Variability of thoron distribution in the surface atmosphere at Borok Geophysical Observatory

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Abstract. The variability of radon-220 (thoron) distribution in the surface atmosphere is investigated by mathematical modeling of thoron turbulent transport, based on the data of continuous field natural observations at Borok Geophysical Observatory (Central Russia). The thoron flux from the surface was set according to the observations. Variations of turbulent diffusion coefficient altitude profiles were calculated by the observations of wind velocity pulsations at two altitudes made synchronously on the same location. The altitude profiles of thoron volumetric activity typical for the atmospheric surface layer are estimated. It is shown that the thoron volumetric activities at any altitudes vary concurrently, but the largest thoron volumetric activity, as well as its gradient, occurs below 0.5 m at nighttime.

1. Introduction
Radon isotopes $^{222}\text{Rn}$ and $^{220}\text{Rn}$ (thoron) make the main contribution to the surface atmosphere ionization over the land under natural conditions [1–3]. Natural radon isotopes are noble radioactive gases escaped from minerals into pore space of rocks and soil and then transported to the atmosphere by diffusion and advection [4, 5]. The soil radon is actively investigated, first of all due to increasing of its volumetric activity is considered to be earthquake precursors [6]. Note that the volumetric activities of the both natural radon isotopes $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are of interest to be observed [7, 8]. Studies of atmospheric radon are important because of its radiation hazard to of the people’s health [9].

The short lifetime of $^{220}\text{Rn}$ leads to the fact that all $^{220}\text{Rn}$ entering the atmosphere decays in its near-surface layer, in contrast to the relatively long-lived $^{222}\text{Rn}$, which has time to spread within the entire atmospheric boundary layer. Thus, the contribution of $^{222}\text{Rn}$ to ionization of the near-surface atmosphere can be quite significant, even despite its low efflux from the soil surface [10]. At the same time, the short lifetime of $^{220}\text{Rn}$ requires a special approach to measure its volumetric activity. The authors have already proposed a method to estimate ultra-low background volumetric activities of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in soil air and in the surface atmosphere [11]. In this paper the early experience is expanded by continuous natural observations of atmospheric surface layer turbulent parameters and mathematical modeling of thoron turbulent transport. The paper presents the variations of thoron volumetric activity altitude profiles, based on the data of continuous observations at the experimental site of the Borok Geophysical Observatory of Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences (BGO IPE RAS).
2. Atmosphere thoron transport modeling

Thoron transport in the atmosphere, taking into account its diffusion and radioactive decay, is described by the equation

\[
\frac{\partial A}{\partial t} + \frac{\partial}{\partial z} \left(K(z,t) \frac{\partial A}{\partial z} \right) - \frac{1}{\tau} A = 0,
\]

where \(A\) is a thoron volumetric activity in the atmosphere, \(\tau\) is a thoron lifetime (80 s), \(K(z,t)\) is an effective diffusion coefficient dependent on altitude \(z\) and time \(t\).

A mean surface thoron flux density \(J_0\) and a zero value of thoron volumetric activity on infinity altitude can be given as a boundary conditions

\[
-K(0,t) \left( \frac{\partial A}{\partial z} \right)_{z=0} = \frac{J_0}{\tau}, \quad A|_{z=\infty} = 0.
\]  

The diffusion coefficient \(K(z,t)\) is assumed to be

\[
K(z,t) = K_M + K_T(z,t), \quad K_T(z,t) = \begin{cases} K_0(t) \left(z/z_0\right)^{m(t)}, & z > z_0, \\ 0, & z < z_0, \end{cases}
\]

where \(K_M\) is a molecular diffusion coefficient, \(K_T(z,t)\) is a turbulent diffusion coefficient and \(z_0\) is a surface roughness parameter. The dependence of the turbulent diffusion coefficient on altitude above the surface roughness parameter \(z_0\) is assumed to be approximated by the power law \([12]\) with a factor \(K_0(t)\) and an exponent \(m(t)\). These approximation parameters can be determined from the observations.

Through discontinuity of a function \(K(z,t)\) in \(z = z_0\), the equation (1) must be replaced in \(z = z_0\) with a continuity condition of thoron flux density

\[
-K_M \left( \frac{\partial A}{\partial z} \right)_{z=z_0 \rightarrow 0} = -\left(K_M + K_0(t)\right) \left( \frac{\partial A}{\partial z} \right)_{z=z_0 \rightarrow 0}.
\]

The equations (1–4) can be greatly simplified. Firstly, we can eliminate a term \(\partial A/\partial t\) from (1), because a thoron lifetime is much less than a diffusion time scale. So a time \(t\) can be considered as a parameter in a boundary problem (1–4). Secondly, we can eliminate \(K_M\) from the equations in region \(z > z_0\), because a molecular diffusion coefficient is much less than a turbulent one. Finally, we can assume that an exponent \(m(t)\) takes only two possible values: \(m = 1\) under a stable atmosphere stratification and \(m = 4/3\) under unstable one. The equation (1) can be solved analytically after these simplifications. The solution is given by

\[
A(z) = \begin{cases} A_0 F_m \left( \frac{z}{h_M} \right), & z \geq z_0, \\ A_+ \exp \left( \frac{z}{h_M} \right) + A_- \exp \left( -\frac{z}{h_M} \right), & z \leq z_0, \end{cases}
\]

where \(h_M = (\tau K_M)^{1/2}, h_1 = \tau K_0, h_{4/3} = (\tau K_0)^{4/3} z_0^2, F_m(x) = K_0(2x^{1/2}), F_{4/3}(x) = x^{-1/3} \exp(-x^{4/3}), K_0\) is modified Bessel function of the second kind of zero order. The factors \(A_0, A_+\) and \(A_-\) can be calculated from equations (2) and (4).

3. Measurement equipment and data

The continuous monitoring of thoron volumetric activity as well as a turbulent regime of the atmospheric surface layer was conducted at the experimental site of the BGO IPE RAS during the summer season of 2016.
A seismic radon station SRS-05 [13] installed near the surface in the weather shelter was used as a sensor of the thoron volumetric activity. The SRS-05 is widely used for monitoring the volumetric activity of radon, primarily in order to detect its increase as one of the precursors of earthquakes. Low sensitivity of the sensor does not allow real-time registration of background values of thoron volumetric activity. At the same time background values of thoron volumetric activity can be estimated by the longtime measurement using the seismic radon station [11].

Two ultrasonic stations METEO-2H [14] installed at heights of 2 and 10 m recorded the main meteorological parameters (air temperature, horizontal components of wind speed and wind direction, vertical wind speed, relative air humidity and air pressure) with a 10 Hz sampling frequency. The software of these stations enables also evaluation of the vertical velocity variance, total energy of turbulent pulsations, friction velocity and the Monin-Obukhov length scale. It makes also possible to estimate the turbulent diffusion coefficient at the corresponding heights. A configuration of the measuring instruments is presented in figure 1.

![Figure 1](image)

**Figure 1.** A configuration of the measuring instruments, installed on the experimental site of the BGO IPE RAS during June – July, 2016.

The obtained data in the so-called fair weather days were chosen to be analysed. Fair weather implies the following conditions: (1) thunderstorms, precipitation, fog, mist and haze were absent; (2) wind speed did not exceed 6 m/s; (3) no low clouds were present, and the total cloudiness did not exceed three.

### 4. Estimation of model parameters by the observational results

To estimate the surface thoron flux density $J_0$, the data observed under stable atmosphere stratification were chosen, because maximum of thoron volumetric activity is observed precisely under stable atmosphere stratification. The stable atmosphere stratification has been identified by the down-directed vertical turbulent temperature flux, estimated by the software of ultrasonic stations. The example of diurnal variations of vertical turbulent temperature flux on altitudes 2 and 10 m are presented on figure 2 (a). It is obvious that stable atmosphere stratification existed at night (00:00–02:30 UT and 15:30–00:00 UT). The diurnal variations of turbulent diffusion coefficient on same altitudes are presented on...
figure 2 (b). It is apparent that a turbulent diffusion coefficient can be well approximated indeed by the power law (3) with $m = 1$ for these time intervals.

![Figure 2](image_url)

**Figure 2.** The results of the observations on the experimental site of the BGO IPE RAS in 13 July, 2016. (a) — The diurnal variations of vertical turbulent temperature flux on altitudes 2 m (light green line) and 10 m (light blue line) with one hour running averaging (green and blue lines). (b) — The approximation of diurnal variations of turbulent diffusion coefficient on altitudes 2 m (green lines) and 10 m (blue line) for $m = 1$ (solid lines) and $m = 4/3$ (dashed lines), vertical bars denote standard deviations for measured turbulent diffusion coefficients at hour time interval centered on the current minute.
The mean thoron volumetric activity observed by the seismic radon station at time intervals with stable atmosphere stratification (14 days totally) was \( A(7 \text{ cm}) = (4.27 \pm 3.67) \text{ Bq/m}^3 \). The mean value of the parameter \( K_0 \) estimated from the ultrasonic stations data at the same time intervals was \( K_0 = (0.032 \pm 0.016) \text{ m/s} \). The analytical solution (5) of stationary boundary problem (1–4), corresponding to these parameters, allows to estimate the surface thoron flux density \( J_0 = (1.5 \pm 1.3) \text{ atoms/m}^2/\text{s} \). The corresponding estimations of mean altitude profiles of thoron volumetric activity and thoron flux density with the surface roughness parameter \( z_0 = 0.1 \text{ m} \), according to grassland and low crops [15], are presented on figure 3. Taking into account that influence of radon turbulent transport in the atmosphere on surface radon flux density is negligible [16], one can use the estimation of \( J_0 \) as a stable model parameter.

![Figure 3](image)

**Figure 3.** The model estimations of mean altitude profiles of thoron volumetric activity (blue line) and thoron vertical flux density (green line), calculated from BGO IPE RAS observations in summer of 2016 under fair-weather conditions and stable atmosphere stratification. Horizontal bars denote standard deviations for estimated values according standard deviations of measured thoron volumetric activity at 0.07 m altitude.

### 5. Results and conclusions

The typical approximation of \( K(z,t) \) diurnal variation, calculated from (3) with \( z_0 = 0.1 \text{ m} \), \( m = 4/3 \) and \( K_0(t) \), estimated by results of the observations on the experimental site of the BGO IPE RAS in 13 July, 2016 (see figure 2), is presented in figure 4 (a). The corresponding diurnal variation of thoron volumetric activity altitude profile obtained through analytical solution (5) of the boundary problem (1, 2, 4) with \( J_0 = 2.5 \text{ atoms/m}^2/\text{s} \) is presented in figure 4 (b).

It is easy to see that the thoron volumetric activity at any altitude across the atmospheric surface layer varies synchronously with the near-surface thoron volumetric activity. The thoron volumetric activity is 2–5 times greater at midnight than at midday. At the same time the gradient of thoron volumetric activity is also much larger at nighttime then daytime. The largest gradient of thoron volumetric activity occurs below 0.5 m at night. So the thoron volumetric activity already above 4 m is always very small and does not depend on time of day in contrast to the volumetric activity of surface \(^{222}\text{Rn} \), which is considerably varied over the day, especially below 2 m [17].
Figure 4. The diurnal variations of altitude profile of turbulent diffusion coefficient (a) and thoron volumetric activity (b) calculated from the results of the observations on the experimental site of the BGO IPE RAS in 13 July 2016.
The presented data agree with the results obtained by direct near-surface measurements of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ activities [18]. It is highly likely that diurnal variations of thoron volumetric activity altitude profiles are typical for the atmospheric surface layer over the land. The proposed technique makes most exact and complete estimates of atmospheric $^{220}\text{Rn}$ variations in the surface layer, based on the continuous monitoring of surface atmosphere turbulent regime. So, the including of $^{220}\text{Rn}$ into variability of integral natural radioactivity in the surface atmosphere can be estimated by the proposed technique in many locations over the world.

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