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Effect of turbulence and air velocity on radon progenys

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In this paper, a simulation of the distribution of radon progeny over the height of the atmosphere, depending on the amount of turbulent mixing and the vertical air velocity, is presented. The obtained results are compared with the change in the activity ratio of Bi-214/Pb-214 isotopes recorded in rainwater during 3-year observations in Prague. It is found that the reasons for the most common values of Bi-214/Pb-214 can be the height of the lower edge of the cloud of 0.2-1.4 km and the vertical air velocity of 0.1 – 0.2 m / s. The ratio changes slightly from changes in the turbulent mixing, the value of the vertical air movement makes the main contribution. It is found that with the increase in the intensity of rain, a shift in the radioactive equilibrium should occur due to an increase in the velocity of vertical air. Atmospheric inversion is able to balance the volumetric activities of the descendants of atmospheric radon, atmospheric inversion can be identified by the equality between the activities of the radon progeny in the atmosphere at different altitudes or in rainwater. It is shown that the search for the relationship between precipitation intensity and gamma radiation is expose to error, without taking into account the influence of the A_{Bi-214}/A_{Pb-214} ratio, due to the unequal activities of the atmospheric isotopes Bi-214 and Pb-214. This error of 7-14% when using gamma radiometry, and of 5-9% when using dosimeters is estimated.

Keywords: radon progeny in the terrestrial atmosphere, mathematical model, vertical air velocity, turbulent diffusion, Bi-214/Pb-214, rain induced gamma activity, advection, inversion.

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Introduction

Radon and its precursors are naturally occurring radioactive nuclides found in the atmosphere around the globe. The radon isotope Rn-222 is formed in the decay chains of primary U-238 contained in the Earth's crust. The intensity of the output of Rn-222 depends on the geophysical features of the upper soil layer. After being released from the earth, radon, being an inert gas, is easily dispersed without interacting with atmospheric aerosols. Having a half-life of 3.8 days, Rn-222 inhabits it with descendants from the decay chain: Rn-222→3.8 days Po-218→3.1 min. Pb-214→26.81 min. Bi-214→20 min. Po-214→164 µs Pb-210.

Daughter radionuclides Pb-214 and Bi-214, which have a significant half-life compared to other radionuclides of the radon family, exist in the atmosphere for a longer time, during which they can associate with large suspensions - dust and water aerosols. Under certain conditions, fine water droplets can collect in clouds as a raindrop, causing rain to occur. Rain droplets are deposited on the surface of the earth, capturing radioactive daughter products of radon decay along the way. This phenomenon, the washing out of the radioactive decay products of radon by rain drops, is called "radon washout"[1].

Since radionuclides of the radon family undergo radioactive decay, these radionuclides can be detected by the type and energy of the emitted particle. All decays of Pb-214 and Bi-214 are accompanied by the emission of gamma quanta carrying away the excess potential energy of the daughter nucleus. By measuring the energies of the emitted quanta, the presence of these radionuclides in rainwater can be detected. Thus, using the intensity of the Pb-214 isotope, in [2] the temporal changes in the gamma radiation counting rate from the rain intensity were restored. In addition to the spectral determination of the increase in the activity of Pb-214 or Bi-214, during precipitation, an increase in the total intensity of gamma radiation and the dose rate is well recorded [3, 4, 5, 6].

In most studies based on the total registration of gamma radiation [7, 8, 9, 10], attempts were made to find a correlation between the change in the gamma background and the intensity of precipitation, but no significant relation was found in them. The most probable reasons for the weak correlation could be: low temporal resolution of the obtained data [11], changes in the precipitation ability of precipitation to wash out associated with their intensity or a likely decrease in the amount of radon daughter products in the atmosphere during prolonged precipitation [5, 12]. One of the insufficiently studied reasons is the nonequilibrium finding of daughter products of radon decay in the atmosphere at the height of the lower cloud boundary. The nonequilibrium presence of Bi-214 and Pb-214 isotopes in the atmosphere and subsequently in rainwater can lead to distortion of the signal received by the devices, since the vast majority of studies aimed at studying the correlation of precipitation and the growth of total gamma radiation use the assumption that these isotopes are in equilibrium. Examples of the equilibrium shift can be seen in the work on the study of rainwater over the period of 3-year measurements in Prague [13].

Since the ratio of precipitation intensity and the growth of terrestrial gamma radiation can be affected by the nonequilibrium presence of radon decay products in the atmosphere, the purpose of this work is to describe the relationship between the activity of radon decay products in the atmosphere and the values of turbulent mixing and vertical ascending airstream.

Mathematical model

In the framework of this work, turbulent mixing and an ascending air flow in a stationary state are considered. The model is constructed on the basis of the verified equations from [14, 15]: The mathematical model includes the radon motion equation:

$$(D_{\mathrm{Mi}}+D_{\mathrm{T}}(z))\frac{d^2A_1(z)}{dz^2}-v_{\mathrm{W}}\frac{dA_1(z)}{dz}-\lambda_1\cdot A_1(z)=0 \quad (1)$$

And equations of motion of radon progeny where i=2-5 represent the following isotopes Po-218 (RaA), Pb - 214 (RaB), Bi-214 (RaC) and Po-214 (RaC'), respectively;

$$(D_{\mathrm{Mi}}+D_{\mathrm{T}}(z))\frac{d^2A_i(z)}{dz^2}-(v_{\mathrm{W}}+v_{\mathrm{F}})\frac{dA_i(z)}{dz}+\lambda_i\cdot \mathrm{A}_{\mathrm{i\text{-}1}}(z)-\lambda_i\cdot \mathrm{A}_{\mathrm{i}}(z)=0 \quad (2)$$

A boundary condition that takes into account the absence of radon and its progeny with increasing height: $A_{1-5}(z\to\infty)=0$,

The initial condition for radon, taking into account its output from the ground surface: $-(D_{\mathrm{Mi}}+D_{\mathrm{T}}(z))\frac{dA_1(z)}{dz}|_{z=0}+v_{\mathrm{W}}\cdot A_1(z)|_{z=0}=q$,

An initial condition that takes into account the content of radon descendants in the surface atmosphere:
$-(D_{\mathrm{Mi}}+D_{\mathrm{T}}(z))\frac{dA_{2-5}(z)}{dz}|_{z=0}+(v_{\mathrm{W}}+v_{\mathrm{F}})\cdot A_{2\text{-}5}(z)|_{z=0}=0$,

Where $A_1(z)$ is a function of the height of the volume activity of radon Rn-222 in the atmosphere, Bq $\cdot m^{-3}$, $A_{\mathrm{i}}(z)$ is a function of the height of the volume activity of the i-th radionuclide in the atmosphere, Bq$\cdot m^{-3}$; q – radon flux density Rn-222 from the ground surface, Bq$\cdot m^{-3}\cdot s^{-1}$; D_{Mi} is the molecular diffusion coefficient, $m^2\cdot s^{-1}$; D_{T} is the coefficient of atmospheric turbulence, $m^2\cdot s^{-1}$; v_{W} is the vertical component of the upward air flow velocity, m/s, at negative values it is directed to the earth's surface, at positive values it coincides with the direction of the z axis; v_{F} is the deposition rate under the influence of gravity, m/s; λ_i is the constant of radioactive decay, s^{-1}.

Results and discussions

Special cases of stationary transport equations for different values of the turbulent diffusion coefficient and the velocity of the ascending air flow can be seen in in Fig. 1

When the values of v_{W} and Dt are close to zero, the radioactive equilibrium between the volumetric activities of Pb-214 and Bi-214 is set to a height of 200 meters. An increase in diffusion by a factor of ten shifts the moment of equilibrium between the volume activities of isotopes to reach a height of 500 meters above the ground. At the same time, a change in the speed of the ascending air flow by 15 times shifts the height of the equilibrium of the volume activities of Pb-214 and Bi-214 to 1.5 km. Turbulent mixing and updrafts contribute to a more intensive removal of Bi-214 from the surface air layer compared to the content of Pb-214. The predominance of the concentration of Pb-214 over Bi-214, at an altitude of several kilometers to the soil surface, strongly depends on the speed of the updraft than on turbulent mixing.

In order to find the ratio of radionuclides of the radon series washed out by rainwater from the atmosphere, it is necessary to integrate the volume activities of radionuclides $A_{\mathrm{i}}(z)$ depending on the height of the lower cloud boundary.

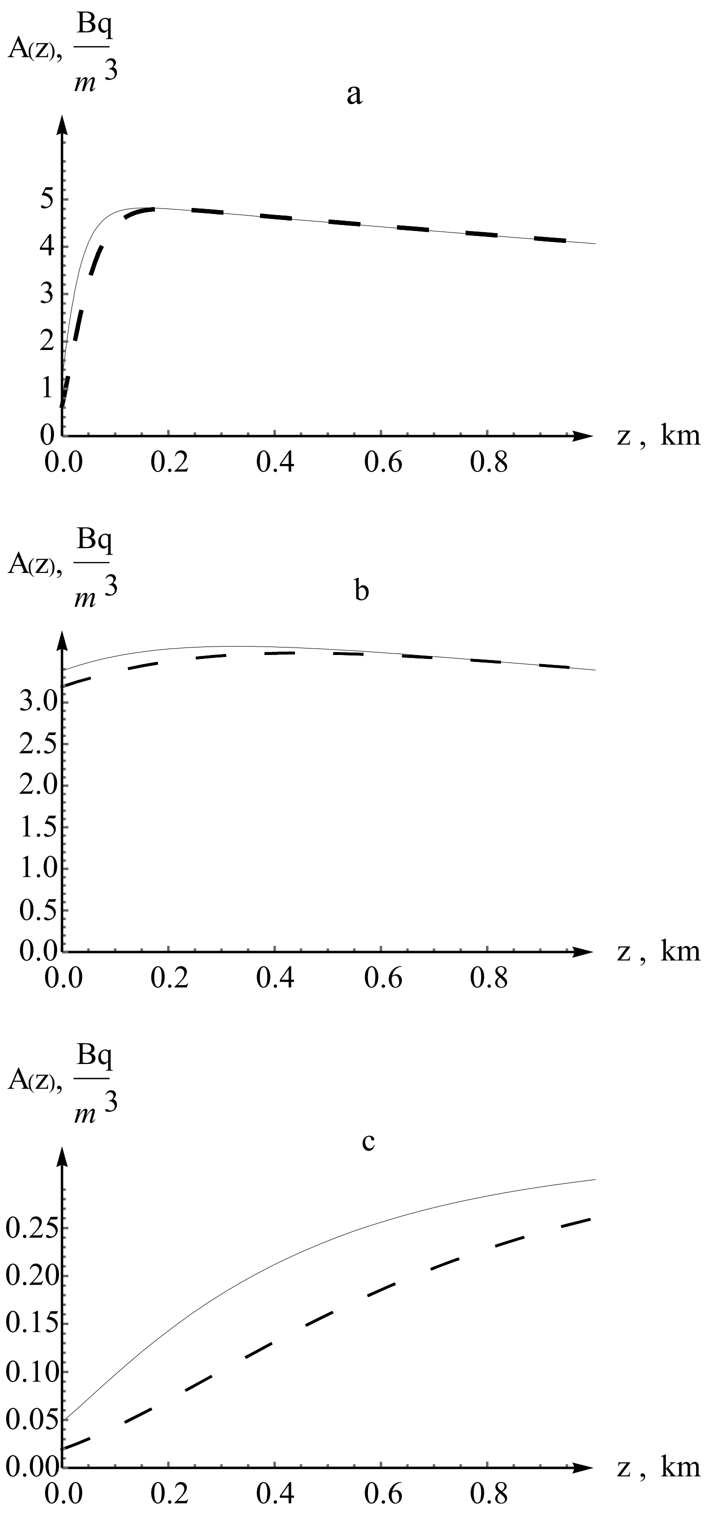

Fig. 1. Changes in the volume activity of atmospheric radionuclides Pb- 214 (solid line) and Bi-214 (dashed line) depend-ing on the turbulent mixing Dt and the air vertical velocity v_W. Fig. 1a. – v_W =0.01, D_T =0.13; Fig. 1b. – v_W =0.01, D_T =15; Fig. 1b. – v_W =0.15, and D_T =15

The integral values of the $A_i^h(z)$ activity of the i-th radionuclide in an atmospheric column with a unit base of 1 m^2 and a height of h, m, are determined from the equation:

$$A_i^h(z) = \int_0^z A_i(z)d(z) \tag{3}$$

Depending on the height of the lower boundary of clouds for the G class of atmospheric stability [16] and various values of v_W, the calculated integral values $A_i^h(z)$ and are given in Tab. 1 as the relations $A_{\text{Rn-222}}^h : A_{\text{Po-218}}^h : A_{\text{Pb-214}}^h : A_{\text{Bi-214}}^h$.

Table 1

The ratio of the height-weighted average of the lower boundary cloud activity Rn-222:Po-218:Pb-214:Bi-214 (relative units) at different speeds of the vertical component of the air for the G class of atmospheric stability

Dt, m^2/s	v_W, m/s	h, km		
		0.6	0.8	1
0.13	0.01	1.00:1.00:0.96:0.93	1.00:1.00:0.97:0.95	1.00:1.00:0.98:0.96
0.13	0.05	1.00:0.98:0.79:0.65	1.00:0.98:0.84:0.73	1.00:0.99:0.87:0.79
0.13	0.1	1.00:0.95:0.60:0.38	1.00:0.97:0.69:0.50	1.00:0.97:0.75:0.58
0.13	0.15	1.00:0.93:0.47:0.23	1.00:0.95:0.56:0.33	1.00:0.96:0.63:0.42
0.13	0.2	1.00:0.91:0.38:0.15	1.00:0.93:0.47:0.23	1.00:0.95:0.54:0.31
Dt, m^2/s	v_W, m/s	h, km		
		1.2	1.4	1.6
0.13	0.01	1.00:1.00:0.98:0.97	1.00:1.00:0.98:0.97	1.00:1.00:0.99:0.98
0.13	0.05	1.00:0.99:0.89:0.82	1.00:0.99:0.91:0.85	1.00:0.99:0.92:0.87
0.13	0.1	1.00:0.98:0.79:0.65	1.00:0.98:0.82:0.70	1.00:0.98:0.84:0.73
0.13	0.15	1.00:0.97:0.69:0.50	1.00:0.97:0.73:0.56	1.00:0.97:0.76:0.61
0.13	0.2	1.00:0.96:0.60:0.38	1.00:0.96:0.65:0.44	1.00:0.97:0.69:0.50

With an increase in the height of the lower boundary of the cloud, the equilibrium between the radon decay products is restored for the ranges of air flow velocities shown in the table. At the same time, the equilibrium is established earlier for small values of the ascending air flow.

A special case of the stationary transport equations for the inversion of the ascending air flow at an altitude of 1 km (h=1 km, vw=0) and Dt=0.5 can be seen in Fig. 1.

During inversion, an exponential decrease in the volume activity of radon and its decay products occurs. The volume activities of radon isotopes are equal at all altitudes. The integral values of Ahi of radon decay products are comparable to each other, and their ratios are $A_{\text{Rn-222}}^h$:$A_{\text{Po-218}}^h$=1, $A_{\text{Po-218}}^h$:$A_{\text{Pb-214}}^h$=1, $A_{\text{Pb-214}}^h$: $A_{\text{Bi-214}}^h$=1. The inversion of the atmosphere contributes to the equilibrium accumulation of radon isotopes in rainwater.

Fig. 1 and 2 show the different behavior of the volume activities of Pb-214 above Bi-214 at a height of 0 meters during inversion, turbulent mixing and an ascending air flow. Taking into account that special cases for these figures are constructed at the same state of the radon flux density from the ground surface (radon flux density = 0.05 Bq/($m^2 * s$)), we can make an assumption about a possible indication of the state of the atmosphere by the radon flux density and the volume activity of radon descendants.

In most works based on the analysis of bismuth and lead activities in collected rainwater, the ratio $A_{Bi-214} : A_{Pb-214}$ is used, which is equivalent to the ratio of weighted average radionuclides of an atmospheric column with a height up to the lower boundary of the cloud h, that is, $A^h_{Bi-214}/A^h_{Pb-214}$.

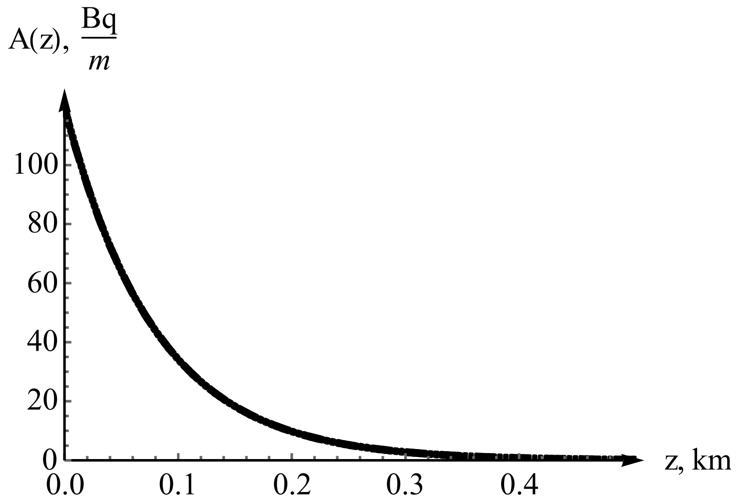

Fig. 2. Establishing the equilibrium of the volume activity of Rn-222 (dotted line) and its offspring: the gray, solid and dotted line of the activities of the radionuclides Po-218, Pb-214, Bi-214, respectively, are superimposed on each other

These relations are presented in Tab. 2. Some of the presented relations fall in the range from 0.6 to 0.7 and exist at the height of the lower edge of the clouds from 200 to 1400m and at the speed of the ascending air flow from 0.05 to 0.2 m / s. This range of $A_{Bi-214} : A_{Pb-214}$ ratios was measured in Prague rainwater [13]. The condition of rapid ascending air flows (0.2 m/s) that we found in this study is most likely related to the urban development of Prague and the influence of this development on the increase in the convective flow. For example, for a less urbanized area of India, such rapid updrafts are quite rare and occupy no more than 10% of the observed events [17].

Tab. 2 shows that the decline in the ratio $A^h_{Bi-214}/A^h_{Pb-214}$ occurs only with an increase in v_W, taking into account the result of work [18] in which a decrease in the ratio A_{Bi-214}/A_{Pb-214} was observed with an increase in the precipitation rate, we can talk about an increase in the upward flow with an increase in the precipitation rate. This statement does not contradict common sense, since cold raindrops passing through the atmosphere cool its upper layers more strongly than before the rain begins and create an additional temperature gradient, leading to an increase in the speed of the ascending air flow.

Since the ratio of Bi-214 and Pb-214 isotopes in rainwater is not constant and consists of 0.6 to 0.8 relative units, for radiometers and dosimeters we can estimate the error that occurs when ignoring this change in the ratio during the analysis of the relationship between the intensity of precipitation and the growth of the gamma background. To do this, it is enough to use information about the quantum yield due to the decay of one isotope Bi-214 and Pb-214, as well as their gamma constants.

This error will be from 7 to 14% for measurements performed using radiometers. And from 5 to 9% for measurements performed using dosimeters.

Table 2

The ratio of the $A^h_{Bi-214}/A^h_{Pb-214}$ activities weighted by the cloud height (relative units) at different ratios of the turbulent diffusion coefficient and the vertical velocity of the air

Dt, m^2/s	v_W, m/s	h, km									
		0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
0.13	0.01	0.91	0.95	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99
0.13	0.05	0.51	0.72	0.82	0.87	0.91	0.93	0.95	0.95	0.95	0.96
0.13	0.10	0.31	0.49	0.63	0.72	0.77	0.85	0.87	0.88	0.88	0.91
0.13	0.15	0.18	0.38	0.49	0.59	0.67	0.77	0.80	0.82	0.82	0.84
0.13	0.20	0.17	0.31	0.39	0.49	0.57	0.68	0.72	0.75	0.75	0.77
0.13	0.40	0.00	0.17	0.21	0.27	0.34	0.44	0.49	0.57	0.57	0.27
0.13	0.50	0.00	0.11	0.20	0.24	0.27	0.39	0.43	0.45	0.45	0.49
1.5	0.01	0.92	0.95	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99
1.5	0.05	0.59	0.74	0.83	0.87	0.90	0.93	0.94	0.95	0.95	0.96
1.5	0.10	0.35	0.52	0.64	0.73	0.78	0.85	0.87	0.89	0.89	0.90
1.5	0.15	0.24	0.39	0.51	0.60	0.67	0.77	0.80	0.82	0.82	0.84
1.5	0.20	0.17	0.30	0.41	0.50	0.58	0.63	0.68	0.72	0.75	0.78
5	0.01	0.93	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99
5	0.05	0.69	0.78	0.84	0.88	0.90	0.93	0.94	0.95	0.95	0.96
5	0.10	0.45	0.57	0.67	0.74	0.79	0.85	0.87	0.89	0.89	0.90
5	0.15	0.31	0.43	0.54	0.62	0.68	0.77	0.80	0.82	0.82	0.84
5	0.20	0.23	0.34	0.44	0.52	0.59	0.64	0.69	0.73	0.76	0.78
15	0.01	0.95	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99
15	0.05	0.79	0.83	0.86	0.89	0.91	0.93	0.94	0.95	0.95	0.96
15	0.10	0.60	0.66	0.72	0.77	0.80	0.86	0.88	0.89	0.89	0.90
15	0.15	0.45	0.52	0.59	0.65	0.70	0.78	0.81	0.83	0.83	0.85
15	0.20	0.34	0.42	0.49	0.56	0.61	0.66	0.70	0.74	0.76	0.79
70	0.01	0.96	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.99
70	0.05	0.89	0.90	0.91	0.92	0.92	0.94	0.94	0.95	0.95	0.95
70	0.10	0.79	0.80	0.82	0.83	0.85	0.88	0.89	0.90	0.90	0.91
70	0.15	0.69	0.71	0.73	0.75	0.77	0.81	0.83	0.85	0.85	0.86
70	0.20	0.60	0.62	0.65	0.67	0.70	0.73	0.75	0.77	0.79	0.81
100	0.01	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98
100	0.05	0.91	0.91	0.92	0.92	0.93	0.94	0.95	0.95	0.95	0.96
100	0.10	0.82	0.83	0.84	0.85	0.86	0.88	0.89	0.90	0.90	0.91
100	0.15	0.73	0.75	0.76	0.78	0.79	0.83	0.84	0.85	0.85	0.86
100	0.20	0.65	0.67	0.69	0.71	0.73	0.75	0.77	0.79	0.80	0.82
160	0.01	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98
160	0.05	0.92	0.93	0.93	0.93	0.94	0.95	0.95	0.95	0.95	0.96
160	0.10	0.86	0.86	0.87	0.87	0.88	0.90	0.90	0.91	0.91	0.92
160	0.15	0.79	0.79	0.80	0.81	0.82	0.84	0.85	0.86	0.86	0.87
160	0.20	0.72	0.73	0.74	0.75	0.77	0.78	0.79	0.81	0.82	0.83

Conclusion

As shown in the paper, the speed of the ascending air flow significantly affects the ratio between the products of atmospheric radon decay, which can be detected by spectrometry or gamma-ray sampling of the terrain during rain. It was found that with an increase in the intensity of rain, a shift of the radioactive balance should occur due to an increase in the velocity of the ascending air flow.

Inversions are able to balance the activities of radon decay products in the atmosphere, an indication of the onset of inversion can be the equality between the activities of the daughter products of radon decay in rainwater and at all atmospheric altitudes.

Gamma survey of the area, due to changes in the integral concentration of radon decay products, may give an error when searching for a dependence on the intensity of precipitation. Such an error can be from 7 to 14% compared to the results obtained from the conditions for establishing radioactive equilibrium when using gamma radiometers, and from 5 to 9% for measurements of the gamma background using dosimeters.

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Влияние турбулентности и восходящих потоков воздуха на дочерние продукты распада радона

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Получены результаты моделирования распределения дочерних продуктов радона в атмосферном столбе по высоте, объясняющие изменение концентраций радионуклидов в дождевой воде в зависимости от высоты нижней кромки облаков. Значения соотношений активностей A_{Bi-214}/A_{Pb-214} радионуклидов дождевой воды от 0.6 до 0.8, могут возникать при высоте нижней кромки облаков от 0.2 до 1.4 км и адвекции от 0.1 до 0.2 м/с соответственно. Произведена оценка шибки от 7 до 14%, возникающая при использовании гамма радиометров, и от 5 до 9% - дозиметров, во время осадков с целью поиска корреляции роста гамма-фона и интенсивности жидких ливневых осадков.

Ключевые слова: продукты распада радона в атмосфере, математическая модель, вертикальная скорость воздуха, турбулентная диффузия, соотношение гамма излучения Bi-214/Pb-214, вымывание радиоактивных аэрозолей осадками, адвекция, инверсия

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