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ANALYSIS OF METEOROLOGICAL EFFECTS OF COSMIC RAY NEUTRON COMPONENT BASED ON DATA FROM MID-LATITUDE STATIONS

P.G. Kobelev
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation RAS, Moscow, Troitsk, Russia, kobelev@izmiran.ru

Yu.B. Hamraev
Uzbekistan-Finland Pedagogical Institute, Samarkand, Uzbekistan, yu-hamrayev@mail.ru

V.G. Yanke
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation RAS, Moscow, Troitsk, Russia, yanke@izmiran.ru

Abstract. Precision neutron monitors providing continuous monitoring with a statistical accuracy of ~0.15 %/hr are effective for studying cosmic ray variations; therefore, contributions from other error sources should not exceed the contribution of this statistical error. Such possible sources primarily include changes in atmospheric pressure and humidity. The aim of the work is to estimate the barometric effect of the neutron component of cosmic rays for the low-latitude stations Tashkent and Alma-Ata (mountain), including periods of maximum solar activity. The technique developed on the basis of multifactor correlation analysis is applicable to processing data from any detectors of the worldwide network of neutron monitors. As a result, we have obtained annual average barometric coefficients of the neutron component at the stations Tashkent and Alma-Ata. The humidity effect was also estimated for the mid-latitude station Moscow. The study draws the conclusion that the approach considered can effectively solve the problem.

Keywords: neutron monitor, barometric coefficient, cutoff rigidity.

INTRODUCTION

In cosmic ray monitoring, variations of various origins are simultaneously observed — atmospheric, magnetospheric, and heliospheric [Dorman, 1957]. Amplitudes of these variations are of the same order. Atmospheric (barometric) variations are in fact to ~20 %; magnetospheric, to ~5 %; heliospheric (Forbush decrease), to ~20 %. One approach to studying cosmic ray (CR) variations of one type is to select periods in which variations of other types can be ignored. This approach is largely subjective since data for studying CR variations often has to be selected intuitively. Moreover, variations in meteorological parameters at low-latitude stations are significantly lower (for example, atmospheric pressure varies to ~ 5 MB) than at high-latitude stations (to ~40 MB). In such cases, when constructing mathematical models of CR variations, it is necessary to use longer data series to ensure the required accuracy.

Another approach involves forming a model of CR variations in the atmosphere, which takes into account variations of all types characteristic of the detector considered and excludes other types. In our case, there are variations of heliospheric and magnetospheric origin. For the neutron component, the mathematical model of atmospheric variations includes those caused by the barometric and air humidity effects. In special cases, there are also variations caused by an insignificant (temperature coefficient is <0.01 %/°C) temperature effect. The negative barometric effect is produced by absorption of the neutron component in the atmosphere; the negative humidity effect, by deceleration of neutrons by hydrogen nuclei of water vapor in the atmosphere and by the transition of neutrons to the energy range below the neutron monitor (NM) energy registration cutoff [Hatton et al.,1964].

A lot of work has been done to assess the atmospheric effects of CRs — for each new detector, the effects were estimated by determining corresponding coefficients [Simpson, 1957; Carmichael, Bercovitch, 1969]. Next, we refer to several works which examined the dependence of the barometric effect on the effective particle energy during latitudinal measurements and the level of solar activity, as well as works which assessed the contribution of changes in absolute air humidity to observed variations in the neutron component.

In [Dorman, 1972; Moraal et al., 1989; Iucci et al., 2000; Nuntiyakul et al., 2014], the dependence of the barometric effect on the geomagnetic cutoff rigidity along the shipping route was studied from offshore latitudinal measurements. In [Yanchukovsky et al., 1976; Yanchukovsky, Filimonov, 1997a; b; Kobelev, Belov, 2011] for solar cycles 22–23 for a number of stations, time variations in the barometric coefficient of the CR neutron component were calculated. When analyzing the data to determine the barometric coefficient, primary CR variations were excluded which made it possible to apply a continuous series of data for the entire period under study. Paschalis et al. [2013] have described the method and the created online application for calculating the barometric coefficient for NM of the global network [http://cosray.phys.uoa.gr/index.php/data/ nm-barometric-coefficient]. Nowadays, in all cases, the correction of NM data is limited only to the correction for the barometric effect. Yanchukovsky et al. [2024] have examined the contribution of air humidity to the surface layer approximation, although the humidity effect is also distributed, in this approximation to obtain vertical distribution of humidity the problem can be solved using an atmospheric model. The estimates of the humidity effect indicate that it should be regularly taken into account when processing NM data.

The barometric coefficients for the NMs Tashkent and Alma-Ata, which were previously used for the entire observation period, are 0.71 and 0.72 %/mb respectively, and the accuracy is not lower than ±0.01 %/mb. The period for which the coefficients were found cannot be reliably determined because in the databases [https://www.nmdb.eu/station/] it is not specified, but barometric coefficients were usually calculated for solar minimum.

The purpose of this work is to estimate the barometric effect of the CR neutron component, using the low-latitude stations Tashkent and Alma-Ata as an example, including a period of very high solar activity. Unfortunately, it is impossible to take into account the air humidity effect even in the surface layer approximation since there is no data on humidity and surface air temperature for the stations Alma-Ata and Tashkent for the period of interest. Another purpose is to estimate the humidity effect for the station Moscow which has available meteorological monitoring data. This will allow an upper estimate of the contribution of the humidity effect for stations with a harsh continental climate.

METHOD OF DATA ANALYSIS AND CORRECTION FOR ATMOSPHERIC EFFECTS

The count rate measured by the neutron detector must be corrected for the barometric and air humidity effects. The third effect of atmospheric origin (temperature) for the neutron component is virtually absent. The temperature-induced variations in the neutron component consisting mainly of stable particles are really more than two orders of magnitude (temperature coefficient less than 0.01 %/°C) smaller than the CR variations due to the barometric effect [Dorman, 1957; Belov et al., 1995].

To estimate the corrected detector count rate N_c, it is necessary to reduce the measured detector count rate N_u to the mean atmospheric pressure P_0 and the mean absolute humidity H_0 (for 20° C temperature and 50 % relative humidity, $H_0=8.7$ g/m^3). At a known barometric coefficient β>0 and a humidity coefficient ε>0, the count rate corrected for these effects

$$N_c = N_u \exp\left[-\beta\left(P_0 - P\right)\right]\times\left[1-\varepsilon\left(H_0 - H_2\right)\right]. \quad (1)$$

Here, N_c, N_u, P, and H_2 are hourly values of count rates, atmospheric pressure at the observation level, and effective values of absolute air humidity, which incorporate vertical distribution of humidity in the atmosphere [Zreda et al., 2012; Kobelev et al., 2021]. In (1), for N_c,N_u, P, and H_2, the time index is omitted.

The relative air humidity h_2 (at a height of 2 m) is determined experimentally, and the absolute humidity [Kalinin, 2023]

$$H_2(t) = h_2(t) H_0(t),$$

where $h_2(t)$ is the measured relative air humidity (%) at an air temperature t_2°C, and $H_0(t)$ is the maximum absolute air humidity at a given temperature

$$H_0(t) = \frac{18.02 P_{100}}{8.314\left(273.15 + t_2\right)}\left[\text{g/m}^3\right].$$

Here, the pressure of vapor saturated to 100 % P_{100} is found from the Buck formula [Buck, 1981]

$$P_{100} = 6.112 \exp\left(\frac{17.67 t_2}{t_2 + 243.5}\right)[\text{mb}].$$

If to introduce corrections the barometric coefficient β and the humidity coefficient ε are still to be predetermine from observed N_u variations, the primary CR variations expected for this detector should also be excluded from observational data, which can be done for the system of equations

$$N_c = N_u \exp\left[-\beta\left(P_0 - P\right)\right]\times \\ \times\left[1-\varepsilon\left(H_0 - H_2\right)\right] / \left(I_E / I_{base}\right). \quad (2)$$

The second multiplier takes into account exponential absorption of particles; the third, linear variation in the particle flux depending on the absolute air humidity; the fourth, primary CR variations.

In (2), I_E / I_{base} is the relative count rate of the reference detector relative to the base period, which, by definition, is related to the expected primary variations in ν_E as $\left(I_E / I_{base}\right)^{-1} = \left(1+\nu_E\right)^{-1} \cong \left(1-\nu_E\right)$. In the zero harmonic approximation, the amplitudes of the ν_E variations expected for this detector are proportional to the CR variations of the nearest reference detector ν_s, i.e. $\nu_E=\delta\nu_s$. The coefficient $\delta=C_0/C_s$ (coefficient of expected CR variations) is defined by the ratio between coupling coefficients of examined and reference NMs [Kobelev et al., 2021], i.e. knowing variations of the reference detector ν_s, we can obtain expected variations $\nu = \delta\nu_s$ in the zero harmonic approximation. In this case, there is no need to calculate coupling coefficients, it is only necessary to determine experimentally the coefficient δ, side-stepping the problem of setting the spectrum of CR variations. Then

$$N_c = N_u \exp\left[-\beta\left(P_0 - P\right)\right]\times \\ \times\left[1-\varepsilon\left(H_0 - H_2\right)\right]\times\left(1-\delta\nu_S\right) = N_u f_P f_H f_\nu. \quad (3)$$

By logarithmizing expression (3) and expanding logarithms $\ln(1\pm z) \cong +z$ in the Taylor—Maclaurin series with respect to the small parameter z, we get the linear expression

$$\ln N_c = \ln N_u - \beta\left(P_0 - P\right) - \varepsilon\left(H_0 - H_2\right) - \delta\nu_s, \quad (4)$$

i.e. the corrections are subtracted from variations in the uncorrected detector count rate. As a result, we obtain a system of linear regression equations for a_0=lnN_c, β, ε, and δ

$$\ln N_u = \ln N_c + \beta\left(P_0 - P\right) + \varepsilon\left(H_0 - H_2\right) + \delta\nu_s + \sigma_e, \quad (5)$$

where σ_e is the random error of the regression equation.

The number of equations depends on the length of the data series under study and in practice is as large as 10^4. The neutron monitor Rome was used as a reference detector for the detectors Tashkent and Alma-Ata. Data for known β and ε should be corrected using expression (1). If it is necessary to find β, ε, and δ, the problem is solved with regression equations (5).

DATA

In this work, we have used:

1. Data from NM 18-NM-64 of the stations Tashkent, Alma-Ata, and the reference station Rome [http://cr0.izmiran.ru/common/links.htm], as well as atmospheric pressure data from local weather stations. The geomagnetic cutoff rigidity is similar for all the detectors and is given in Table 1 [https://crst.izmiran.ru/cutoff].
2. Data from NM 24-NM-64 of the station Moscow and the reference station Novosibirsk [http://cr0.izmiran.ru/common/links.htm] to assess the role of the humidity effect. Surface temperature and relative humidity data was obtained from the weather station Vaisala WXT530 [http://www.awsgroup-msk.cugms.en:27416/aws-group.rmp/], located in IZMIRAN.

Key parameters of the neutron detectors Tashkent (the Institute of Geology and Seismology of the Republic of Uzbekistan) and the mountain station Alma-Ata (the Institute of Ionosphere of the Republic of Kazakhstan) and the parameters of the reference detector are listed in Table 1. The period of operation of the NM Alma-Ata is from 1973 to the present, but pressure data has been available only since 1991. The period of operation of the NM Tashkent was 1976–1992, but, unfortunately, pressure data are available only for 1991–1992. Thus, we have a complete data set (uncorrected and pressure) from the stations of interest only for 1991–1992. This period is, however, very interesting due to the solar maximum ever recorded since the beginning of the space age. Table 1 also presents parameters of the reference NM for estimating expected CR variations. Data from all the detectors is available in the data archive [http://cr0.izmiran.ru/common/links.htm]. The input data in the atmospheric variation model is N_u (left scale) and P (right scale), which are shown in Figure 1, *a*, *b*.

RESULTS

We have constructed multifactorial model of atmospheric CR variations (5) to assess and explain the role of the factors β, ε, and δ and their relationship. Nonetheless, due to the lack of data on air humidity for the stations Tashkent and Alma-Ata, we dealt only with a two-factor model. The result is presented in Tables 2, 3.

As follows from Table 2, there is no mutual correlation between the parameters P and ν (<0.3), as expected. The regression analysis allowed us to determine the coefficient of determination and the coefficients of regression of linear system of equations (5) and their errors. The result is summarized in Table 3. The quality of the model is characterized by the parameter R^2; for Tashkent, the coefficient of regression R^2=0.972, i.e. 97 % of CR variations are attributed to the constructed regression equation; and only 3 %, to the factors and errors we ignored. The coefficients of regression are also listed in Table 3.

Table 1

Key parameters of neutron detectors

	λ°	φ°	R_c (1987), GV	h, m	P_0, mb	N, s^{-1}
Tashkent	41.20	69.37	7.199	565	960	132
Alma-Ata	43.25	76.92	6.428	3340	675	1335
Rome	41.90	12.52	6.236	60	1009	131

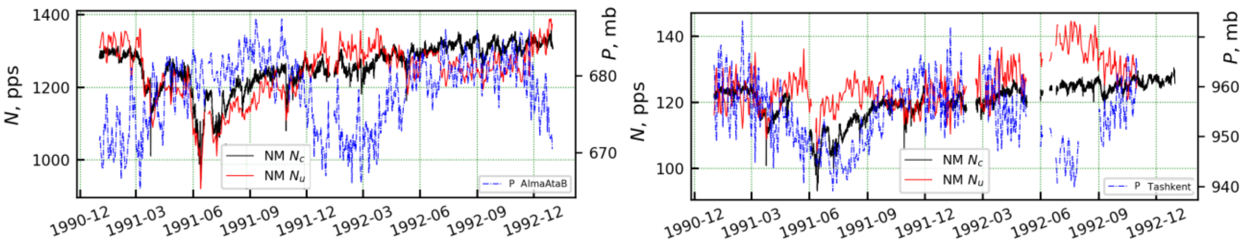

Figure 1. Time variations in measured N_u and N_c corrected for the barometric effect (left scale) and atmospheric pressure variations (right scale) at the stations Alma-Ata (*a*) and Tashkent (*b*) for 1991–1992. Correction for the barometric effect was made by the authors of the data with their own barometric coefficients

Table 2

Correlation matrix for neutron monitors

Station Alma-Ata				Station Tashkent			
	P		N_u		P	ν_s	N_u
P	1	0.096	0.574	P	1	–0.372	0.512
ν_s		1	0.849	ν_s		1	0.588
N_u			1	N_u			1

Table 3

Result of regression analysis for the neutron monitors Alma-Ata and Tashkent

	N, s^{-1}	R^2	σ_e, %	a_0±1	β±0.016, %/mb	μ±1, g/cm^2	δ±0.014, %/%	*cond*
Alma-Ata	1335	0.966	1.16	1223	0.668	155	1.126	125
Tashkent	132	0.967	0.98	117	0.686	151	1.096	213

Table 3 shows the condition number *cond*, which acts as a test for multicollinearity of the system of equations and determines the sensitivity of the output function to changes at the input (if the right side of the equation for δX is perturbed, the left side will change no more than $\delta Y = cond\,\delta X$). Ideally, *cond*=1; in our practice, several hundred, which is an indicator of a fairly good conditionality of the system. The absorption range defined as $\mu=1/\beta$ is also presented.

Figure 2 exhibits correction factors of Equation (3) for the stations Alma-Ata and Tashkent for 1991–1992. The correction factors of the atmospheric pressure f_P and primary CR variations f_V vary within 0.9–1.1, going beyond them only during large changes in atmospheric pressure or during significant primary CR variations.

In Figure 3 are scatter plots for daily mean parameters. At the top is dependences of the count rate free from primary variations on atmospheric pressure; at the bottom, the count rate dependences on primary CR variations corrected for atmospheric pressure. In each case, along with the scattering cloud there are regression lines and corresponding error corridors 1σ and 2σ wide. Variations in the count rate anticorrelate with atmospheric pressure variations; in this case, we assume β>0, and the sign determines the multiplier P_0–P.

The statistics from the detector Alma-Ata is better than that from the station Tashkent, yet the constructed model of atmospheric variations for the station Alma-Ata works a bit worse. Consequently, some factors were ignored in the model. This might have been the air humidity effect, which can be significant at mountain stations. The latter is confirmed by Table 3, from which it follows that the mean square error in the σ_e model is 1.5 times greater for the station Alma-Ata. It is, however, also possible that this is the effect of snow during the autumn-spring period, whose correction requires an ad hoc approach [Kobelev et al., 2022]. In the scatter plot of Figure 3, this manifests itself as regular departure of a group of points far beyond 3σ.

In bottom panels are the detector count rates corrected for atmospheric pressure versus primary CR variations. The coefficient of regression in both cases is seen to be δ~1, which indicates a strong effect of the independent variable ν (variations in the reference detector due to primary variations) and characterizes the degree of significance of this factor for improving the accuracy of the model.

Figure 4 exhibits histograms of detector count rates for the two stations considered, which make it possible to display tendencies for the measured parameters to change and visually assess the law of their distribution. The N_u distribution can have any form since it is usually highly modulated. The distribution of N_{cP} corrected for atmospheric pressure is seen to be narrower. It should be expected that the distribution of N_{cPv}, corrected for CR variations of all types embedded in the model, has the form of a normal distribution in residuo. This is clearly seen in right panels of Figure 3. For the high-mountain NM Alma-Ata (see Figure 4, *a*), the histogram of N_{cPv}, corrected for atmospheric pressure and primary CR variations, is slightly shifted to the left, which is due to the effect of snow in winter, ignored in model (5) [Kobelev et al., 2022].

As follows from Table 2, the width of the N_{cPv} distribution is 2.7 % for the station Tashkent and 4.2 % for the station Alma-Ata.

Figure 5 compares the CR variations expected and corrected for the barometric effect for the detectors Alma-Ata and Tashkent for 1991–1992.

We have noted above that due to the lack of humidity measurement data in Tashkent and Alma-Ata, humidity effects were ignored when estimating atmospheric effects. Let us assess the air humidity effect in the surface layer approximation, using data from NM Moscow and the reference detector Novosibirsk. Figure 6 illustrates the relative air humidity h_2, the surface air temperature t_2, and the absolute air humidity H_2, calculated on their basis, derived from weather stations' data. For 2021–2022, the following coefficients of regression were obtained for model (5): the barometric coefficient β=(0.743±0.017) %/mb, the humidity coefficient ε=(0.035±0.002 %/g/m^3, and the coefficient of expected

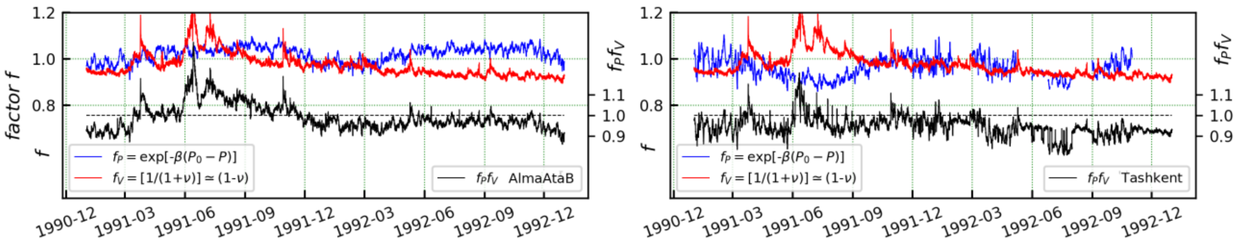

Figure 2. Time variation in correction factors of Equation (3) for the stations Alma-Ata (*a*) and Tashkent (*b*)

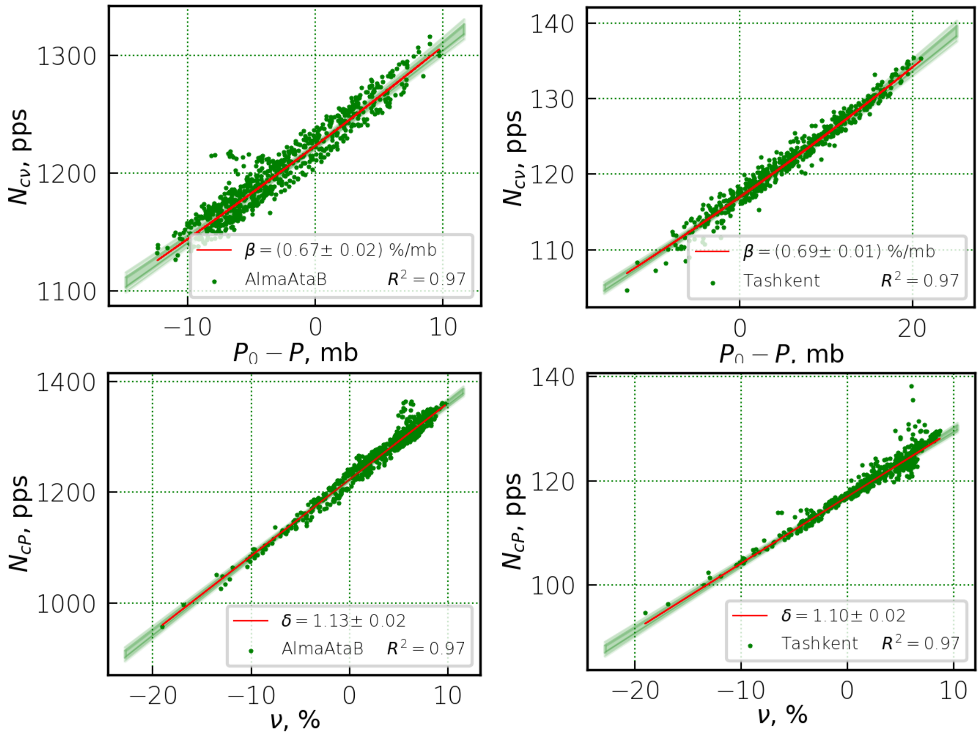

Figure 3. Scatter plots formed during analysis of data from the detectors Alma-Ata (*a*) and Tashkent (*b*) for 1991–1992

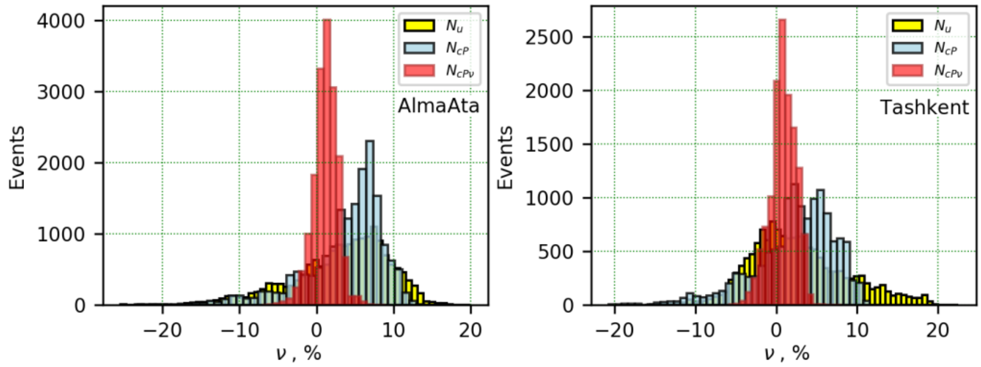

Figure 4. Distributions of CR variation amplitudes for the neutron monitors Alma-Ata (*a*) and Tashkent (*b*) according to data for 1991–1992

CR variations δ=(0.361±0.005) with a high coefficient of determination R^2=0.993. The correlation matrix is shown in Table 4. As follows from Table 4, there is no mutual correlation between P, H_2, and ν (<0.3) either.

We can conclude that the result obtained for the humidity effect agrees with the results received in [Yanchukovsky et al., 2024] for a mid-latitude station and for the same period.

The expected barometric effect is 30 % at atmospheric pressure drops ΔP=40 mb, the maximum expected humidity effect is 1.6 % at the annual absolute humidity drop ΔH_2=40 g/m^3 (Δt_2=40 °C, Δh=80 %).

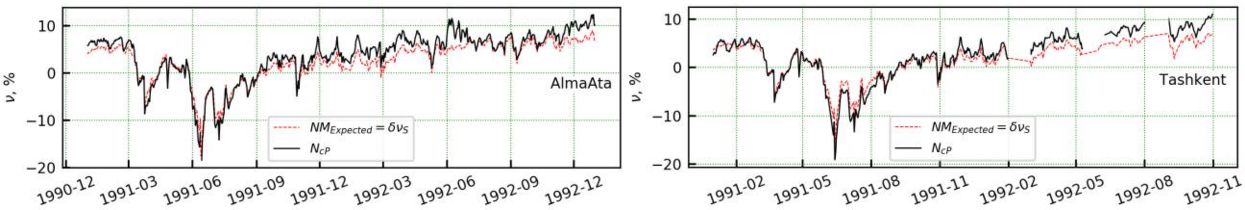

Figure 5. Comparison between time changes in observed neutron component variations expected (according to the data from the reference station Rome) and corrected for the barometric effect for the neutron monitors Alma-Ata and Tashkent

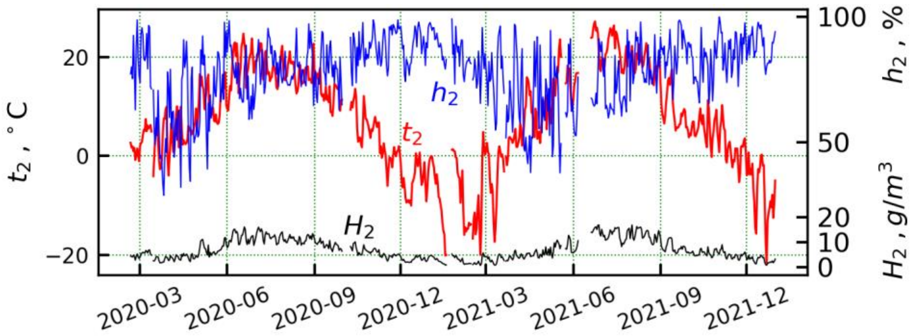

Figure 6. Time variations in relative air humidity h_2, surface air temperature t_2, and absolute air humidity H_2, calculated from them

Table 4

Correlation matrix
for the neutron monitor Moscow

	P	H_2	ν	*N*
P	1	–0.121	0.001	0.993
H_2		1	0.104	–0.111
ν			1	0.059
N				1

CONCLUSIONS

We have proposed a formula for the three-parameter model of CR variations in the atmosphere, including heliospheric CR variations and variations of atmospheric origin (barometric and air humidity effects).

Due to the lack of data on air humidity for the low-latitude stations Tashkent and Alma-Ata for the period of high solar activity in 1991–1992, we have determined only the barometric coefficient corrected for primary CR variations. The barometric coefficient for Tashkent is 0.686±0.016 %/mb. The contribution coefficient of primary CR variations is close to 1 and is equal to 1.096±0.014 since we employed the reference station Rome with similar characteristics. The coefficient of determination R^2=0.97. The barometric coefficient for Alma-Ata for the same period is 0.668±0.016 %/mb. Despite the best statistics, the model of atmospheric variations built for the mountain station Alma-Ata works a bit worse. This is primarily due to the effect of snow.

In the three-parameter model of CR variations in the atmosphere, the barometric and humidity coefficients for the mid-latitude station Moscow for 2021–2022 are β=(0.743±0.017) %/mb, ε=(0.034±0.002) %/g/m^3, which agrees well with the results obtained by Yanchukovsky et al. [2024].

Since the humidity effect is significant, it would be useful to equip all CR stations with weather stations with humidity and temperature detectors to take it into account.

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