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INTENSITY OF THE NEUTRON COMPONENT OF COSMIC RAYS AND AIR HUMIDITY

V.L. Yanchukovsky
A.A. Trofimuk Institute of Oil and Gas Geology and Geophysics SB RAS,
Novosibirsk, Russia, YanchukovskiyVL@ipgg.sbras.ru

M.A. Kalyuzhnaya
A.A. Trofimuk Institute of Oil and Gas Geology and Geophysics SB RAS,
Novosibirsk, Russia, kalyuzhnayama@ipgg.sbras.ru

R.Z. Khisamov
A.A. Trofimuk Institute of Oil and Gas Geology and Geophysics SB RAS,
Novosibirsk, Russia, khisamovrz@ipgg.sbras.ru

Abstract. Neutron monitor data is currently corrected only for the barometric effect. We cannot, however, exclude that changes in air humidity affect the intensity of the cosmic-ray neutron component recorded by neutron monitors. In this regard, we have carried out continuous measurements of air humidity and temperature when observing variations in the cosmic ray intensity with a neutron monitor in Novosibirsk. Analysis of the results of observations of meteorological parameters and cosmic ray intensity in Novosibirsk, as well as data from the global network of neutron monitors, made it possible to identify neutron component intensity variations caused by changes in air humidity. The estimated humidity effect indicates the need to regularly take it into account in the neutron monitor data. To do this, along with atmospheric pressure, regular measurements of humidity and air temperature should be performed.

Keywords: cosmic rays, atmosphere, neutrons, monitor, air humidity.

INTRODUCTION

Variations in atmospheric parameters [Dorman, 1957] cause variations in the integral generation multiplicity of cosmic ray (CR) secondary particles. The atmospheric CR variations are mainly due to barometric and temperature effects. The contribution of these effects is not the same for different secondary components. For the neutron component consisting mainly of stable particles, the temperature effect is practically absent since only a small part of neutrons can be generated by unstable particles. The neutron component intensity is mainly affected by the easily recorded barometric effect. Neutron monitor data is currently corrected only for the barometric effect. Note, however, that measurements carried out more than half a century ago [Hendrick, Edge, 1966] revealed a humidity effect on the cosmic ray neutron intensity near Earth's surface. Unfortunately, the detected effect was classified as noise during the measurements. Dorman [1972] also indicates that there is a humidity effect for the CR neutron component.

The neutrons formed in the atmosphere as a result of inelastic interactions of CRs with the nuclei of air atoms undergo elastic collisions, thereby losing energy and being eventually absorbed. Logarithmic energy losses of neutrons in the elastic collisions with nuclei are inversely proportional to the atomic weight of an element [Bekurts, Virtts, 1968]. As the atomic weight increases, the number of collisions increases and the energy loss decreases. Hydrogen is by far the most efficient absorber. Slowing down fast neutrons to a thermal level needs a minimum number of collisions (~18) with the hydrogen nucleus [Bekurts, Virtts, 1968]. The main source of hydrogen atoms in the air is water vapor. If the chemical composition of the air practically does not change, in the absence of variations in the primary CR flux the rate of neutron production in the atmosphere will be almost constant. Nonetheless, even in the absence of atmospheric pressure variations, water vapor oscillations in the air will cause intensity variations in the neutron component detected. This effect amounts to several percent [Zreda et al., 2012] with significant changes in the partial pressure of water vapor (difference between dry and humid air). The neutron flux density in various energy ranges near Earth's surface is inversely proportional to air and soil humidity [Desilets et al., 2010]. To facilitate the analysis, it is advisable to divide the neutron energy spectrum into several energy ranges:

- The energy range <1 eV — a region of thermal and superthermal neutrons whose energy spectrum is the Maxwellian spectrum;
- The energy range 1 eV – 50 keV — a region of resonance energy neutrons whose density is distributed over energies according to the law $E^{3/2}$, i.e. it increases smoothly with decreasing energy and the Fermi spectrum transforms into the Maxwellian spectrum of thermal neutrons;
- The energy range 50 keV – 1 MeV — a region of intermediate energy neutrons whose energy spectrum depends not only on slowing-down processes, but also on the evaporation neutron spectrum with an average energy of 1 MeV;
- The range 1 MeV – 10 GeV — a region of fast and relativistic neutrons whose energy spectrum is described by a power function.

When studying the state and distribution of moisture near Earth's surface, the general information to be analyzed is the intensity of the neutrons detected. The neutron energy spectrum contains additional information on the state and distribution of moisture. Simultaneous measurements of thermal, epithermal, and fast neutrons can make it possible to distinguish snowfall from rain as was done in [Desilets et al., 2010].The observed response of the natural neutron flux to humidity changes has now become widely used in establishing networks of continuous observations of average soil humidity [https://blog.secnrs.ru/2022/12/на-конференции-cop27-магатэ-уделило-особо/; https://www.iaea.org/ru/publi-cations/magazines/bulletin/59-3; https://www.iaea.org/ru/newscenter/news/kosmicheskie-luchi-pomogayut-izmerit-uroven-vlazhnosti-pochvy; Zreda et al., 2008]. For these purposes, mobile and stationary soil humidity probes using cosmic rays are being developed [https://ru-ecology.info/post/103688904160015/; Zreda et al., 2012].

The neutron component at CR stations is observed with neutron monitors [Hatton, Carmichael, 1964] — local neutron generation detectors which utilize lead as a condensing agent, and polyethylene is a moderator of neutrons formed in lead. The presence of a local neutron generator and a moderator in monitors makes it possible to significantly reduce the contribution of neutrons formed and slowing down in the atmosphere and surrounding objects [Dorman, 1975]. Yet, there is no guarantee that this contribution is completely excluded.

The worldwide network's CR stations equipped with neutron monitors are under different conditions. At the CR stations, air humidity is determined, on the one hand, by precipitation and temperature, and on the other, by factors such as runoff efficiency, vegetation level and type, soil characteristics, etc. It is therefore necessary to continuously measure air humidity directly at a CR observation station in order to determine the humidity effect in neutron monitor data.

AIR HUMIDITY MEASUREMENTS

Air humidity and temperature has been continuously monitored in Novosibirsk since October 14, 2021. The measurements are made at an interval of 15 min using a humidity and temperature data processor DTV-03.RS [https://relsib.com/category/datchiki-vlazhnosti-i-temperatury-dvt-03]. Advantages of DTV-03.RS are high measurement accuracy, interchangeable sensor element, resistance to high humidity, extended temperature measurement range. The main characteristics of the processor:

- Measurement range: –40 ... +100 °C, 0 ... 98 % rel. humidity;
- Measurement accuracy: relative humidity from ±2.5 %, temperature from ±0.4 °C;
- Improved temporal stability;
- Standard digital communication protocol RS 485 Modbus;
- The configurator program contains an embedded parameter recording program in the form of a table or a plot.

The air humidity and temperature processor is placed in the Selyaninov screen five meters from the CR station.

DATA

The results of the direct measurements are represented by relative humidity as a percentage and temperature in Celsius degrees. Let us turn to absolute humidity. The water vapor behavior [Amelin, 1972] can be approximated as the ideal gas behavior, which is described by the Mendeleev — Clapeyron equation

$$PV = nRT. \tag{1}$$

Here, P and V are the pressure and volume of water vapor respectively; R is the gas constant; T is the measured temperature; n is the amount of water vapor in moles ($n=m/M$), the molecular weight of water is 18.02. The saturated steam pressure P_{sat} [hPa] (when relative humidity h=100 %) as a function of temperature T [°C] is given by the Magnus — Tetens formula:

$$P_{\text{нас}} = 6.112\exp\left[(17.67\,T)/(T+243.5)\right]. \tag{2}$$

When turning to pressure P at any value of relative humidity, it is sufficient to multiply the expression for P_{sat} by the coefficient (h/100). Then, the absolute humidity H [g/m^3] is the mass of water [g] per unit of air volume [m^3]:

$$H = \frac{6.112\exp\left[(17.67\,T)/(T+243.5)\right]2.1674h}{(273.15+T)}, \tag{3}$$

where T is the current temperature [°C]; h is the relative humidity [%].

Atmospheric pressure and the CR neutron monitor's counting rate are measured every minute. For continuous measurements of absolute air pressure, a BRS-1M network type barometer with a maximum permissible measurement error ± 33 Pa is employed. The barometer can provide information via the RS232 interface in a periodic mode (every 250 ... 300 ms) or on demand at a rate of 1200 baud.

The results of the continuous measurements of temperature, humidity, and pressure over a long period are presented in Figure 1.

We have examined continuous CR observations performed with neutron monitors at ten stations of the worldwide network. The main characteristics of the CR stations are listed in Table.

We used the counting rate I values corrected for changes in the atmospheric pressure for the period from October 14, 2021 to September 30, 2023. All raw data is reduced to the daily average values. For each neutron monitor for the entire time interval under study, we have found the average values $\bar{I}$ relative to which the intensity variations $\delta I = \frac{I-\bar{I}}{\bar{I}}100\%$ were estimated. Figure 2 presents data from the ten neutron monitors for this period.

ESTIMATED HUMIDITY EFFECT

The CR stations whose data we use are located in both hemispheres, are significantly spaced in longitude, and are situated in different climatic zones. When averaging data from these stations, we minimize the humidity effect contribution against the selected primary component of CR

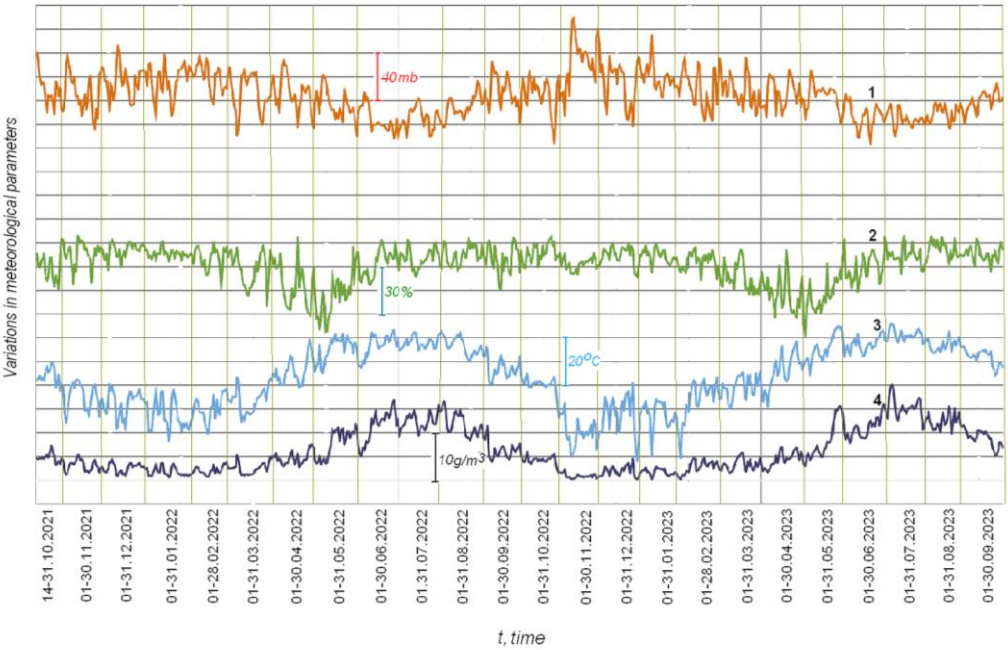

Figure 1. Daily average atmospheric pressure (curve 1), relative humidity (curve 2), temperature (curve 3), and absolute humidity (curve 4) in Novosibirsk for the period from October 14, 2021 to September 30, 2023

Parameters of the worldwide network's CR stations

№	Cosmic Ray Station	Coordinates	Altitude, m	Instrument	Geomagnetic cutoff rigidity, GV	Links
1	Athens, Greece	37.97°N 23.78° E	260	6-NM-64	8.53 (2000 г.)	https://www.nmdb.eu/station/athn/
2	Hermanus, South Africa	34.43° S 19.23° E	26	12-NM-64	4.58 (1965)	https://www.nmdb.eu/station/hrms/
3	Irkutsk, Russia	52.47° N 104.03° E	475	18-NM-64	3.56 (1965 г.)	https://www.nmdb.eu/station/irkt/
4	Kiel, Germany	54.34°N 10.12° E	54	18-NM-64	2.36 (2000 г.)	https://www.nmdb.eu/station/kiel/
5	Moscow, Russia	55.47° N 37.32° E	200	24-NM-64	2.43 (1965 г.)	http://cr0.izmiran.ru/mosc/ https://www.nmdb.eu/station/mosc/
6	Novosibirsk, Russia	54.8° N 83.00° E	163	24-NM-64	2.91 (1965 г.)	https://www.nmdb.eu/station/nvbk/
7	Oulu, Finland	65.05° N 25.47° E	15	9-NM-64	~0.8 (1965 г.)	https://www.nmdb.eu/station/oulu/
8	Potchefstroom, South Africa	26.68° S 27.09° E	1351	15-МГТ	6.98 (1965 г.)	https://www.nmdb.eu/station_information/PTFM_2018-07-01.html
9	Sanae IV, Antarctica	71.67° S 02.85° W	856	6-NM-64	0.73 (1965 г.)	https://www.nmdb.eu/station/snae/
10	Yakutsk, Russia	62.01° N 129.43° E	105	24-NM-64	1.65 (1965 г.)	https://www.nmdb.eu/station/yktk/

In brackets is the epoch to which the effective cutoff rigidity belongs

variations, i.e. the CR variations due to modulation of primary CRs outside Earth's atmosphere and magnetosphere, which corresponds to midlatitudes. Indeed, the diurnal air humidity variation is observed in local time. Accordingly, averaging data from the longitudinally spaced CR stations leads to a decrease in the contribution of changes in air humidity during the day. The use of observational data at different stations in the Northern and Southern hemispheres reduces the contribution of seasonal changes in air humidity (winter–summer) to the averaged data from neutron monitors. The primary component of CR variations can simultaneously be recorded by all stations of the worldwide network at UT. So, averaging data from the worldwide network's stations will reliably identify the primary component of CR variations, thereby minimizing the contributions of various meteorological effects, including humidity variations. The variations obtained by averaging data from all the stations (except for the data from the station Novosibirsk) are shown in Figure 3, which also displays changes in absolute air humidity and variations in the counting rate of the neutron monitor in Novosibirsk, corrected for atmospheric pressure changes. Figure 3 also illustrates the difference $\delta I_{\mathrm{NVBK}}(t)-\overline{\delta I}(t)$, where $\overline{\delta I}(t)=\frac{1}{n}\sum_k \delta I_k(t)$, and $\delta I_k(t)$ are variations in the counting rate of the station k.

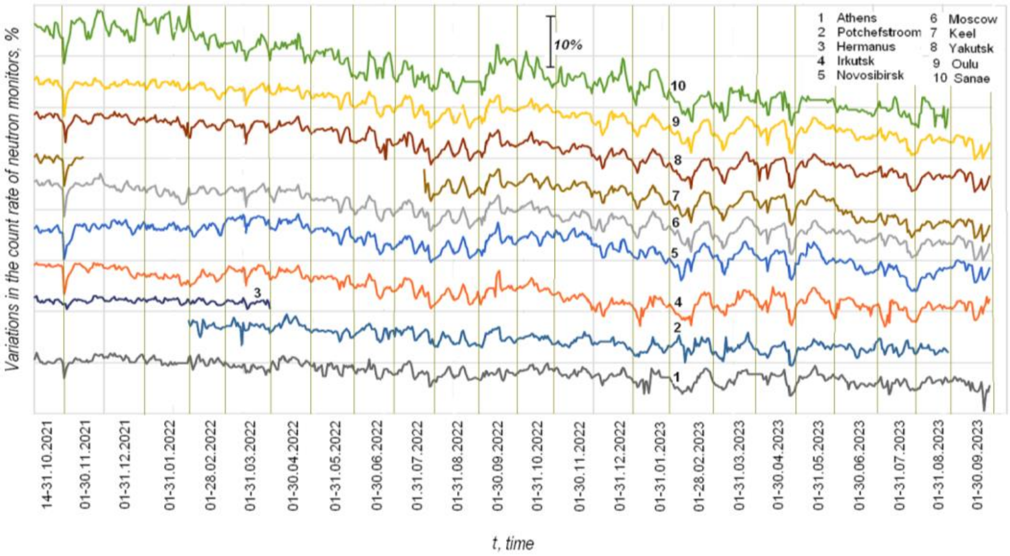

Figure 2. Variations in the counting rate of ten neutron monitors of the worldwide network's CR stations for the period from October 14, 2021 to September 30, 2023

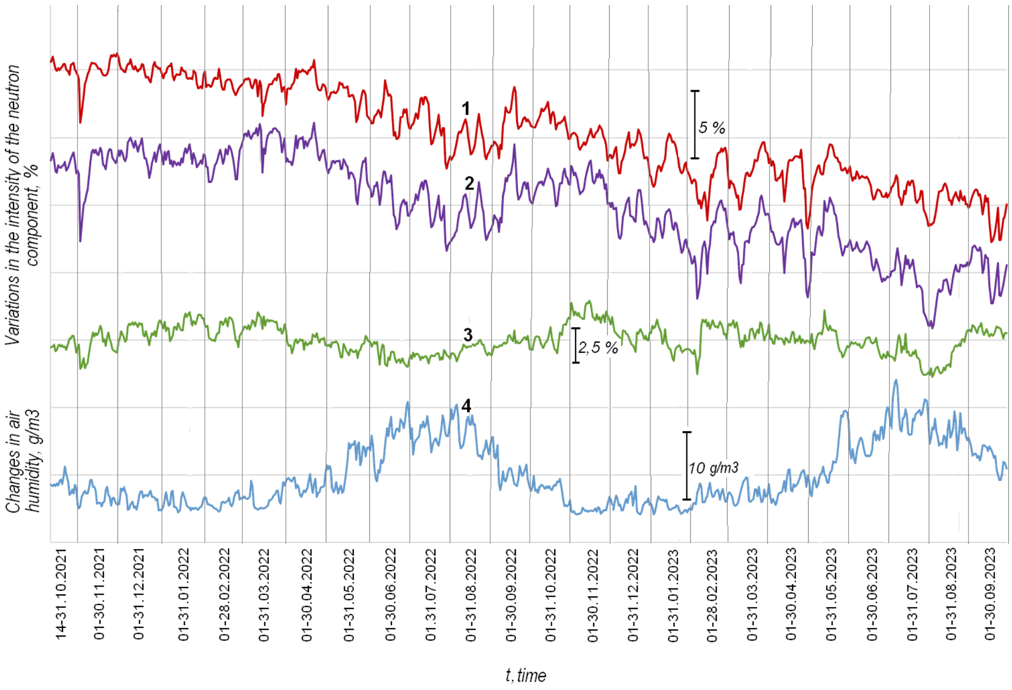

Figure 3. Neutron component intensity variations averaged over all the above CR stations (curve 1), the Novosibirsk neutron monitor's counting rate variations (curve 2), difference between these parameters (curve 3), and variations in absolute humidity (curve 4) in Novosibirsk over the same period

Figure 3 shows time variations in the difference $\delta I_{\text{NVBK}} - \overline{\delta I}$ (curve 3), which occur strictly in antiphase with variations in absolute humidity ΔH (curve 4). The difference $\delta I_{\text{NVBK}} - \overline{\delta I}$ contains information about air humidity since it proves to be correlated with variations in absolute humidity ΔH (curve 4) over the entire time interval of interest. To assess the humidity effect, let us use the raw data on the counting rate of the Novosibirsk neutron monitor, which is not corrected for atmospheric pressure. Represent the monitor's counting rate variations caused by variations in atmospheric pressure and air humidity, as well as in the primary component of CR variations, as a linear regression equation

$$\delta I_{\text{NVBK}}(t) = \alpha \Delta H(t) + \beta \Delta P(t) + \gamma \overline{\delta I}(t), \tag{4}$$

where $\delta I_{\text{NVBK}}(t) = \dfrac{I_{\text{NVBK}}(t) - \bar{I}_{\text{NVBK}}}{\bar{I}_{\text{NVBK}}} \cdot 100\,\%$ are the observed variations in the Novosibirsk neutron monitor's counting rate (resulting factor *y*); $\Delta H(t) = H(t) - \overline{H}$ are variations in air humidity (factor x_1); $\Delta P(t) = P(t) - \overline{P}$ are variations in atmospheric pressure (factor x_2); $\overline{\delta I}(t)$ is the average variation in the counting rate of the worldwide network's nine neutron monitors (factor x_3).

In expression (4), α is the humidity coefficient; β is the barometric coefficient; γ is the regression coefficient with averaged data from the nine neutron monitors corrected for atmospheric pressure variations and reflecting primary CR variations. To determine the values of α, β, and γ, the least squares method is employed which for linear regression equations is reduced to solving a system of normal equations [Korn, Korn, 1984]. For the multivariate regression, we also apply the regression equation on a standardized scale [Gorlach, 2006]. Both methods give a similar result. The following values are obtained: $\alpha=-0.160\pm0.007\%/(\mathrm{g/m}^3)$; $\beta=-0.713\pm0.0041\%/\mathrm{mb}$; $\gamma=0.958\pm0.006$. The cumulative correlation coefficient characterizing the strength of the relationship between all the variables p=0.961. Using the barometric coefficient β and the humidity coefficient α, determine the neutron monitor's counting rate variations caused by atmospheric pressure and absolute humidity variaitons, and exclude them from the observed variations δI_{NVBK} for the period of interest. The result is presented in Figure 4.

DISCUSSION

A significant contribution to the NM-64 neutron monitor's counting rate begins with energies of ~10 MeV (fast neutrons). Elastic interactions are more or less typical of all particles, not only of thermal and superthermal neutrons. The elastic interactions in the surrounding air make fast neutrons to slow down too and to move to other energy regions (intermediate, resonance, suprathermal, or thermal neutrons). Thus, they drop out of the fast neutron flux to which the neutron monitor is sensitive; this leads to a decrease in the counting rate. As humidity changes, the content of the effective moderator, hydrogen, in the air changes too. This causes the monitor's counting rate to vary. The reliability of the result, in our case the humidity coefficient for a neutron monitor, depends on the choice of an appropriate method for analyzing experimental material and the quality of raw data. Data on CR neutron component intensity variations was obtained from continuous observations with a 4-section neutron monitor 24NM-64 (Novosibirsk) with a particle collection area of 24 m^2, which ensures a 0.12 % statistical accuracy of hourly data. The analysis employed daily average values, so the statistical error in the raw data did not exceed 0.024 %. We used the results of continuous observations for the period from October 14, 2021 to September 30, 2023, i.e. for 717 days. Air humidity data was obtained using a certified humidity and temperature sensor DVT-03, which currently provides the highest measurement accuracy. Atmospheric pressure data was acquired by a certified network type barometer BRS-1M after its calibration testing. The statistical error in the averaged data from nine neutron monitors is determined by the statistical accuracy of each of the CR stations. Eight of the nine CR stations employ the standard NM-64 neutron monitor. On average, the statistical error in hourly data does not exceed 0.19 %. The error in the daily average values averaged over the worldwide network's nine stations is no more than 0.013 %. The results of continuous measurements of air humidity confirm the presence of an annual wave in the change in absolute air humidity of the order of 12–13 g/m^3 (see Figure 2, curve 4), which is consistent with the meteorological observations in Novosibirsk. With such a humidity coefficient (relatively small), humidity variations within the specified limits during the year cause a seasonal variation in the monitor's counting rate more than 2 % (see Figure 4, curve 3), which must be excluded from the data.

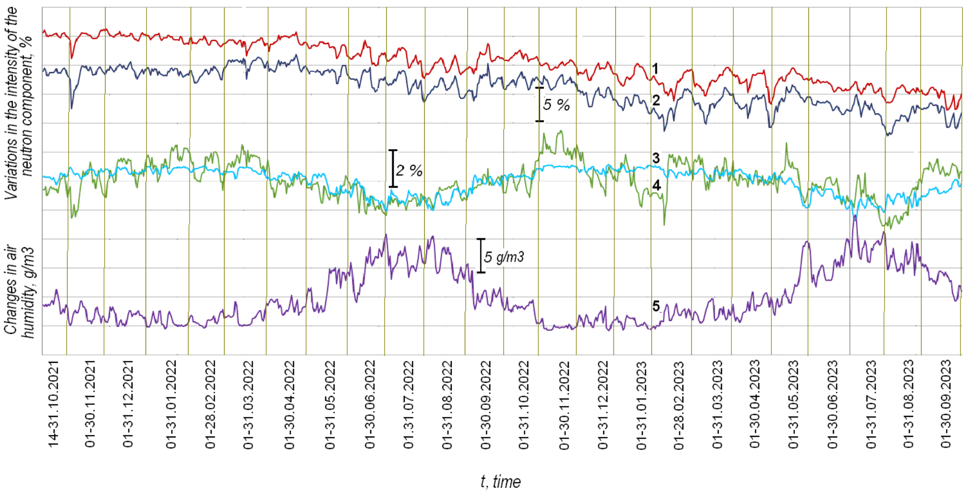

Figure 4. Neutron component intensity variations averaged over all the above stations (1), and the Novosibirsk neutron monitor's counting rate variations corrected for changes in atmospheric pressure and humidity (2), the neutron monitor's counting rate variations caused by changes in absolute humidity (3), the difference $\delta I_{\mathrm{NVBK}} - \overline{\delta I}$ (4), and changes in absolute humidity (5)

CONCLUSION

We have experimentally detected the air humidity effect for the CR neutron component recorded by neutron monitors. Using continuous observations, we have estimated the humidity coefficient of the recorded CR neutron component intensity. Although the humidity effect ($-0.160\%/(\mathrm{g/m}^3)$) is much less than the barometric effect ($-0.713\%/\mathrm{mb}$), it causes a seasonal variation in the neutron component intensity. Thus, in order to exclude the atmospheric component of variations from neutron monitor data, we should take into account not only the barometric effect, but also the air humidity effect. For this purpose, in addition to atmospheric pressure measurements, continuous air humidity and temperature observations should be carried out at the place of cosmic ray detection.

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