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MOUNTAINOUS REGIONS OF THE RUSSIAN ARCTIC AS A PLATFORM FOR SPACE WEATHER RESEARCH

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Abstract. Due to the structural features of the geomagnetic field, Earth’s subpolar regions are the most affected by cosmic ray variations and other space weather phenomena. High grounds located in these regions are especially promising in terms of space weather research. Nowadays, there are only two high-altitude subpolar space weather observatories highly sensitive to solar activity, both located in Antarctica. In the Russian Arctic, we have several mountainous regions with geophysical conditions similar to that of the Antarctic ice sheet. In this paper, we calculate physical quantities that determine conditions for space weather observation in these regions and explore the expediency of building new scientific stations there. We show that establishment of the stations would enhance sensitivity of space weather observatory network and increase the number of detectable solar proton events.

Keywords: the Arctic, space weather, cosmic rays, solar activity, solar modulation, ground-level enhancements, neutron monitors.

INTRODUCTION

Space weather is a set of characteristics of the interplanetary medium and the processes occurring in it, which affect Earth and human activity, such as the radiation level in near-Earth space governed by cosmic rays (CRs) — high-energy particle fluxes. Most CRs are born either in our galaxy or are generated by the Sun, so they are commonly referred to as galactic CRs (GCRs) and solar energetic particles (SEPs) respectively. Particle fluxes of both types are influenced by solar and geomagnetic activity and continuously change with time. SEP events, known as solar proton events (SPE), are caused by solar flares and coronal mass ejections [Reames, 1999], whereas modulation of GCRs is due to their interaction with the solar wind and structures in the interplanetary magnetic field [Potgieter, 2013]. SPEs in which the particle flux and energy are sufficient for the event to be recorded by ground-based detectors are classed as Ground Level Enhancements (GLEs) [Poluianov et al., 2017].

Cosmic rays play an essential role in human life and many physical processes on Earth as the main source of ionization in the lower and middle atmosphere [Bazilevskaya et al., 2008], as well as of radiation exposure in space [Chen et al., 2023]. The cosmic ray flux is monitored by spacecraft and ground-based facilities such as neutron monitors (NMs) [Simpson, 2000].

Currently, Russia is actively developing the Arctic, which, due to the structural features of the geomagnetic field, is most affected by space weather. Construction of new research stations in the Russian Arctic will allow us to obtain unique information on solar and geomagnetic activity effects, as well as to perform environmental monitoring in territories under development.

1. CR PROPAGATION IN EARTH'S MAGNETOSPHERE AND ATMOSPHERE

In order for a ground device to detect the arrival of CRs, they should pass through Earth's magnetosphere and interact with air molecules and atoms, whereupon the formed secondary particles have to propagate through the atmosphere above the device. Thus, each point on Earth's surface can be characterized by the following concepts: the asymptotic cone of acceptance [Rao et al., 1963], the geomagnetic cutoff rigidity R_c [Gerontidou et al., 2021], and the atmospheric cutoff energy E_c [Poluianov, Batalla, 2022]. Larger values of R_c and E_c are taken as the energy threshold for detected particles.

The value of R_c is determined by the structure of geomagnetic field and takes values from zero at the magnetic poles to 15–20 GV near the magnetic equator [Gerontidou et al., 2021]. The value of E_c depends on the atmospheric depth h, expressed in g/cm^2, and was initially found empirically. A series of experiments known as latitude surveys [Nuntiyakul et al., 2018] has shown that at sea level the atmospheric cutoff energy assumes a value ~430 MeV that corresponds to 1 GV rigidity in the case of CR protons. Thus, for ground-based detectors placed in a region with $R_c < 1$ GV, the atmospheric cutoff prevails over the geomagnetic one, and the energy threshold of detected particles depends on how high the detector is located. Such detectors are commonly referred to as polar detectors.

Poluianov and Batalla [2022] have used the results of latitude surveys to calibrate the method of determining the atmospheric cutoff energy depending on the atmospheric depth. The atmospheric cutoff energy was found to vary from 430 MeV at sea level to ~280 MeV at h=500 g/cm^2, which corresponds to an altitude ~5.5 km above sea level. Since the CR flux sensitivity to solar activity increases with decreasing particle energy, high-altitude polar detectors are particularly susceptible to CR variations and to SPEs.

2. NEUTRON MONITOR NETWORK EXPANSION

For a long time, the only high-altitude polar neutron monitor was NM SOPO, but in 2015 NM DOMC was installed on the Antarctic ice sheet. In the same year, another GLE was recorded only by these two detectors, which are highly sensitive to low-energy CRs [Poluianov et al., 2017]. Thus, the construction of the high-altitude polar observatory led to the introduction of a new class of events, the so-called sub-GLE [Poluianov et al., 2017]. In addition to DOMC and SOPO, several more NMs have increased sensitivity to CR variations. For example, NM VSTK that is out of operation now [Poluianov et al., 2024]. NM SNAE is located above sea level, but not high enough for a complete detection of sub-GLEs. Mishev and Usoskin [2020] have proposed to install a new neutron monitor SUMT at a research station in Greenland. For brevity, all of the above NMs will be referred to as existing.

There are several places in the Russian Arctic where conditions for observing ice are similar to those on the Antarctic and Greenland ice sheets. In Figure 1, *a*, these locations are marked with circles; and existing NMs, with five-point stars, a triangle, and a diamond. Mt. Yudichvumchorr (YDVC) is the highest mountain in the Khibiny Mountains and has a flat top; at the foot of the mountain range is the town of Apatity, where an active neutron monitor is located, and the town of Kirovsk in which there are lifts to the mountains. Mt. Payer (PAYR) is the highest point of the Polar Urals, and its top is also a plateau. The village of Kharp and the railway station are located at a distance ~60 km from the peak, and all-terrain roads stretch to the foot of the mountains.

Mt. Kamen (KAMN) is the highest point of the Putorana Plateau, and the nearest city is Norilsk. Peak Pobeda (PBDA) is the highest peak of the Chersky Range and northeastern Russia, at a distance of 50 km from which is the village of Sasyr. Kamen and Pobeda are located on the territories of the Putorana Nature Reserve and Moma Natural Park respectively, which can greatly complicate the construction of new stations in this area. The Orulgan Range (ORGN) is part of the Orulgan Sis Nature Reserve; the nearest settlements, which can be reached by plane or winter road, are located 150 km from the mountain range. Finally, the highest point of the Chukotka Mountains, Mt. Iskhodnaya (IKNY), is extremely inaccessible. One of the nearest settlements is Cape Schmidt located ~200 km away; in its territory there is a geophysical observatory with a neutron monitor of the same name. Thus, as for the possibility of construction and subsequent maintenance, the YDVC and PAYR observatories are the most promising.

More detailed information on NMs is presented in Table. The average atmospheric depth at the NM locations was obtained using MATLAB Aerospace Toolbox [https://www.mathworks.com/products/aerospace-toolbox.html]; the effective vertical geomagnetic cutoff rigidity was calculated with IZMIRAN tool [https://tools.izmiran.ru/cutoff] for 2030 by the IGRF model for the main field [Alken et al., 2021] and by the TS89 model with K_p=1 for the external field [Tsyganenko, 1989]. To determine the atmospheric cutoff energy, the calculation results presented in [Poluianov, Batalla, 2022] were interpolated by cubic polynomials (gray line in Figure 1, *b*).

We have calculated asymptotic directions of approach of vertically incident particles with rigidity from 0.8 GV to 20 GV. The corresponding directions are indicated in Figure 1, *a* by dots whose color corresponds to the station label. Existing NMs, as well as NMs YDVC, PAYR, and KAMN, have relatively narrow cones of acceptance, while the cones of acceptance of NMs ORGN, PBDA, and IKNY are extended in longitude. With installation of new detectors, in addition to SOPO+DOMC, such sub-GLE detection NM pairs appear as SNAE+YDVC, YDVC+PAYR, PAYR+KAMN, and PBDA+SNAE. Figure 1, *b* plots the cutoff energy as a function of atmospheric depth for all existing and proposed stations. Cutoff energies for the polar NMs located near sea level are schematically represented by six-point stars. NM PBDA is at the same sensitivity level as SOPO, whereas the other proposed detectors fall in between SOPO and SNAE.

To check how effective the proposed NMs are in detecting SPEs, we have calculated the detector response to three events whose spectra are shown in Figure 2, *a*. The angular distribution of SPEs was assumed to be isotropic, while parameters of energy spectra for GLE 71 and sub-GLE were taken from [Mishev et al., 2014, 2017] respectively. To assess the statistical significance of the signal, the response to SPEs is given in σ_{GCR}, which is the statistical uncertainty of the NM response to GCRs that in this case is the background. The GCR spectrum is given by the force field approximation [Gleeson, Axford, 1968] with a solar modulation potential of 1 GV. The data collection time by the standard unit 6NM64 is assumed to be 1 min, and the detector response is calculated using the function presented in [Mishev et al., 2020].

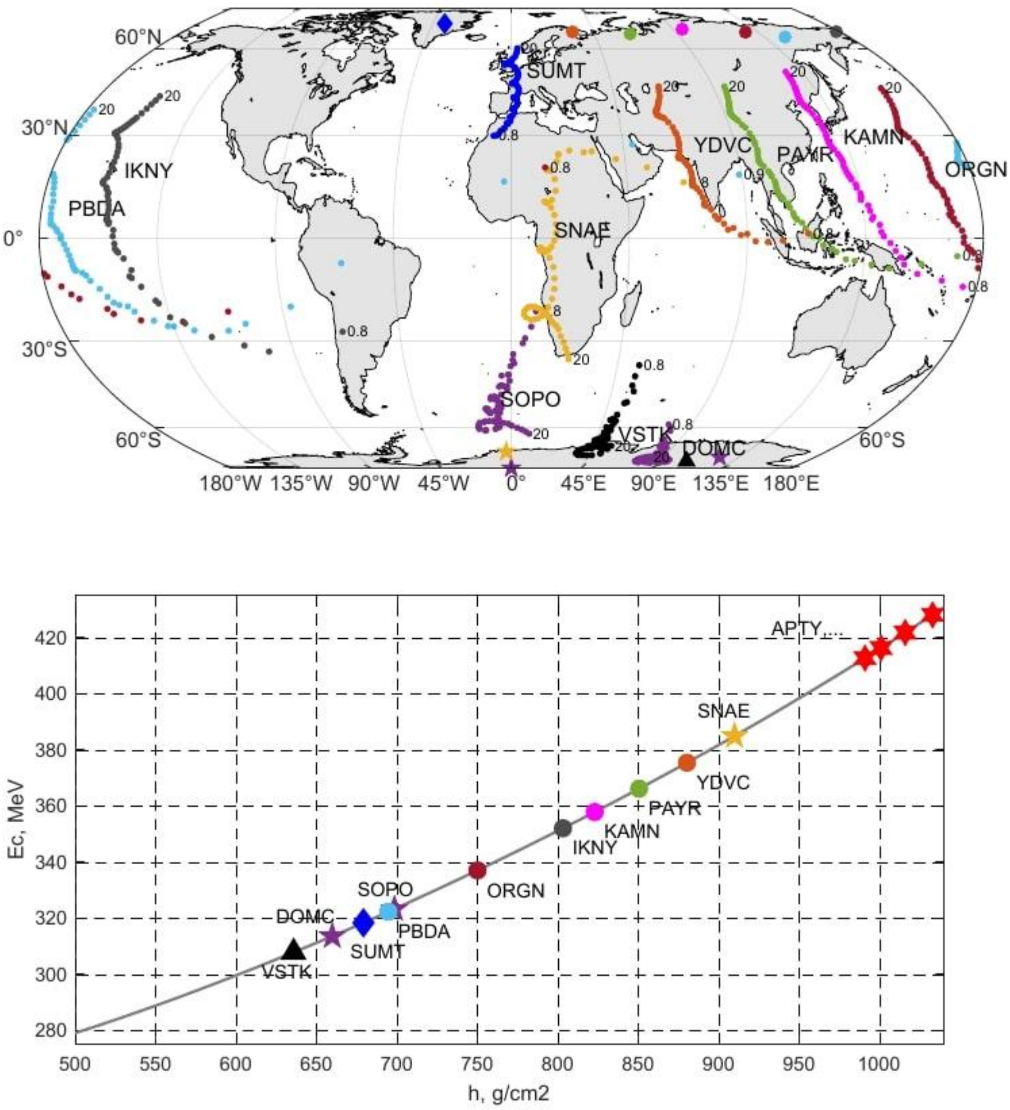

Figure 1. Geographic location of neutron monitors and their asymptotic directions of approach of vertically incident particles (*a*), as well as atmospheric cutoff energy at locations of neutron monitors (*b*)

Characteristics of neutron monitors

Geographical object	Abbreviation	Latitude, deg.	Longitude, deg.	Height, m	*h*, g/cm^2	E_c, MeV	R_c, GV
Existing NMs							
station South Pole	SOPO	–90.00	0	2820	698	323	0.36
station Dome C	DOMC	–75.06	123.20	3233	660	314	0.19
station Sanae IV	SNAE	–71.67	–2.85	856	910	385	0.47
station Camp Summit	SUMT	72.34	–38.27	3126	679	318	0.31
station Vostok	VSTK	–78.47	106.87	3488	636	308	0.21
Proposed NMs							
Yudichvumchorr	YDVC	67.73	33.47	1200	880	375	0.34
Payer	PAYR	66.72	64.38	1472	851	366	0.51
Kamen	KAMN	69.13	95.07	1701	822	358	0.47
The highest point of the Orulgan Range	ORGN	67.58	128.13	2409	750	337	0.56
Pobeda	PBDA	65.17	146.00	3003	695	322	0.83
Iskhodnaya	IKNY	67.82	178.28	1887	803	352	0.49

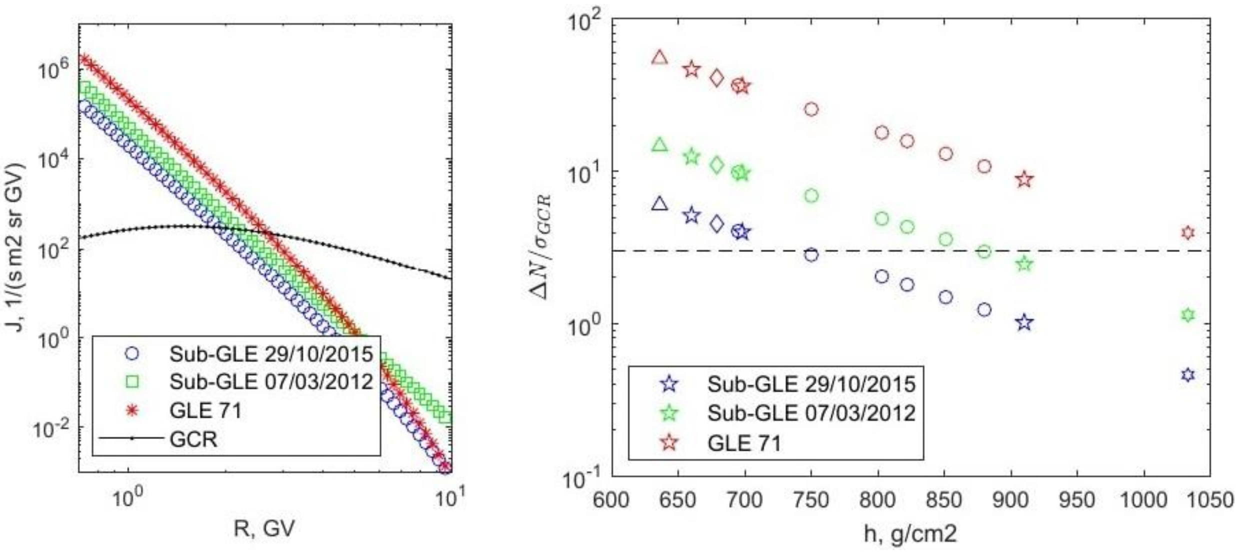

Figure 2. Energy spectra of solar proton events and galactic cosmic rays (*a*); statistical significance of the response of the neutron monitors considered to solar proton events (*b*)

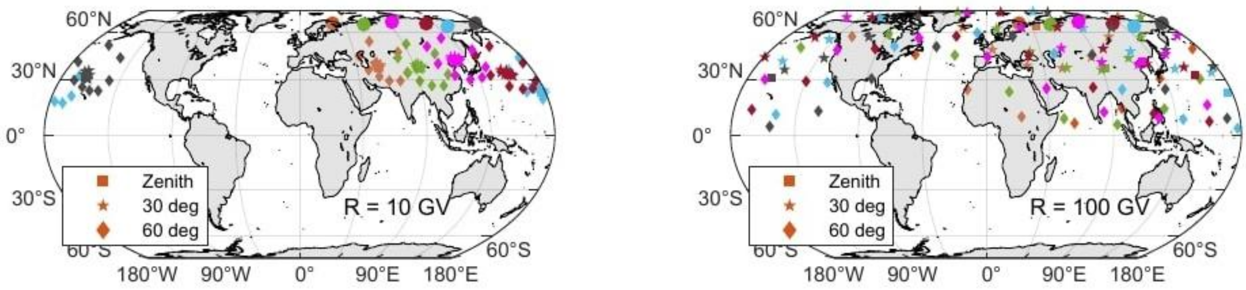

Figure 3. Asymptotic directions of approach of particles with rigidity of 10 GV (*a*) and 100 GV (*b*) arriving at different angles

The calculation results are shown in Figure 2, *b*. Six-point stars mark responses of polar NM, located at sea level, to SPEs. In the case of weak GLE 71, all devices record a statistically significant increase in the count rate. If we talk about the relatively strong sub-GLE on March 07, 2012, the neutron monitor located at sea level, as well as the NM observatory SNAE, did not detect this event at the confidence $3\sigma_{GCR}$, while the signal recorded by the other stations remains statistically significant. In the case of the weak sub-GLE on October 29, 2015, most NMs proposed for the Russian Arctic also lacks sensitivity for its reliable detection, and only PBDA demonstrates sensitivity on a level with Antarctic stations. We can conclude new high-altitude polar NMs in the Russian Arctic would indeed lead to an increase in the number of detectable SPEs.

3. ADDITIONAL INSTRUMENTS

In addition to neutron monitors, instruments sensitive to other components of secondary cosmic rays can be installed at a scientific station, for example, low-energy neutron detectors [Nuntiyakul et al., 2018] and muon telescopes [Kato et al., 2021]. Cosmic ray fluxes of different types react variously to environmental features, which allows us both to obtain more information about CRs and to identify other phenomena against their background.

Magnetometers could be an alternative. On the one hand, geomagnetic disturbances resulting from the interaction of the magnetosphere with solar wind streams are most pronounced in sub-polar latitudes, and a new geomagnetic observatory could complement the INTERMAGNET network, which lacks measurements in the Russian Arctic [https://intermagnet.org/metadata/#/map]. On the other hand, joint monitoring of the cosmic ray flux and geomagnetic activity can be useful in studying space weather phenomena [Danilova et al., 2023].

Figure 3 exemplifies asymptotic directions of approach of particles to muon telescopes located in the same place as proposed NMs. The calculation has been carried out for particles with rigidity of 10 GV (*a*) and 100 GV (*b*) incident vertically or at zenith angles of 30° and 60°. For each zenith angle, we have taken into account eight azimuthal directions with 45° increments. In the case of particles with 10 GV rigidity, asymptotic directions form narrow cones, and each muon telescope scans a specific area of the celestial sphere. For particles with 100 GV rigidity, the spread of asymptotic directions turns out to be much wider, and the acceptance cones of muon telescopes cover almost the entire Northern Hemisphere. Thus, data from new muon telescopes located in these places can effectively complement the measurements of existing detectors [Kato et al., 2021].

CONCLUSION

The paper presents the idea of building new observatories for space weather monitoring in the Arctic zone of the Russian Federation. We have analyzed several alternatives for the location of observatories, and have calculated physical quantities characterizing the conditions for observing solar and geomagnetic activity in these locations. We have restored asymptotic directions of approach, and have modeled the response of potential detectors to solar proton events of varying intensity. We can conclude that establishment of new scientific stations would significantly increase the sensitivity of the network of ground-based detectors to space weather phenomena.

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