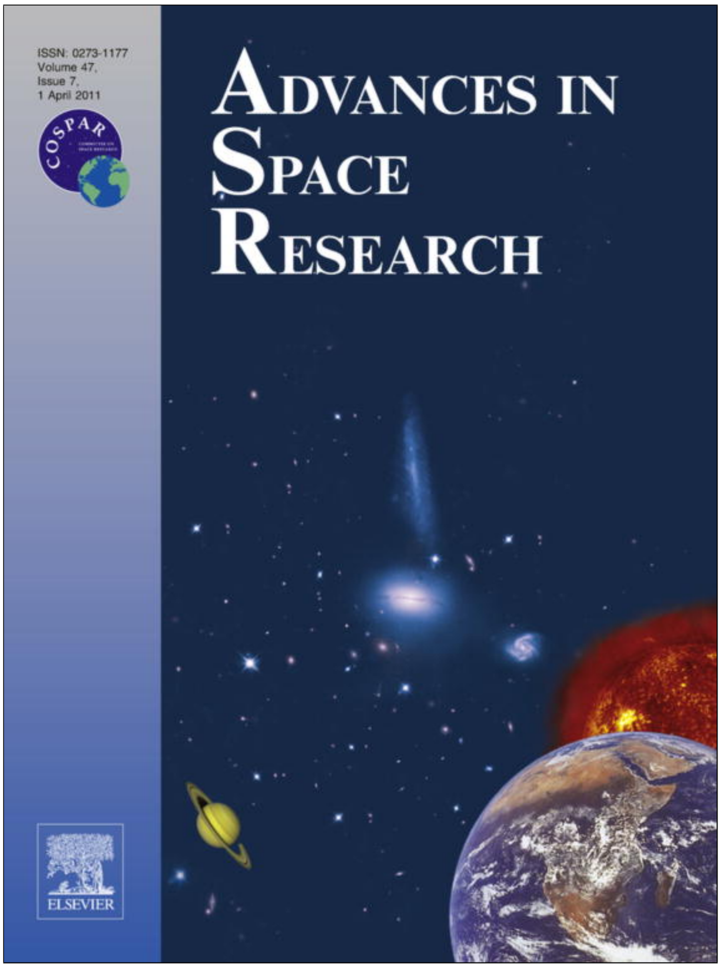
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Calculation of the barometric coefficients at the start of the 24th solar activity cycle for particle detectors of Aragats Space Environmental Center

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Abstract

After the major modernization of the data acquisition electronics of the particle detectors operated at Aragats Space Environmental Center (ASEC) calculations of the barometric coefficients of all the monitors were performed in the beginning of the 24th solar activity cycle. The barometric coefficients of particle detectors located at altitudes of 1000 m, 2000 m and 3200 m a.s.l. measuring various secondary cosmic ray fluxes were compared with theoretical expectations and monitors operated on different longitudes and latitudes. The barometric coefficients were also calculated for the several neutron monitors of recently established Eurasian database (NMDB) and SEVAN particle detector networks. The latitude and altitude dependencies of the barometric coefficients were investigated, as well as the dependence of coefficients on energy of the primary particles.

Keywords: Barometric coefficients; Neutron monitors; Cosmic rays

1. Introduction

Particle detectors of the Aragats Space Environmental Center (ASEC) (Chilingarian et al., 2003, 2005) are located on the slopes of the mountain Aragats and in CRD headquarters in Yerevan, Armenia; geographic coordinates: 40°30′N, 44°10′E, altitudes – 3200 m, 2000 m and 1000 m a.s.l. Various ASEC detectors, measuring fluxes of secondary cosmic rays, are sensitive to different energetic populations of primary cosmic rays. Two neutron monitors of 18NM64 type operate at Nor-Amberd and at Aragats research stations (further denoted as NANM and ARNM) detect secondary neutrons. The Nor-Amberd muon multidirectional monitor (NAMMM) detects low energy secondary charged particles and secondary muons with energies above 250 MeV. The Aragats Multidirectional Muon Monitor (AMMM) registers high energy secondary muon flux (threshold energy – 5 GeV). The Aragats Solar Neutron Telescope (ASNT) measures secondary neutral and charged particles. ASNT is a part of the world-wide network coordinated by the Solar-Terrestrial Laboratory of the Nagoya University. Another monitoring system, based on the scintillation detectors of the Extensive Air Shower (EAS) surface arrays, MAKET-ANI and GAMMA (3200 m a.s.l.), detects low energy secondary charged particles. The new world-wide SEVAN particle detector network at present operates in Armenia, Bulgaria and Croatia (Chilingarian and Reymers, 2008; Chilingarian et al., 2009). SEVAN detectors measure low energy secondary charged particles, neutral particles (gammas and neutrons) and high energy secondary muons. NAMMM and ASNT measuring channels are equipped with Amplitude-to-Digital (ADC) convertors and micro controller based advanced electronics. Data Acquisition (DAQ) electronics and flexible software triggers allow to register not only the count rates of the detector channels, but also the histograms of energy releases; correlations of the charged and neutral fluxes; and many other physical

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phenomena. Details of detector operation can be found in Chilingarian et al. (2007) and Arakelyan et al. (2009).

There is overall understanding that networks of particle detectors located at the Earth's surface can provide forecasting and alert on upcoming solar storms based on the modulation effects that solar activity superimposed on the rather stable flux of galactic cosmic rays (CR). For reliable and timely forecast we need adequate models of the major solar energetic events in progress. The information on the highest energy solar cosmic rays, available from surface based particle detectors, can be used to test such models and to obtain overall knowledge on the particle acceleration in flares and by fast shock blasts; on transient modulation effects posed by sun on the galactic cosmic ray (GCR) flux; on the interactions of solar wind with magnetosphere; on the dynamics of the magnetosphere and many others.

Cosmic ray flux incident on the terrestrial atmosphere and measured elementary particles on the Earth surface comprise very different entities although genetically connected with each other. Primary particles interactions with atmospheric nuclei and different meteorological effects can hide genuine variations of the primary flux and hinder the understanding of dynamics of ongoing physical processes in the solar-terrestrial chain. To recover the primary particles fluxes incident on the Earth's atmosphere it is necessary to know the relationship between observed count rates of the detectors and the primary particles fluxes, as well as the influence of the meteorological effects on the flux of secondary particles reaching the Earth surface. Dorman's theory of meteorological effects (Dorman, 2004) gives the detailed classification of the effects; it mentioned the barometric one as major influencing particle fluxes. Therefore, it is the greatest importance to accurately measure the barometric coefficients to "unfold" the solar modulation effects. Besides this main goal there exists several independent research problems connected with rigidity, height and solar cycle phase dependence of the barometric coefficient. All these dependences can be investigated at ASEC and by SEVAN network due to different altitudes, various cutoff rigidities and planned long-term operation.

At the minimum of solar activity, the GCR flux is enriched by abundant low energy (below 10 GeV) particles, blown out from solar system by intense solar wind at maximum of solar activity. Particle detectors located at high latitudes are sensitive to lower primary energies as compared with detectors located at middle – low latitudes, because of lower cutoff rigidity. Detectors located at high altitudes are sensitive to lower primary energies and register more cascade particles than sea level detectors. Detectors registering muons are sensitive to higher energies of primary particles compared with detectors measuring neutrons. Thus, the following relations between barometric coefficients of various particle detectors located in different places and measuring diverse species of secondary CR can be expected:

1. Barometric coefficient absolute value for the same secondary particle flux is greater for detectors located at high latitudes as compared with low latitudes;
2. Barometric coefficient absolute value for the same secondary particle flux should be greater at minimum of solar activity as compared with maximum;
3. Barometric coefficient absolute value for the same secondary particle flux should be greater for high mountain altitudes as compared with lower locations;
4. Barometric coefficient absolute value should be larger for neutrons as compared with muons;
5. Barometric coefficient absolute value should be larger for low energy muons as compared with high energy muons;
6. Barometric coefficient absolute value should be inverse proportional to zenith angle of incident particle flux;
7. Barometric coefficient absolute values should be lower for the greater dead times of neutron monitor.

All the mentioned dependences were investigated and discovered during the last 50 years by the networks of neutron monitors and muon detectors (Dorman, 2004). However, due to the peculiarities of detection techniques, scarce statistics, highly different local meteorological conditions, cycle to cycle variations of solar activity the obtained results on the mentioned dependencies are yet more qualitative and additional investigations of the interrelations of barometric coefficients are needed. ASEC provides ideal platform for such researches.

The ASEC neutron monitors (NM) are equipped with new electronics providing registration of the 3 time series with 3 electronic dead times (Arakelyan et al., 2009). The first dead time equals to 0.4 μs for collecting almost all secondary neutrons generated in the lead of NM, entering proportional chamber and interacting with gaseous boron. The second dead time is equal to 250 μs and the third one equals to 1250 μs. Analysis of the 3 time series of the one and the same NM and comparison of 2 monitors' data located at 2 altitudes will be presented in the paper. Barometric coefficients of all 6 time series are calculated and compared. The muon detectors located at ASEC provide high precision online measurement of 1 min and 10 s time series of low and high energy muon flux. The relative error of 1 min time series varies from 0.18% to 0.6%; median energy of primary protons – from 10 till 20 GeV, see details in Zazyan and Chilingarian (2009). Also there are possibilities to measure muon flux under different angles of incidence. Thus, with data from ASEC monitors we can investigate almost all relations mentioned above. We include in our analysis data from SEVAN (Chilingarian and Reymers, 2008; Chilingarian et al., 2009) network and data from some high latitude neutron monitors from NMDB data base (Klein et al., 2009).

The paper is organized in the following way: the second chapter will explain the statistical techniques used for the barometric coefficient calculations; Section 3 will present the barometric coefficients obtained for ASEC monitors at the end of 23rd cycle – beginning of the 24th solar cycle; in Section 3 we will compare our results with previously obtained data and will check consistency of obtained results with expectations, enumerated in the points 1–7 above (the point 2 will be answered only after finishing of the 24th solar activity cycle).

2. Regression methods used for the barometric coefficient calculation

The estimate of the barometric coefficient β can be found by liner correlation between intensity of cosmic-rays I_i and corresponding data of atmospheric pressure P_i (Dorman, 1974).

$$\beta = r \cdot \sigma_I / \sigma_p, \tag{1}$$

where

$$\sigma_I^2 = \sum_{i=1}^{N} (I_i - I_0)^2 \Big/ N; \quad \sigma_P^2 = \sum_{i=1}^{N} (P_i - P_0)^2 \Big/ N;$$

$$I_0 = \sum_{i=1}^{N} I_i \Big/ N; \quad P_0 = \sum_{i=1}^{N} P_i \Big/ N;$$

$$r = \sum_{i=1}^{N} (I_i - I_0)(P_i - P_0) \Big/ \sigma_I \sigma_P N.$$

The error of estimation β can be calculated as follows:

$$\frac{\Delta\beta}{\beta} = \pm \frac{1}{r} \sqrt{\frac{1 - r^2}{N - 3}}. \tag{2}$$

Data for calculation of barometric coefficients of ASEC monitors were selected in 2008, when there were higher than 15 mb continuous changes of atmospheric pressure during the day, and also there were not disturbances of the Interplanetary Magnetic Field (day variations do not exceed 1.5–2 nT). The values of the IMF were obtained from instrument SWEPAM, Advanced Composition Explorer (ACE) spacecraft (http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_MAG.html).

The least square method was used to obtain the regression coefficients. Large values of the correlation coefficient prove the correct selection of the reference data.

In Table 1 we summarize the calculated barometric coefficients of ASEC monitors. In the columns accordingly are posted the altitude; cutoff rigidity; barometric coefficient; goodness of fit in the form of the correlation coefficient; count rate; relative error; "Poisson" estimate of relative error (standard deviation divides by average count rate).

The values posted in the last two columns should be very close to each other if the particle arrival can be described by the Poisson process. Any small deviation manifested the correlation between detector channels; any large correlation – failures in electronics or data acquisition software.

The shortest dead time collected all secondary neutrons generated in lead by primary hadrons. As it was demonstrated in Chilingarian and Hovhannisyan (2009), genetically related secondary neutrons can be registered in neighboring channels of the monitor if the dead time is about ~1 ms.

Therefore, due to this embedded correlation "Poisson" and measured relative errors for the shortest dead time deviated from each other. When enlarging the dead time, the one-to-one relation between high energy hadron entering the detector and detector count is established, inter-channel correlation vanishes and Poisson and measured relative errors get equal.

In Table 2 we present barometric coefficients for SEVAN detectors located in Aragats and in Yerevan (Chilingarian and Reymers, 2008; Chilingarian et al., 2009). SEVAN detectors comprise of 3 scintillators inter-layered with lead filters. The middle thick layer is sensitive to the neutral particles. Analyzing the outputs from each layer we can outline different species of the particles incident on the detector. For instance, by combination (0 1 0 – signal only in the middle scintillator) neutral particles "are selected". Probability of a neutral particle to give a signal in the upper 5 cm. Thick scintillator is less than 5%; and – the probability that a neutron will give a signal in the middle 25 cm, thick scintillator is ~25%. The combination (1 1 1 signals in all scintillators) "selects: muons with energies greater than 250 MeV – the energy necessary to cross 10 cm of lead".

In Table 3 we compare barometric coefficients of neutron monitors from Neutron Monitor Data Base (NMDB) (Klein et al., 2009) a new European project which objective is to collect and present minute data from Eurasian detectors. The cutoff rigidities of selected monitors, ranging from 0.81 to 8.72 GV, give good representation of the network.

3. Discussion

Large range of the barometric coefficient values, covering approximately one order of magnitude, from 0.08% for the >5 GeV muon flux till 0.73% for the neutron flux, demonstrate unique sensitivity of ASEC detectors to primary rigidities from 7 to 20 GV (median values of the primary proton energy distributions for Aragats neutron monitors and Aragats underground muon detector, calculated in Zazyan and Chilingarian (2009)).

As we expected the barometric coefficients of ARNM are systematically larger than barometric coefficients of NANM (point 1 of the relations list in Section 1). The additional information on 3 different dead times of NMs provides possibilities to access different primary energies. Indeed, from Fig. 1 we can see that for both ARNM and NANM larger dead times are correspondent to smaller barometric coefficients, i.e. to higher primary energies. As it was expected the absolute value of barometric coefficients increase with decreasing dead time, because of increasing sensitivity to lower energy primaries more influenced by pressure changes (point 7). In Fig. 1 is additionally depicted barometric coefficient obtained from data of

Table 1
Barometric coefficients, count rates and relative errors of ASEC monitors.

Monitor	Altitude (m)	Rc (GV)	Barometric coefficient (%/mb)	Correlation coefficient	Count rate (min)	Relative error	$\frac{1}{\sqrt{N}}$
Aragats neutron monitor (**18NM64**) 0.4 µs	3200	7.1	-0.730 ± 0.018	0.997	43954	0.007	0.0047
Aragats neutron monitor (**18NM64**) 250 µs	3200	7.1	-0.713 ± 0.018	0.997	39654	0.006	0.0050
Aragats neutron monitor (**18NM64**) 1250 µs	3200	7.1	-0.688 ± 0.018	0.996	35911	0.005	0.0052
Nor Amberd neutron monitor (**18NM64**) 0.4 µs	2000	7.1	-0.695 ± 0.013	0.997	28508	0.009	0.0059
Nor Amberd neutron monitor (**18NM64**) 250 µs	2000	7.1	-0.678 ± 0.012	0.997	24988	0.009	0.0063
Nor Amberd neutron monitor (**18NM64**) 1250 µs	2000	7.1	-0.670 ± 0.021	0.995	22561	0.008	0.0066
Nor Amberd neutron monitor without lead (2 counters)	2000	7.1	-0.698 ± 0.031	0.989	683	0.038	0.0383
Nor Amberd multidirectional muon monitor (Section 1) (upper layer) $E > 7$ MeV	2000	7.1	-0.324 ± 0.012	0.992	81557	0.004	0.0035
Nor Amberd multidirectional muon monitor (Section 1) (lower layer) $E > 250$ MeV	2000	7.1	-0.223 ± 0.013	0.987	44420	0.006	0.0047
Nor Amberd multidirectional muon monitor (Section 2) (upper layer) $E > 7$ MeV	2000	7.1	-0.323 ± 0.013	0.991	81548	0.004	0.0035
Nor Amberd multidirectional muon monitor (Section 2) (lower layer) $E > 250$ MeV	2000	7.1	-0.225 ± 0.013	0.987	44423	0.006	0.0047
Aragats multichannel muon monitor $E\mu > 5$ GeV	3200	7.1	$-0.08 \pm 7.6\mathrm{E}{-05}$	0.924	267589	0.0018	0.0019
Aragats Solar Neutron Telescope (5 cm)	3200	7.1	-0.507 ± 0.022	0.994	96721	0.003	0.0023
Aragats Solar Neutron Telescope (60 cm)	3200	7.1	-0.427 ± 0.017	0.994	175372	0.005	0.0035
Aragats SEVAN upper detector	3200	7.1	-0.466 ± 0.018	0.994	20768	0.005	0.0069
Aragats SEVAN middle detector	3200	7.1	-0.406 ± 0.012	0.996	6573	0.011	0.0123
Aragats SEVAN lower detector	3200	7.1	-0.361 ± 0.016	0.992	12481	0.008	0.0089
Nor Amberd SEVAN upper detector	2000	7.1	-0.274 ± 0.016	0.975	9100	0.011	0.0105
Nor Amberd SEVAN middle detector	2000	7.1	-0.342 ± 0.023	0.969	3988	0.015	0.0158
Nor Amberd SEVAN lower detector	2000	7.1	-0.262 ± 0.017	0.973	5103	0.014	0.0141
Yerevan SEVAN upper detector	1000	7.1	$-0.251 \pm 7.85\mathrm{E}{-05}$	0.994	14815	0.008	0.0082
Yerevan SEVAN middle detector	1000	7.1	-0.238 ± 0.014	0.981	3414	0.016	0.0171
Yerevan SEVAN lower detector	1000	7.1	-0.190 ± 0.025	0.903	9505	0.011	0.0102

Table 2
Barometric coefficients, count rates and relative errors of SEVAN monitors for different coincidences.

Monitor	Altitude (m)	Rc (GV)	Barometric coefficient (%/mb)	Correlation coefficient	Count rate (min)	Relative error	$\frac{1}{\sqrt{N}}$
Aragats SEVAN low energy charged particles (coincidence 1 0 0)	3200	7.1	-0.5 ± 0.018	0.995	15389	0.007	0.0080
Aragats SEVAN high energy muons (coincidence 1 1 1 + coincidence 1 0 1)	3200	7.1	-0.351 ± 0.038	0.96	3868	0.014	0.0161
Aragats SEVAN neutrons (coincidence 0 1 0)	3200	7.1	-0.511 ± 0.018	0.995	1959	0.019	0.0225
Nor Amberd SEVAN low energy charged particles (coincidence 1 0 0)	2000	7.1	-0.281 ± 0.022	0.957	5941	0.013	0.0129
Nor Amberd SEVAN high energy muons (coincidence 1 1 1 + coincidence 1 0 1)	2000	7.1	-0.242 ± 0.022	0.952	1988	0.026	0.0224
Nor Amberd SEVAN neutrons (coincidence 0 1 0)	2000	7.1	-0.54 ± 0.070	0.899	674	0.037	0.0385
Yerevan SEVAN low energy charged particles (coincidence 1 0 0)	1000	7.1	-0.3 ± 0.014	0.987	9446	0.010	0.0102
Yerevan SEVAN high energy muons (coincidence 1 1 1 + coincidence 1 0 1)	1000	7.1	-0.149 ± 0.035	0.765	4714	0.015	0.0145
Yerevan SEVAN neutrons (coincidence 0 1 0)	1000	7.1	-0.4 ± 0.039	0.943	425	0.048	0.0485

2 proportional counters without lead filters located in Nor Amberd. As it was expected, these chambers are most influenced by atmospheric pressure, due to their sensitivity to the lowest energy atmospheric neutrons.

To observe the dependence of the barometric coefficient for neutron component on cutoff rigidity Rc (Bachelet et al., 1965a,b,c; Dorman et al., 1968; Alania et al., 1968) and also for comparison with barometric coefficients calculated by Dorman et al. (1968), barometric coefficients were calculated for stations located at different altitudes and having different apparent cutoff rigidities (presented in Table 3). In Fig. 2 we post the barometric coefficients of ARNM (18NM64) and NANM (18NM64), IZMIRAN (Moscow, 24NM64), Oulu (Finland, 9NM64), Rome (Italy,

Table 3
Barometric coefficients, count rates and relative errors of Nor Amberd, Aragats, IZMIRAN (Moscow), Oulu (Finland), Rome (Italy) and Athens neutron monitors, data from NMDB.

Monitor	Altitude (m)	Rc (GV)	Barometric coefficient (%/mb)	Correlation coefficient	Count rate (min)	Relative error	$\frac{1}{\sqrt{N}}$
Nor Amberd neutron monitor (**18NM64**) 0.4 μs	2000	7.1	-0.695 ± 0.013	0.997	28508	0.009	0.0059
Aragats neutron monitor (**18NM64**) 0.4 μs	3200	7.1	-0.730 ± 0.018	0.997	43954	0.007	0.0047
IZMIRAN (Moscow) neutron monitor (**24NM64**)	200	2.46	$-0.74 \pm 5.11\text{E}-05$	0.999	16054	0.012	0.0078
Oulu (Finland) neutron monitor (**9NM64**)	0	0.81	$-0.757 \pm 3.37\text{E}-05$	0.999	5990	0.019	0.0129
Rome (Italy) neutron monitor (**17NM64**)	60	6.32	$-0.719 \pm 3.25\text{E}-05$	0.999	9180	0.016	0.010
Athens neutron monitor (**3NM64**)	40	8.72	-0.694 ± 0.021	0.994	9180	0.027	0.017

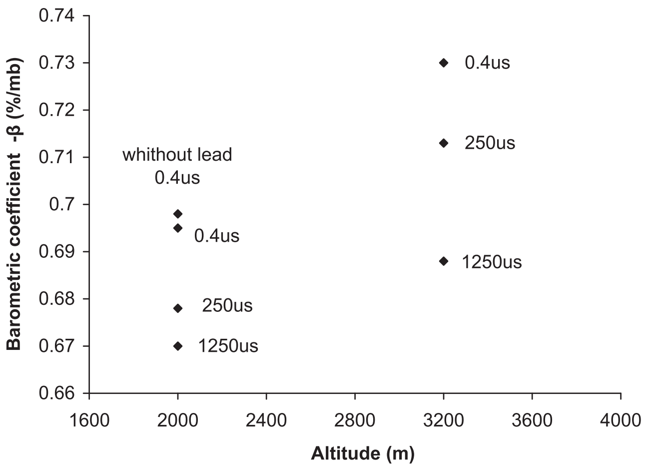

Fig. 1. Comparison of the barometric coefficients for NANM (2000 m) and ARNM (3200 m) calculated for different dead times.

17NM64) and Athens (3NM64) neutron monitors which were calculated by 2008 year data. The barometric coefficients of these monitors, included in NMDB data base (http://www.nmdb.eu), are compared with barometric coefficients for NM64 type neutron monitors calculated by (Dorman et al., 1968). They use 22 NMs from worldwide network and each triangle in Fig. 2 represents mean value of the barometric coefficient averaged by the groups of stations with close rigidities. For the 2008 data we use dead time equal to 1250 μs, the value commonly used in the world-wide network of neutron monitors in 60th. Both series of calculations were performed at years of solar activity minimum and are very close to each other. Calculated barometric coefficients, as we can see in Fig. 2, increase with the decrease of cutoff rigidity, thus proving overall expectation of latitude/rigidity dependence formulated in the point 1 of relations list. Also, in Fig. 2 we can see that the relation of the barometric coefficients for the Aragats monitors located at same latitude, but different altitudes is corresponding to the expectations of point 3 of the list in Section 1, i.e. higher location of the same type of monitor is corresponding to the larger absolute value of the barometric coefficient.

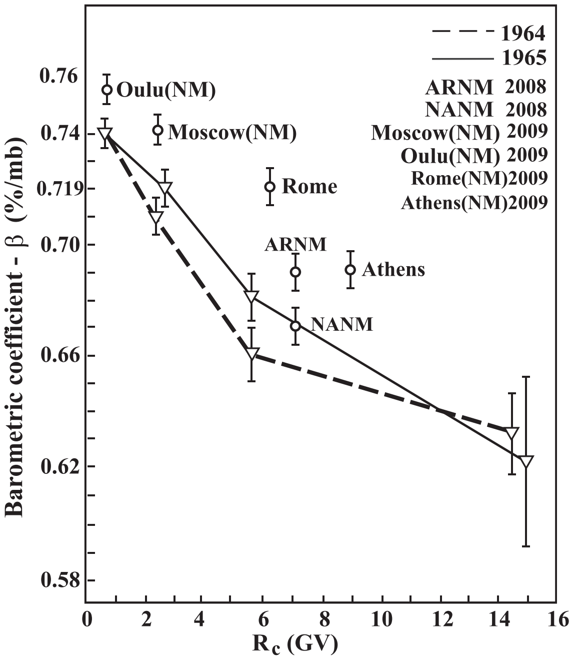

Fig. 2. Comparison of the barometric coefficients of ARNM, NANM, IZMIRAN (Moscow), Oulu (Finland), Rome (Italy) and Athens neutron monitors calculated by the data of 2008 (denoted by circles) with barometric coefficients of 22 NMs from worldwide network averaged by the groups of stations with close rigidities (denoted by triangles), from reference Dorman et al. (1968).

Barometric coefficients calculated for the SEVAN detectors additionally illustrate that indeed the measured fluxes "selected" by detector electronics are enriched by different species of cosmic rays. Of course, we cannot measure "pure" flux of neutrons, due to the contamination of gamma-quanta and muons. However, as we see from Table 2, events selected as "neutrons" (coincidences 0 1 0 and 0 1 1) demonstrate barometric coefficients approximately twice as events selected as muons.

ASEC muon channels demonstrate that the absolute value of barometric coefficients is inversely proportional to the muon energy. We present the summary of barometric coefficients of neutron and muon fluxes in Figs. 3 and 4. We

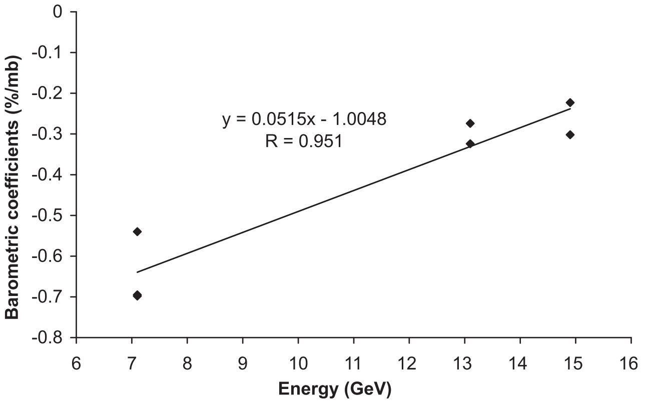

Fig. 3. The dependence of the barometric coefficients of secondary neutrons, secondary charged particles and secondary high energy muons (threshold energy >250 MeV) from median values of the primary proton energy for Nor Amberd particle detectors at 2000 m.

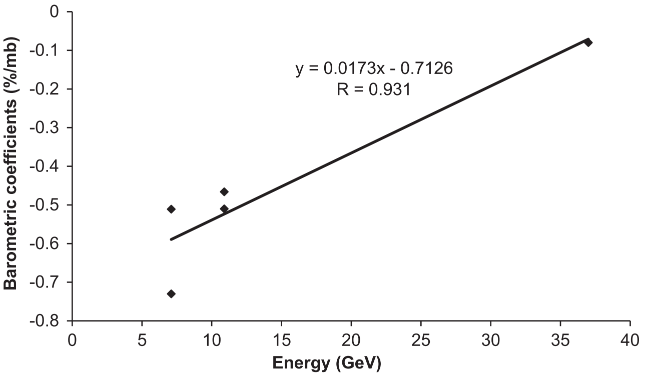

Fig. 4. The dependence of the barometric coefficients of secondary neutrons, secondary charged particles and secondary high energy muons (threshold energy >5 GeV) from median values of the primary proton energy for Aragats particle detectors at 3200 m.

use in the figures barometric coefficients of the NMs and muon detectors located at Aragats and Nor Amberd station. Correspondent median energy for each ASEC detector was estimated by simulations in Zazyan and Chilingarian (2009). In Fig. 3 (Nor Amberd station) we use data from the NANM (median energy of primary proton ~7 GeV); top layer of the NAMMM (Chilingarian et al., 2003, 2005) – (median energy of primary proton ~13 GeV); bottom layer of the NAMMM – (median energy of primary proton ~15 GeV). In Fig. 4 (Aragats station) we use data from the ARNM (median energy of primary proton ~7 GeV); top layer of the ASNT – (median energy of primary proton ~13 GeV); Aragats multichannel muon monitor $E\mu > 5$ GeV – (median energy of primary proton ~37 GeV). Description of ASEC monitors you can see in Chilingarian et al. (2003, 2005).

The depicted dependences of the barometric coefficients on median values of the primary proton energy at altitudes 2000 m and 3200 m prove that the barometric coefficients absolute value is inversely proportional to the median energy of the "parent" primary proton/nuclei.

4. Conclusion

1. Expected relations of barometric coefficients mentioned in Section 1 are proved by the data, obtained with ASEC particle detectors measuring neutron and muon fluxes with different cutoff rigidities.
2. Large range of the barometric coefficient values, covering approximately one order of magnitude, from 0.08% for the >5 GeV secondary muon flux till 0.73% for the secondary neutron flux, demonstrates unique sensitivity of ASEC detectors to different energies of the primary protons.
3. Barometric coefficients of monitors belonging to the new SEVAN particle detector network demonstrate that 3 layers of monitors are sensitive to different species of the secondary cosmic rays, namely: low energy charged particles (combination 1 0 0), neutrons (combinations 0 1 0 and 0 1 1) and high energy muons (combinations 1 1 1 and 1 0 1). It is independent check of the SEVAN, proving results obtained by simulations.
4. Barometric coefficients calculated for the ASEC monitors prove expectations about its dependence on the altitude and median energy of primary proton/nuclei for the definite particle detector. Obtained coefficients are used for correcting ANM and NANM data to appear in the Neutron Monitor Data Base (NMDB) in Kiel, Germany: a European project to collect on-line data of neutron monitors. Data is also transferred to the mirror site in the USA (http://www.aragats.am/) and Europe (http://www.fzk.aragats.am/).

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