

The radon flux density from the Earth's surface as an indicator of a seismic activity

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Abstract. The radon flux density from the Earth's surface is suggested here as an indicator of a seismic activity along with the soil gas radon concentration in current use for this purpose. Numerical calculations performed by the diffusive-convective radon transport equation for porous media are presented to show that the radon flux density is more sensitive to convective velocity variations than the soil gas radon concentration. It is demonstrated that the greatest advantages of the approach put forward in this work can be expected for homogeneous geological media.

1 Introduction

A search for reliable methods of short-term seismic-activity predictions is an important geophysical challenge. A number of authors (Virk et al., 1997; Segovia et al., 1997, 1999; Zmazek et al., 2000; Outkin et al., 2001; Steinitz et al., 2003) make this kind of predictions on the basis of soil-gas information, mainly the radioactive radon gas (^{222}Rn) data. An increase in the stress level in fracture zones preceding earthquakes may induce significant changes in temperature and pressure gradients and, consequently, cause convective flows to increase (Thomas, 1988; Fleischer, 1997; Monnin, 2001). These flows contribute to the soil-gas transport from great depths to the Earth's surface. Thus, an enhanced seismic activity responsible for changes in the convective velocity may account for anomalous temporal variations of the radon concentration and that of other gas species in the subsurface soil air (Fleischer, 1997; Steinitz et al., 2003). Based on the temporal soil-gas radon variations, we may be able to recognize the physical processes operative in the Earth's crust during a seismic event.

The amplitude of the temporal variations of the soil-gas radon concentration depends on the meteorological conditions (Bunzl et al., 1998; Winkler, et al., 2001; Iakovleva

and Ryzhakova, 2003), geological features in a given area, and distance from the epicenter of an earthquake (Fleischer, 1997; Steinitz et al., 2003).

The larger variations of the soil-gas radon concentration usually exhibit higher correlation coefficient between the radon concentration measured in the surface soil layer and the magnitude of the earthquake, and hence, higher reliability for the earthquake prediction. Therefore, radon-monitoring sites are usually chosen in the areas where higher radon concentration in the surface soil layer can be expected. Consequently, people choose the monitoring sites with a highly heterogeneous geological structure characterized by the presence of high-activity radon sources located at great depths (rocks with high uranium content) and/or tectonic fracture zones in the Earth's crust. Steinitz et al. (2003) showed a statistically significant correlation between earthquake events and soil-gas radon concentration, which was found in an area where rocks with an uranium content of ~ 100 ppm occur at a depth of several hundreds of meters.

In the case of a non-uniform geological media, however, serious problems may arise. The complexity and diversity of geological structures may give rise to differences in the dynamics of the subsurface soil gas radon concentration. As a consequence, the geological structure has not been adequately studied, which plagues an interpretation of radon monitoring data and comparison of the results obtained at different measuring points and in different areas. The interpretation of the data is also difficult due to the effect of the atmospheric condition since temporal variations of the soil gas radon concentration caused by changes in meteorological conditions alone may be as wide as tenfold (Yakovleva, 2002).

Many of the difficulties can be circumvented by radon monitoring in areas with a comparatively homogeneous geological structure. However, the increasing of soil gas radon concentration due to the seismic activity may not be as much as in heterogeneous geological media. Using the known diffusive-convective model, the calculated result shows that the soil gas radon concentration will not be in excess of the

Table 1.

Parameter	Model 1 (homogeneous media)				Model 2 (non-uniform media)			
					Thickness of a surface emanating layer			
					30 m		100 m	
Convective velocity, cm s^{-1}	$4 \cdot 10^{-4}$	10^{-3}	$5 \cdot 10^{-3}$	10^{-2}	10^{-3}	$2 \cdot 10^{-3}$	10^{-3}	$4 \cdot 10^{-3}$
Soil gas radon concentration at a depth of 50 cm, kBq m^{-3}	12	16	20	20	18	48	16	23
Soil gas radon concentration at a depth of 1 m, kBq m^{-3}	16	19	20	20	21	51	19	23
Radon flux density from the Earth's surface, $\text{mBq m}^{-2} \text{s}^{-1}$	46	94	447	892	102	444	94	420

highest possible value (A_{max} or A_{∞}) for a homogeneous porous media, no matter how high the convective velocity would be. For most of sedimentary rocks, this value is $\sim 20 \text{ kBq m}^{-3}$ (Durrani and Ilić, 1997). In other words, as the convective velocity varies between $-4 \cdot 10^{-4}$ and $1.5 \cdot 10^{-3} \text{ cm s}^{-1}$ (due to the influence of weather conditions alone (Yakovleva and Ryzhakova, 2003)) and up, the soil gas radon concentration will be lower than or equal to its equilibrium value (Table 1). In this case, it appears to be hardly to establish a clear correlation between the soil gas radon concentration and earthquake events. Thus, the soil gas radon concentration in areas with a comparatively homogeneous geological structure may be served as a relative weak indicator for an increase in the seismic activity.

The reliability of predictions for seismic activity can be improved by measuring a parameter associated with increased convective velocity, viz., radon flux density from the Earth's surface. Based on the diffusive-convective radon transport model for porous media (Nazaroff and Nero, 1988), numerical calculations will be performed to demonstrate the advantages of using the radon flux density parameter from the Earth's surface for earthquake predictions.

2 Modelling

Two models will be considered separately, i.e. homogeneous and heterogeneous geological structures.

Model 1: The geological structure of the studied area is comparatively homogeneous and is made up of loams with the following parameters: effective diffusion coefficient is $0.03 \text{ cm}^2 \text{ s}^{-1}$, radon emanation coefficient is 0.2, soil specific activity of ^{226}Ra is 30 Bq kg^{-1} ; soil particle density is 2.7 g cm^{-3} , and soil porosity is 0.45. There are no radon anomalies, i.e. no rocks with high uranium content, extensive fractures, or cracks in the Earth's crust are found.

Model 2: The geological structure of the studied area is non-uniform and is made up of two emanating layers. The choice was for the purpose of the best visualization. The surface layer is loam with the same parameters as in Model 1. The other layer is a high-activity radon source, e.g. rocks with a specific ^{226}Ra activity of 1000 Bq kg^{-1} . The calculations

employ the solution to the diffusive-convective radon transport equation for a porous media with two emanation layers (Yakovleva, 2002). The calculations are simplified by assuming that the soil density and porosity, radon emanation and diffusion coefficients are the same for the two layers.

The convective velocity is chosen to be $4 \cdot 10^{-4} - 10^{-2} \text{ cm s}^{-1}$ for numerical calculations accounting for the results of investigations performed in an area without any earthquake risk (Fleischer, 1997; Yakovleva and Ryzhakova, 2003).

3 Results and discussion

Table 1 shows the calculated data on the soil gas radon concentration at different depths and radon flux density from the Earth's surface for those two models with different convective flux velocity.

In Model 1, an order-of-magnitude increase in the convective velocity can be seen to produce an order-of-magnitude increase in the radon flux density. However, the soil gas radon concentration is slightly affected only. A high sensitivity of the radon flux density to convective velocity variations makes it as a suitable parameter for short-term earthquake predictions. Notably, in the case of uniform geological environment, a good correlation can be expected between the radon flux density and earthquake magnitude.

In Model 2, variations of the soil gas radon concentration and radon flux density depend critically on the depth of occurrence of the high-activity radon source, its activity, and convective velocity. In the case where the thickness of the surface emanating layer is 30 m, a two-fold increase in the convective velocity causes a four-fold increase in the radon flux density. However, the soil gas radon concentration is merely doubled. Thus, we can conclude that the radon flux density is also more sensitive to convective velocity variations than the soil gas radon concentration for a non-uniform media.

A comparison of columns 4, 7 and 9 in Table 1 shows that the radon flux density may be the same for varying convective velocity, that is, the convective velocity cannot be identified unambiguously from the radon flux density measurements alone. This may be particularly true for an un-

known or poorly explored geological structure of the area under study. Problems may arise in the interpretation of data obtained from areas with a varying geological structure. In such situations, it is necessary to perform concurrent measurements of the soil gas radon concentration and radon flux density to provide unambiguous conclusions.

4 Conclusions

An analysis of the calculated data given in Table 1 suggests the following conclusions:

1. The radon flux density is more sensitive to convective velocity variations than the soil gas radon concentration. Consequently, it can be used as a better indicator of earthquakes;
2. Well comparability and reproducibility of the results obtained from radon flux density measurements at different measuring points are required for reliable short-term earthquake predictions. These can be provided by choosing measuring sites with the greatest possible homogeneity of the geological structure and similar physical-geological parameters;
3. Concurrent measurements of the soil gas radon concentration and radon flux density from the Earth's surface will help to improve the sensitivity of earthquake predictions and reliability of the results obtained.
4. Other soil gas species may have the same behaviour of radon gas, however, experimental investigations are necessary to verify the feasibility of the model for further application of earthquake prediction.

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