till 17 UT (13–22 local time).

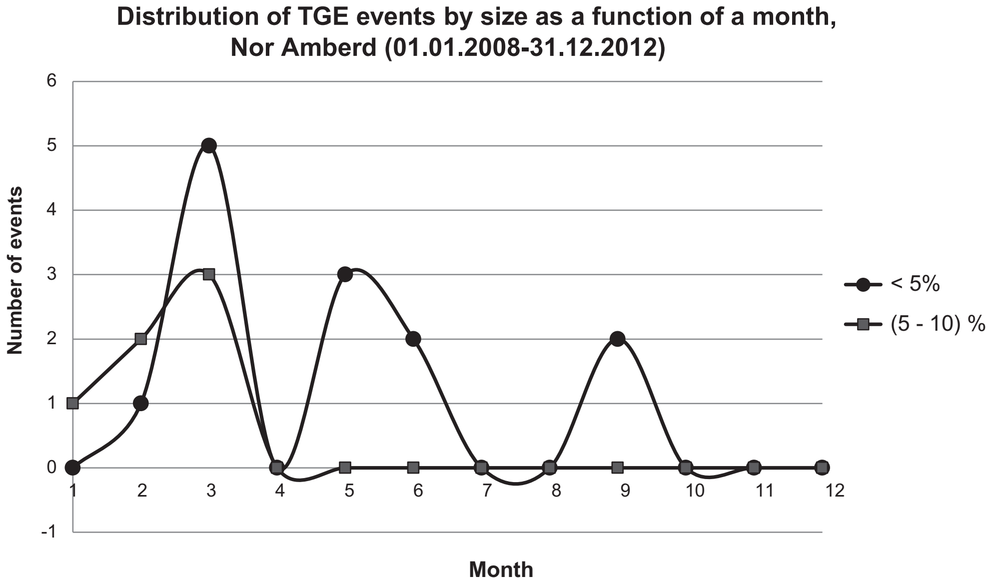

Fig. 8. Distribution of TGE events by enhancement size at Nor Amberd in 2008–2012.

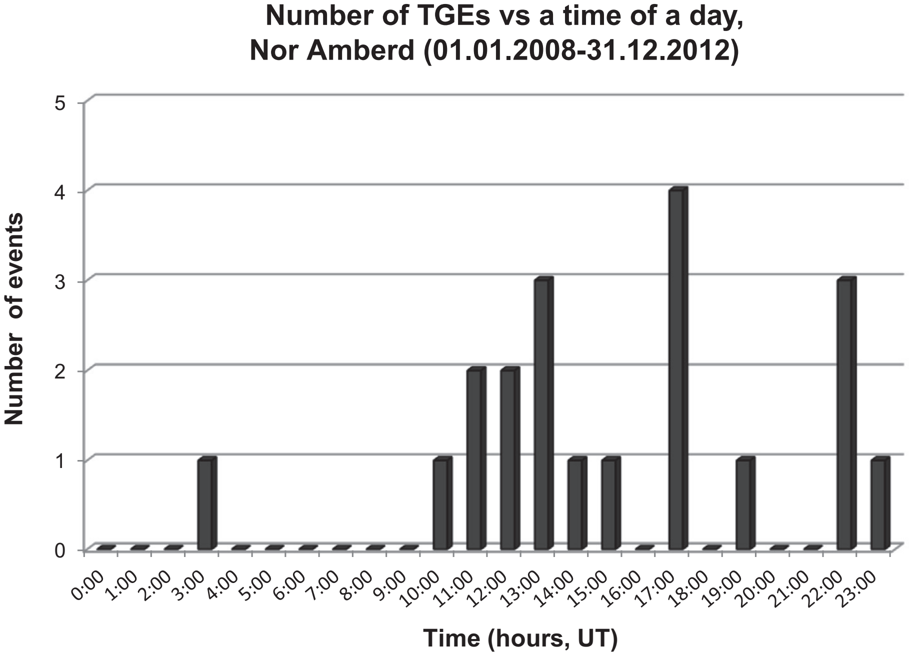

Fig. 9. Distribution of TGE events as a function of a time of a day at Nor Amberd in 2008–2012.

The mean duration of TGEs is ~10 min (see Fig. 5); sometimes it prolonged up to half-an-hour and more.

There are much less TGEs detected in Nor Amberd, comparing with Aragats. Although the thunderstorm activity in both locations is about the same, the topography of Nor Amberd destination doesn't allow thunderclouds to descend down near to detectors. Unlike Aragats station located on broad highland near large lake, Nor Amberd station is located near sharp uprising of mountain preventing low location of clouds.

At Nor Amberd by 5 cm thick scintillators detected only 20 TGEs in 2008–2012 (compare with 277 at Aragats in the same years). 14 events have amplitude lower than <5%, and 6 events – amplitude of above 5%. The maximal value of observed enhancements was 8.6%. In the observed years the most productive months were March and May. The maximum number of TGE events was detected in March 2009. In the Fig. 6 is presented the histogram of 20 TGEs' registered by 5 cm thick scintillators of NAMMM in 2008–2012.

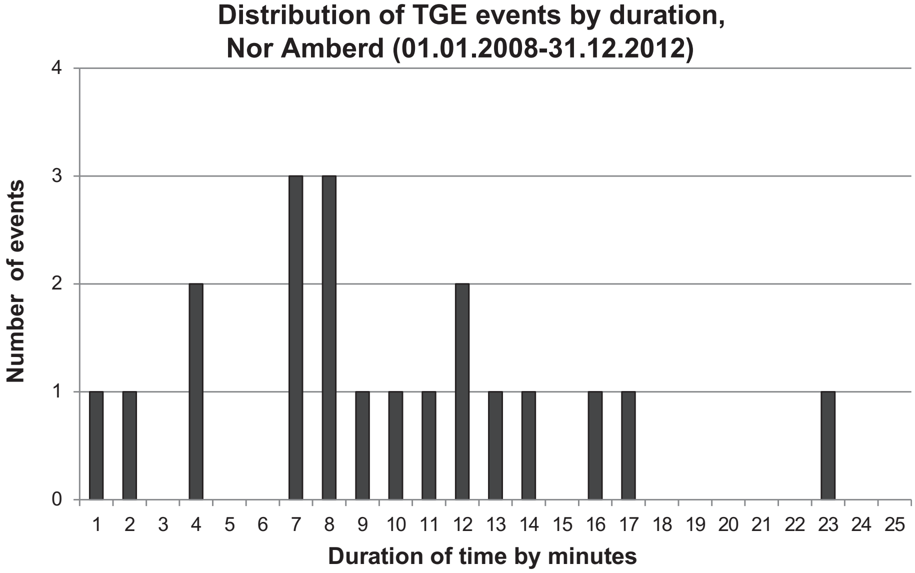

Fig. 10. Distribution of TGE events by duration at Nor Amberd in 2008–2012.

In the Fig. 7 we can detect high frequency of TGE events on March 2009. This month coincide with strong thunderstorm activity at Nor Amberd. However, even in January there were detected particle fluxes from thunderclouds.

The distribution of TGEs by amplitude demonstrates maximum in March (see Fig. 8).

The distribution of the daytime of Nor Amberd TGEs presented in Fig. 9, demonstrates that the most probable time is shifted to evening–night local times comparing with Aragats TGEs. The Fig. 10 demonstrates that mean duration of TGEs is ~10 min compatible with duration of Aragats TGEs.

4. Conclusion

In years of low solar activity 2008–2012 Aragats Space Environmental Center particle detectors located at Aragats, Nor Amberd and Yerevan have measured ~300 Thunderstorm Ground Enhancements (TGEs), thus proving existence of the new high-energy phenomena in the terrestrial atmosphere.

Several papers were published based on the collected TGEs' exploring characteristics of emerging in thunderclouds electron, gamma ray and neutron fluxes (Chilingarian et al., 2010, 2011, 2012a,b; Chilingarian, Mailyan et al., 2012; Chilingarian and Mkrtchyan, 2012).

190 events from 277 at Aragats, have amplitude less than 5%, 55 events have amplitude between 5% and 10% and 32 events have amplitude greater than 10%. Only 13 TGEs have amplitude exceeding 20%. The maximal value of observed enhancement was 271% (September 19, 2009) and the minimal registered – 0.8%. In the observed years the most productive months were: May and June in 2008, May–July in 2009. The maximum number of TGE events was detected in October 2010. TGEs at Aragats mostly happen in day-evening time: from 9 till 17 UT (13–22 local time). The mean duration of TGE is ~10 min; sometimes it prolonged up to half-an-hour and more. 14 events from 20 at Nor-Amberd, have amplitude lower than <5%, and 6 events – amplitude of 5 ÷ 10%. The maximal value of observed enhancement was 8.6% and minimal value was 1.33%. In the observed years the most productive months were March and May. The maximum number of TGE events was detected in March 2009. The most probable time is evening–night by local time and the mean duration of TGE is ~10 minutes compatible with duration of Aragats TGEs. Amplitude of only one event registered at Yerevan is 3.8%. The duration of TGE was 14 min.

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