Mathematical and geophysical methods for searching anomalies of the Radon signal related to earthquakes

F Ambrosino\(^1\)*, W De Cesare\(^2\), V Roca\(^3\) and C Sabbarese\(^1\)

\(^1\) Department of Mathematics and Physics, University of Campania “Luigi Vanvitelli”, Viale Lincoln 5, 81100, Caserta, Italy
\(^2\) Vesuvius Observatory - National Institute of Geophysics and Volcanology, Via Diocleziano 328, 80124, Napoli, Italy
\(^3\) Department of Physics “Ettore Pancini”, University of Napoli “Federico II”, Via Cinthia 21, 80126, Napoli, Italy

*email: fabrizio.ambrosino@unicampania.it

Abstract. A detailed analysis of a time-series of the Radon (\(^{222}\)Rn) specific activity is carried out to identify anomalies that can be correlated with earthquakes occurrence in the monitored area. New hybrid methods are developed for this purpose and the advantages of each single component method are exploited. These methods are applied to two-years data series recorded continuously in the soils of a site within the seismo-volcanic area of Phlegrean Fields (Naples-Italy). Since the measurement system distinguishes and separately measures the \(^{222}\)Rn and \(^{220}\)Rn, an alternative estimation of the remote fraction of the gas and its anomalies has been also performed using the \(^{220}\)Rn trend. The results of different methods are compared to recognize and to highlight Radon anomalies. Clear relationships have been found between anomalies and earthquakes of local origin and selected according to a specific formula of the earthquake preparation zone. The effectiveness of the methods and the goodness of the results are established by the high values of the cross correlation factors between the anomalies and the occurrence of the earthquakes.

1. Introduction

\(^{222}\)Rn is a radioactive, inert, water-soluble gas produced in Uranium decay series; its monitoring is very useful in relation to seismic phenomena thanks to the long half-life of 3.82 days. In fact, the tectonic stress deformation developed inside the Earth's crust during seismic events causes fracturing of rock mass, develops the subsequent opening of various pathways and, consequently, anomalous surface emission of the gas can be produced. For instance, anomalies in the Radon signals can occur even at distances of a few hundred kilometres from a monitored earthquake, depending on its epicentre and magnitude [1-3]. Moreover, meteorological and environmental factors are important and not negligible because they influence the emanation and the exhalation rate of Radon in the superficial soil [4]. Thus, time-series analysis of the specific activity of Radon in soil gas can potentially reveal important information regarding crustal and surface processes, and also highlight precursor signals of the earthquake.

Research studies have been proposed in the framework of searching for correlation between Radon and earthquake occurrence, using different methodologies of time-series analysis [5-8]. This study addresses the application of four new methodologies with the aim of identifying anomalies instead of anomalous peaks, to better taking into account the several variation dependences of the signal. Three
of the used methods are based on hybrid mathematical approaches, consisting of combinations of different algorithms, which provide greater precision by exploiting the advantages of each individual method [9-11]. The fourth method considers the trend of the $^{220}$Rn isotope, which has a half-life of $55.6 \text{ seconds}$, in order to eliminate the locally produced fraction of $^{222}$Rn signal that is influenced by superficial and atmospheric effects [12].

2. Experimental setup

The investigated Radon time-series was recorded by continuous monitoring of the soil gas in a site inside an old dismissed railway gallery located within the Mount Olibano of the Phlegrean Fields area in Naples district (Italy). This area is interesting because characterized by high level of seismic risk caused by tectonics and volcano-tectonic activity [13]. $^{222}$Rn and $^{220}$Rn specific activities (expressed in Bq/m$^3$) were monitored by the RaMonA (Radon Monitoring and Acquisition) electrostatic collection device, by pumping the soils gas at a depth of $0.80 \text{ meters}$ into a chamber containing a Silicon detector for the $\alpha$-spectrometric detection of the ionized Polonium isotopes, which are the progeny of the radioactive gas. Temperature, relative humidity, pressure parameters were also recorded by the device [14]. The analysed time-series was recorded in the period January 1$^{st}$, 2016 – December 31$^{st}$, 2017.

3. Radon time-series analysis

Three proposed methods are based on hybrid approaches, which have been implemented in Matlab® computing environment, and are the combination of:

1° Multiple Linear Regression and Auto-Regressive Moving Average statistical methods;

2° Empirical Mode Decomposition with Support Vector Regression techniques;

3° Singular Spectrum Analysis and a forecasting methodology.

The parametric combination 1° first creates a multiple linear regression model \( y = b_0 + b_1 x_1 + \text{error} \), performed by least-squares fit, linking Radon signal (y) and meteorological parameters (\( x_1 \)) and, then, on the residue obtained from data minus the model, is performed the forecasting of the future values according to the linear and moving-average combination of previous data [15,16]. The adaptive combination 2° decomposes the signal (in trend, smooth, noise, periodic and seasonal components) and then the training of regression models on each component is made to predict the original series [12,17]. In detail, each component comes from the spline interpolation of the iterative minimum and maximum envelopes of the series with the local minima and maxima, and moreover each component is a function that has only one extreme between zero crossings, along with a mean value of zero. The parametric combination 3° consists first in the eigen-decomposition of the converted multi-dimensional matrix of the signal as eigenvalues and left and right orthonormal eigenvectors, where equal pairs of eigenvalues correspond to persistent oscillations; then the forecasting of the series is obtained by the sum of the last eigenvectors of the reconstructed signal along the diagonal of the multi-dimensional matrix [18]. These hybrid methods, essentially, analyse and estimate the different modulations in the time-series and predict the future signal in order to derive the anomalous signals. In addition, the three methodologies form effective strategies of time-series analysis combining the assets of each single method and producing a lower uncertainty compared with the individual methods more commonly used in the literature [19].

The fourth method 4° is named ‘Remote Radon Estimation’ (RRE) and is based on geophysical considerations; it makes possible to distinguish the remote component of the Radon signal, connected to the superficial phenomena, using the local variations of the $^{220}$Rn isotope [12]. Since it has a half-life of $35.6 \text{ seconds}$ and, hence, a short migration length, the detected quantity is produced only locally and its variations are only due to local and surface effects. This methodology takes into account the specific activities, emanation coefficient, decay constant of the two isotopes, and the decay time of Radon within the tubes for pumping the gas inside the RaMonA chamber [12].

The identification of an anomaly is performed on the final signal obtained after the application of one of the four methods. Precisely, a positive or negative anomaly is located respectively above or below the 95% confidence intervals from the starting signal, where the two confidence bounds are calculated as confidence coefficient (1.96) multiplied by the standard deviation that is divided by the square root of the length of the signal. Finally, all the anomalies detected are normalized by
subtracting to their value the mean value of the analysed series and this result is divided by the standard deviation.

**Figure 1.** Anomalies (denoted as light symbols for negative and dark symbols for positive, in the first two graphs) found by the application of the four proposed methods for the analysis of the Radon time-series in Mount Olibano gallery, compared to 37 earthquakes selected to be of local origin and with the Dobrovolsky empirical formula (bottom graph).
4. Results

The results of the analysis of the climatic effects influencing the Radon signal show that the external temperature is the main driving force of the Radon. Anomalies coming from the application of the four proposed methods on the monitored Radon time-series are displayed vs time in figure 1. In the same figure the earthquakes (taken from the US Geological Survey database - https://earthquake.usgs.gov) having influence on the Radon monitoring site of Mount Olibano gallery are also indicated. The earthquakes are selected of local origin and with the Dobrovolsky empirical formula [1, 20] that describes the area of tectonic deformation (with radius \( R \) expressed in \( km \)) caused by an earthquake with magnitude \( M \): \[ R = 10^{0.43M} \]. According to this formula, an earthquake that influenced the chosen Radon monitoring site is considered if the distance between the Mount Olibano and the earthquake location is within the radius of the manifestation zone of that earthquake. In figure 1, clear relationships are visible between the Radon anomalies provided by the four methods and the major earthquakes occurred in Italy and Greece. The strong correlations between the two events, persistent across the different approaches, show the effectiveness of this analysis and demonstrate the actual relationship between the anomalies of the Radon and the occurrence of earthquakes.

The overall results are supported and validated significantly by the cross-correlation statistical analysis:
- 85% on average among the four methods;
- 87% on average of values found for the four methods between Radon anomalies and earthquakes.

In particular, the RRE geophysical method shows cross-correlation statistical values of 80%, 86%, 84% and 88% with the results of the mathematical methods 1°, 2°, 3° and earthquakes, respectively.

5. Conclusions

This paper is focused on the development and application of four new methodologies used for the time-series analysis of the Radon signal recorded in a site of the interesting seismic area of Phlegrean Fields (Naples-Italy). The principal goal of this study is the anomalies identification, which are compared with earthquakes having influence in that area. The comparison of different mathematical and geophysical procedures is also another important goal. Significant results, supported by statistical evaluation, come from these analyses, which demonstrate the strength of the applied methods and prove as the Radon could be an important geochemical precursor of earthquakes occurred in the surroundings of the gas monitoring site. In particular, the RRE geophysical method based on \(^{220}\text{Rn}\) local production and emission also provides results in good agreement with the others.

Acknowledgments

Authors wish to thank the staff of the Vesuvius Observatory, branch of the INGV (National Institute of Geophysics and Volcanology of Naples) for the Radon data management.

References

[1] Friedmann H 2012 Radiat. Prot. Dosim. 149 (2) 177-84.
[2] İnan S and Seyis C 2010 Acta Geophys. 58 (5) 828-37.
[3] Ghosh D, Deb A and Sengupta R 2009 J. Appl. Geophys. 69 (2) 67-81.
[4] Yakovleva VS, Nagorsky PM, Kondratyeva AG and Mishina NV 2016 IOP Conf. Ser.: Mater. Sci. Eng. 142 012051.
[5] Novikov A, Ulin S, Dmitrenko V, Vlasik K, Bychkova O, Petrenko D, Uteshev Z and Shustov A 2016 J. Phys.: Conf. Ser. 675 042007.
[6] Dacey J 2010 Phys. World 23 5.
[7] Ali Yalım H, Sandıkçıoğlu A, Ertugrul O and Yıldız A 2012 J. Environ Radioact. 110 7-12.
[8] Walia V, Virk HS and Bajwa SB 2006 Pure Appl. Geophys. 163 (4) 711-21.
[9] Suhartono, Rahayu SP, Prastyo DD, Wijayanti DGP and Juliyanto 2017 J. Phys.: Conf. Ser. 890 012160.
[10] Du P, Wang J, Yang W and Niu T 2018 Renew. Energ. 122 533-50.
[11] Yahya NA, Samsudin R and Shabri A 2017 J. Phys.: Conf. Ser. 890 012140.
[12] Sabbarese C, Ambrosino F, De Cicco F, Pugliese M, Quarto M and Roca V 2017 Radiat. Prot. Dosim. 177 (1-2) 202-06.
[13] Piochi M, Bruno PP and De Astis G 2005 Geochem. Geophys. 6 Q07005 (7) 1-25.
[14] Sabbarese C, Ambrosino F, Buompane R, Pugliese M and Roca V 2017 Appl. Radiat. Isot. 122 180-5.
[15] Razali SNAM, Rusiman MS, Zawawi NI and Arbin N 2018 J. Phys.: Conf. Ser. 995 012041.
[16] De Cicco F, Pugliese M, Quarto M, Roca V, Sabbarese C, Savino F, Aquino I and De Cesare W 2017 Environ. Earth Sci. 76, 317-27.
[17] Agustina SD, Mustakim, Okfalisa, Bella C and Ramadhan MA 2018 J. Phys.: Conf. Ser. 1028 012240.
[18] Filho ASF and Lima GAR 2016 J. Phys.: Conf. Ser. 759 012085.
[19] Wang J, Yang W, Du P and Li Y 2018 Energy J. 148 59-78.
[20] Dobrovolsky IP, Zubkov SI and Miachkin VI 1979 Pure Appl. Geophys. 117 (5) 1025-44.