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DETECTION OF RADON EMISSIONS DURING 2016/2017 EARTHQUAKES IN ABRUZZO (ITALY)

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ABSTRACT

«Aracne» is an Italian monitoring network, part of the «Tellus» project, for the real-time detection of radon emissions from Earth's subsoil. The Aracne network was launched in August 2015, with the first multi-parameter station in Pizzoli, in central Italy, followed in December 2016 by the one of Cagnano Amiterno and finally the station of Capitignano, which will be installed by early 2018. The stations provide data at 10-minute intervals, together with all meteorological values outside the station and at the exact measuring point, such as humidity and temperature measured at about 20 cm from the radonometer that is being used. The stations are identical both for instrumentation and for measuring place characteristics, designed in such a way to maintain constant temperature and humidity. This project makes the stations of the Aracne network unique in the world as far as detection methodology is concerned. The Pizzoli station provided very interesting data during the seismic crisis that hit central Italy on 24 August 2016, 30 October 2016 and 18 January 2017 with three earthquakes of Mw 6.0, Mw 6.5, Mw 5.5 respectively.

INTRODUCTION

Radon is currently considered a very efficient marker of the dynamic phenomena that occur in the Earth's crust [1-3].

However, radon emissions are influenced by many different meteorological factors, among which the most important are atmospheric pressure, temperature, humidity and wind speed [4-9]. A correct and accurate measurement of environmental factors is decisive for acquiring the capability of giving a real-time correlation, during the measurement of radon, with a possible earthquake future event. A thorough determination of radon emission rates from natural materials is necessary as well [10,11]. In this regard, we have developed a software (AAD, Automatic Anomaly Detection) to automatically analyze the results and give a major contribution to speed-up the manual analysis of collected data [12].

For a more relevant and accurate data collection, the Tellus project involves the installation of 14 stations in a small area of about 625 Km^2 [12,13]. Each station provides different data, depending on the geology of the subsoil and the presence in it of certain fluids that are relevant to determine the mobility of radon.

In this study we analyze the data of the Pizzoli station only. Those data have been continuously collected, starting from its activation date (August 2015) until today, with the exclusion of a few hours during the 6.0 Mw earthquake of 24 August 2016 at 01:36 UTC when, because of it, electricity was missing from the moment of the earthquake until the early hours of the afternoon.

MATERIALS AND METHODS

The Aracne-Tellus Network

The network was started in August 2015, and currently consists of two active stations and one has recently been completed [12]. Twenty-three areas have been identified in the Italian territory: one of them is in Sardinia, where the seismic activity is almost absent: this choice is justified by the need of having the possibility to measure a "background level" of the Radon emissions, i.e. those emissions that do not depend from seismic activity. The other 22 areas are sited in zones of high seismicity, throughout the Italian territory. Each of these zones, whose monitoring area is about 625 Km^2, will be equipped by a certain number of stations, namely between 9 and 14, according to the territorial specificities. The stations are equipped with a radon meter with a 1-liter ionizing chamber, a Davis-type weather station [14] with console - positioned next to the radon meter for the detection of temperature and humidity at the measuring point - a dehumidification system to keep temperature and humidity constant.

The cavity (where the radon meter is placed) can be considered almost hermetic, thanks to a special pressure lock. The radon meter and the weather station console are positioned at about 140 cm below ground level. Inside the cavity, there is also a high precision seismometer able to record seismic events even close to zero magnitude.

Outside the station, there is a central unit for detecting temperature, humidity, rain gauge, atmospheric pressure, wind speed and direction, in addition to the moon phases, powered by a small solar panel. These data are transmitted in Wi-Fi to the internal console every 10 minutes. Together with the data on the radon concentration, detected every 10 minutes too, they are transmitted to a dedicated server where the AAD software analyzes them and generates a complete graphic representation of all ~~the~~ measured parameters. The analysed data and the plot are uploaded on a specific web page every 60 minutes. This frequent update permits an effective control of the parameters by the operators of the research group.

When the AAD system detects an abnormal pattern of the radon concentration curve, a special procedure starts. There is further processing and analysis of the environmental parameters, then a warning is sent to the control staff, by means of an email message that includes all the measured and processed data.

The aim of the Aracne network is to identify anomalies in radon emissions in order to associate them with the seismicity of the monitored territory, and to have a reliable tool to detect the preparation of large earthquakes, even in areas geologically close or bordering the seismogenic faults subject to monitoring.

Measurements and data evaluation

In August 2015, the multi-parameter station of Pizzoli (AQ) was installed and started up. The first days of November of the same year the tests were completed and the measurements were started [13]. Since then, they have been continuously collected, analysed and stored every 10 minutes until the present time. The amount of collected data is significant, and to date (December 2017) about 110,000 counts in total are stored and available.

This long period of observation has permitted to find evident correlations of the radon concentration with several environmental parameters. In particular, we have determined the correlation of radon concentration with atmospheric pressure, external humidity, external temperature and wind speed.

Thanks to the determination of these correlations, we have been able to discriminate among the anomalies measured by the station. The software is capable to predict – according to the measured values of the environmental parameters – an expected value of the radon concentration, which, as we stated before, can considerably vary depending on such parameters. Therefore, we can identify an “environmentally caused” radon anomaly. If a radon concentration significantly different from the predicted value is measured, the anomaly is classified among those worth of attention and further analyzed, since it could be of seismogenic nature. In fact, important anomalies have been recorded by our station on several occasions before some major earthquakes occurred during the seismic crisis that hit Central Italy from August 2016 to early 2017.

For a correct analysis of earthquakes, associated with radon anomalies, the Dobrovolsky formula [1,15] can be used for a first assessment. The formula determines the radius in km of the zone within which precursor phenomena can occur.

$$R = 10^{0.43M} \text{ Km} \quad (1)$$

where M is the earthquake magnitude and R the radius in km.

Applying the formula, we consider seismic events of all magnitudes if they are within a radius of 10 km from the station. For instance, instead, we can have precursor phenomena with earthquakes of M 3.4 up to 30 km, M 4.1 up to 60 km, M 4.6 up to 100 km, M 5.4 up to 200 km, M 6.5 up to 600 Km from the station.

By combining the radon emission values with all the relevant environmental factors, it is therefore possible to have a first approach to the recognition of those anomalies that could be a seismic precursor. The anomalies can occur in different forms, such as increase or decrease of radon emissions.

During the 48 months of detection, we also noticed an interesting correlation between the large windy masses coming from the Northeast, which then invest the Apennine chain perpendicularly, with strong increases in radon emissions and strong earthquakes in 48/72 hours after the anomalous detection.

RESULTS AND DISCUSSION

In this section, we illustrate some of the main anomalies detected before, during and after the seismic crises that affected central Italy.

Two months before the earthquake of Amatrice, in a situation of seismogenic calm, a strong decrease in the emission of radon was detected. In the following 96 hours we recorded an earthquake of M 2.8 with epicenter in Barete (AQ) about 5 Km North-West from the station of Pizzoli (AQ) with hypocentral depth of 14 Km (Figure 1).

In the 48 hours before the first major earthquake in Amatrice (RI) (Mw 6.0), two strong increases in radon emissions were recorded. The epicenter was identified between Accumoli and Amatrice, about 32 km north-west from Pizzoli station with a depth of 8 km.

Immediately after the strong earthquake, electric power net was lost and the station went off. After the re-ignition, which took place in the early hours of the afternoon, the radon emissions were very high due, most probably, to the strong and continuous stresses due to the very high number of replicas of considerable magnitude (Figure 2).

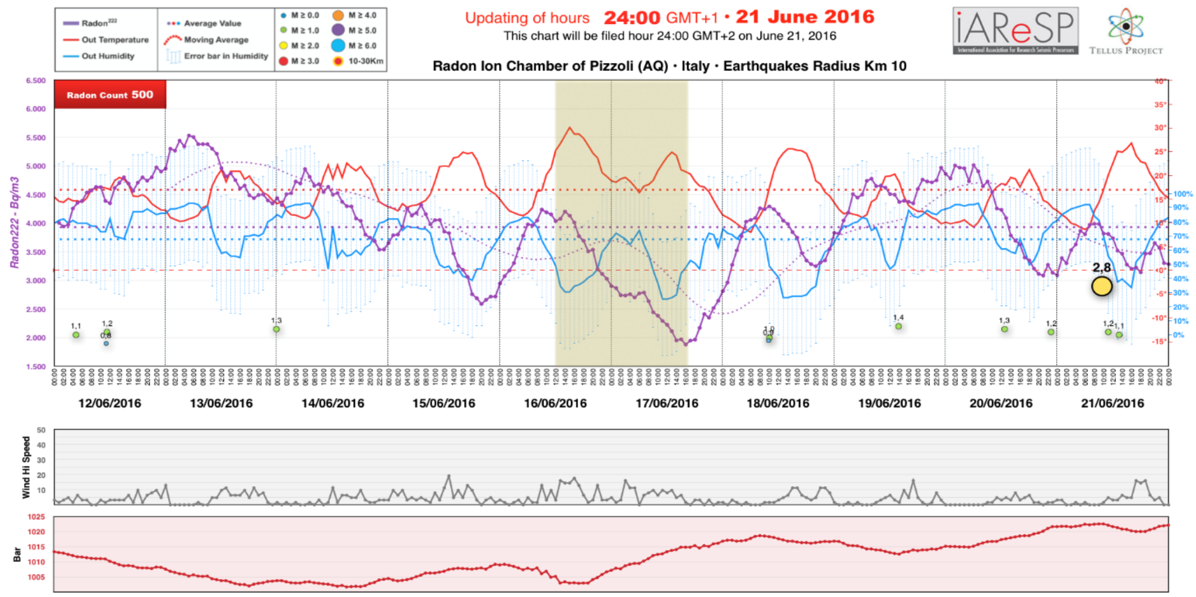

FIGURE 1
Results of June 21st, 2016

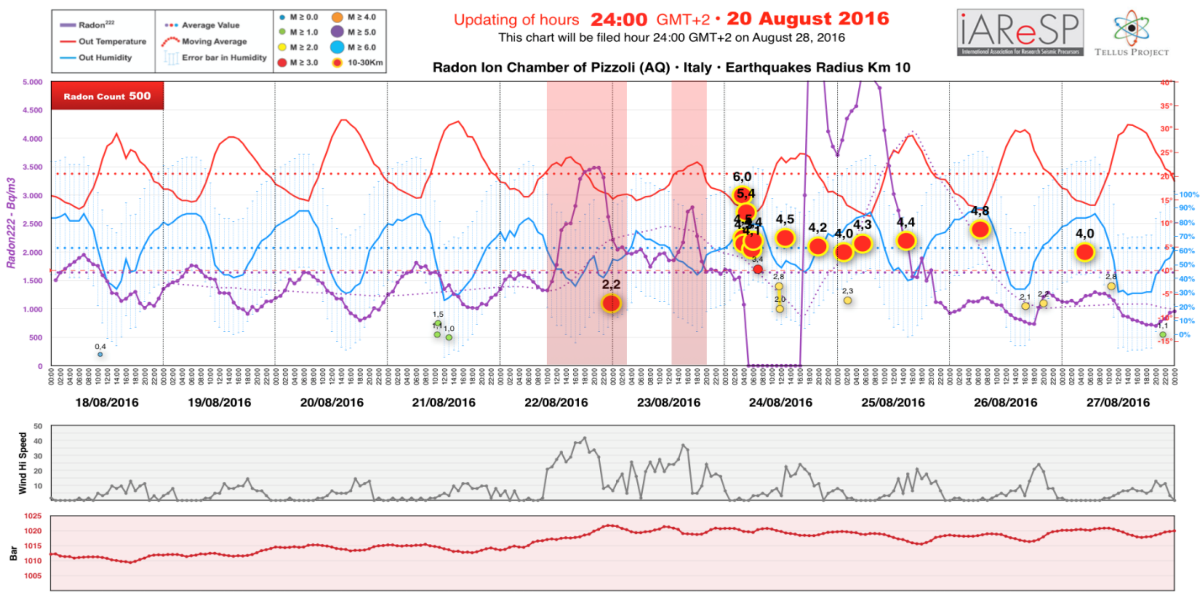

FIGURE 2
Results of August 20th, 2016.

In mid-October, the seismic sequence of Amatrice was greatly attenuated and the sequence of replicas was very low. The last major earthquake of Mw 4.0 dates back to 3 September. On 12 October 2016, we recorded a significant drop in radon levels and 40 hours later we recorded an earthquake of Mw 3.3 with an epicenter east of Amatrice about 21 km from Pizzoli station with a hypocentral depth of 11 km. Three days later, on the 15th of October, we recorded a new and more substantial decrease in radon levels and a new strong earthquake of Mw 4.0 less than 24 hours later from the anomaly. The earthquake had an epicenter to the north-west of Accumoli about 37 Km North-West from the Pizzoli station with a depth of 9 km (Figure 3).

On October 26, we recorded two earthquakes of 5.4 Mw and 5.9 Mw with epicenter in the northernmost area at a distance of about 57 km from Pizzoli. For these events, we did not find any particular anomalies except for an average increase in the daily levels of radon. On 27 and 28 October we recorded two major anomalies, followed 48 hours later by the strongest earthquake of the Sequence (Mw 6.5) at a distance of about 46 Km from Pizzoli (Figure 4).

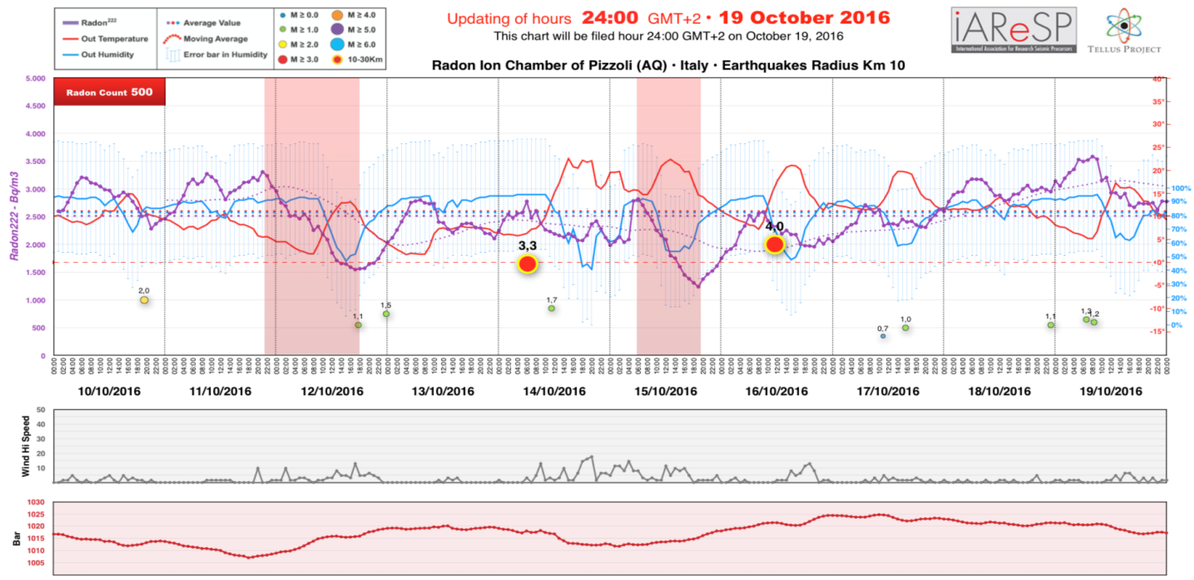

FIGURE 3
Results of October 19th, 2016.

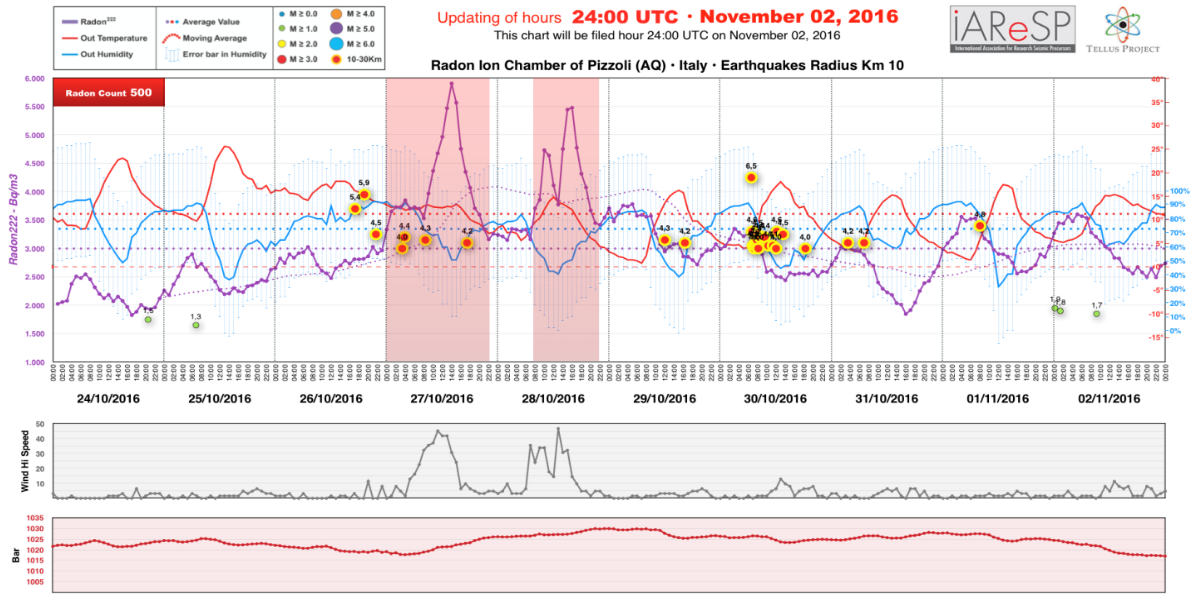

FIGURE 4
Results of November 2nd, 2016.

On 9 November 2016 an earthquake of Mw 3.1 was recorded, just 13 km from Pizzoli. About 48 hours earlier, we detected a strong decrease in radon concentration followed by a sharp increase.

On 12 and 13 November there were two earthquakes of Mw 4.1 at 32 Km from Pizzoli and Mw 3.3 at 16 Km from Pizzoli. Also on this occasion, we recorded a sharp decrease in the radon measurements, just a few hours before the events (Figure 5).

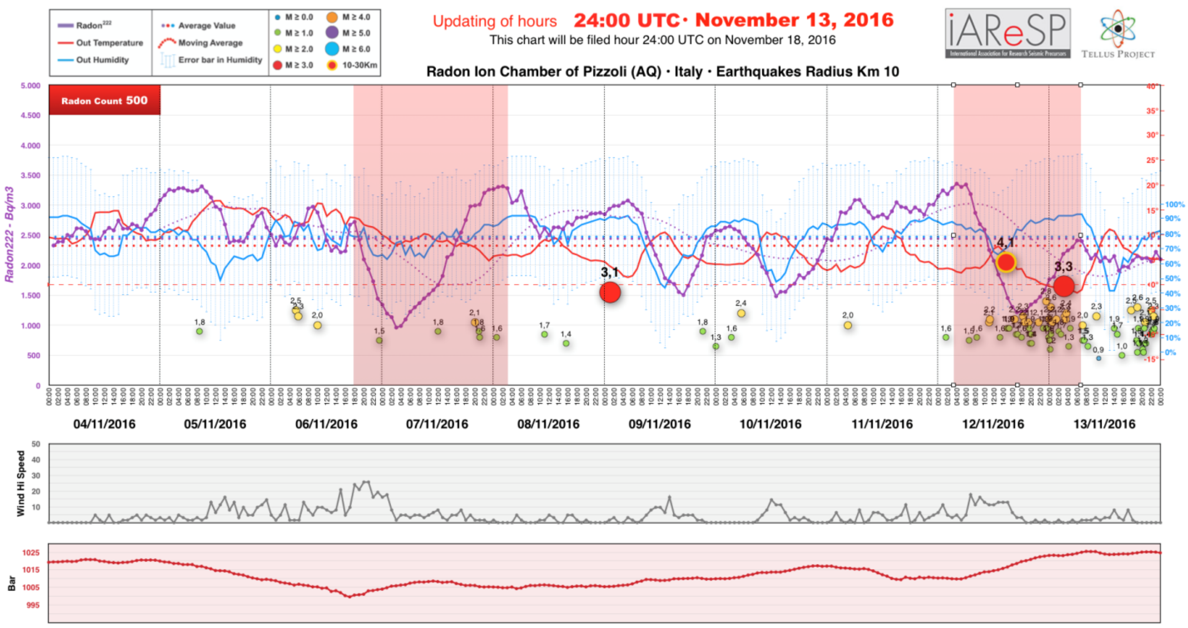

FIGURE 5
Results of November 13th, 2016

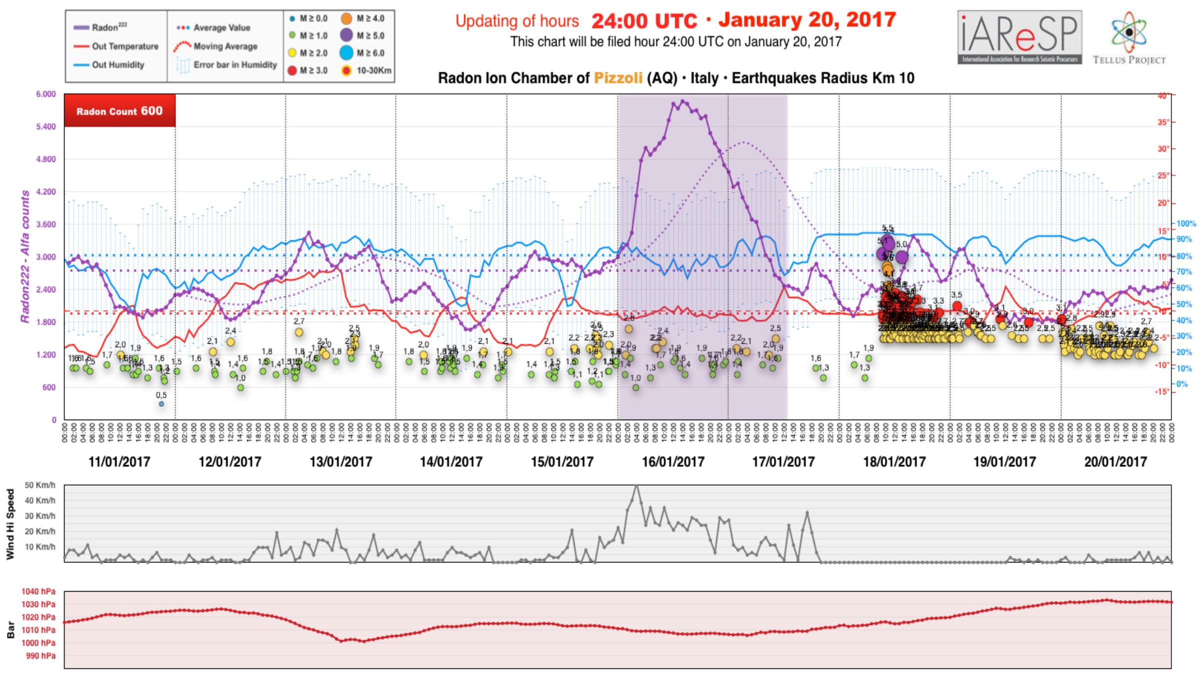

FIGURE 6
Results of January 20th, 2017

On January 18, 2017, the third sequence of the great seismic crisis of Central Italy began. Four earthquakes with a magnitude between Mw 5.0 and Mw 5.5, in a location north-west of the Pizzoli station are recorded at a distance between 5 and 10 km. About 48 hours before, the Pizzoli station recorded a very strong increase in radon (Figure 6).

On November 30, 2017 we found a new sharp decrease in radon levels followed by a new strong earthquake of 4.2 Mw within 72 hours after the anomaly, with an epicenter at about 20 km north of the Pizzoli station (Figure 7).

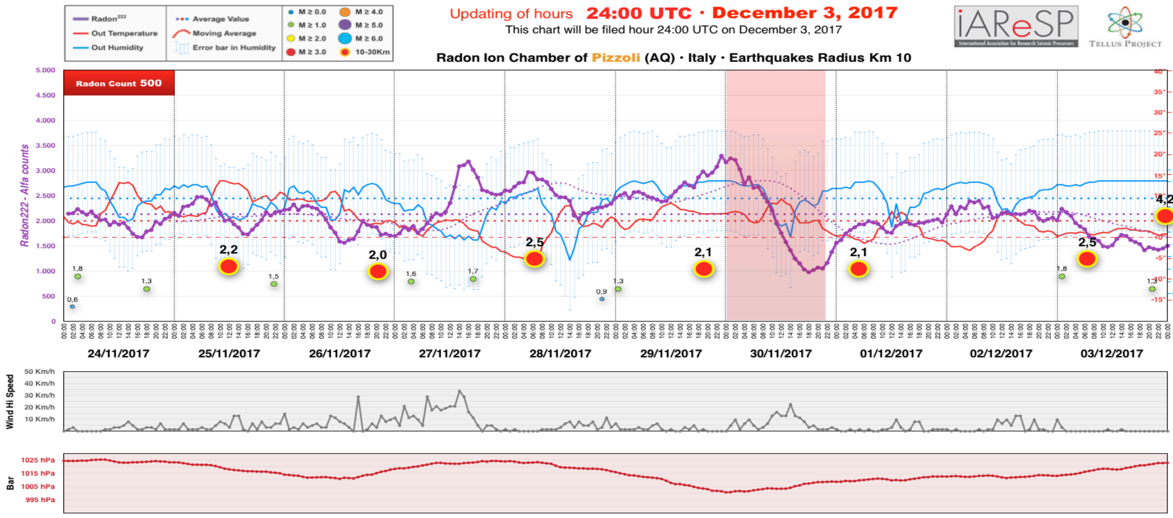

FIGURE 7
Results of December 3rd, 2017.

Starting from the early hours in the morning of December 13th, 2017, we noticed a strong decrease in radon emissions, which - in the following 72 hours – returned to average levels for the current period (Figure 8). This decrease has been successfully explained, and it is due to environmental factors. In particular, due to the hot winds coming from south, the outdoors temperature in those days exceeded the seasonal average, remaining constant for about 3 days without producing the usual day/night temperature variations.

In the following days, we have not detected earthquakes. This anomaly, for the reasons described above, cannot be considered a false positive: in fact, we identified its cause in the so-called «chimney effect» [16].

The chimney effect is due to the difference in temperature between inside and outside the building, depending on which a difference in pressure (ΔP) is formed. Because of this internal lower pressure, the cold air containing radon is absorbed from the ground, causing a decrease in the measured values of radon. The warmer the interior of the house and the colder the outside, the more intense the effect will be.

Often, this kind of anomaly of radon emissions occurs only concurrently with a phase of increasing temperature.

The ΔP can be calculated as follows:

$$\Delta P = \alpha\left(\frac{1}{t_e + 273} - \frac{1}{t_i + 273}\right) \qquad (2)$$

where t_e and t_i are the outdoor and indoor temperatures, measured in °C, and α is a constant coefficient, equal to 3462 Pa. K

The lower the outdoor temperature, instead, the greater the amount of radon detected.

In the specific case, shown in Figure 8, the increase in the outside temperature, constant over time. generated the opposite effect, with a decrease in the radon measurement, which has been successfully identified an environmental anomaly.

At the end of our of 2016/2017 data review, we would like to discuss the results and try to explain why we find, in some cases, sudden increase of the radon release just before an earthquake, while in other cases we have an increase or a decrease some days before or after the event.

The mechanism by which radon is released from rocks before an earthquake is – in theory – clear. Why, until now, no reliable method has been developed in order to actually predict earthquakes? This is due to an insufficient understanding of the other environmental causes (non dealing with earthquakes) that cause radon release. Some of these causes have a roughly daily cycle, while other ones depend on enviromental factors that are not predictable with a daily periodicity. Therefore, anomalies do not always occur in the same direction, and it can happen that two environmental factors have effects that could partially erase each other.

For instance, on a daily basis, we find the maximum peak of radon early in the morning, when the temperature reaches the minimum and we have the maximum humidity. The minimum peak is detected in the afternoon hours, when the temperature reaches the maximum and humidity the minimum. However, if early in the morning we have a strong and sudden increase in atmospheric pressure, the effect should decrease the radon concentration which at the same time should remain high due to the low temperature and high humidity. In these cases it is more difficult to understand if a possible anomalous trend may depends on environmental factors or on seismogenic factors. In those rare occasions it is still necessary to wait about 3/4 days to detect possible seismic events. On the other hand, the "clean" anomalies, i.e., anomalous radon trends not depending on environmental phenomena, are immediately recognized by the software.

After a thorough analysis of the available data we can confirm that all the anomalies we did not explain in other ways have been always followed by an earthquake. On the occasion of the three most important earthquakes (Amatrice 6.0, Norcia 6.5, Capitignano 5.5) we found the three biggest anomalies in the records of the Pizzoli station.

On several occasions, instead, anomalies, even great ones, have been identified as caused by environmental factors and have not been followed by earthquakes. All the strong anomalies that have not been followed by an earthquake have a very clear metereological explanation. However, on very few occasions, we have detected small anomalies, not explicable with meteorological factors, which have not been followed by an earthquake. However, since such anomalies should have been quite small, they are difficult to identify.

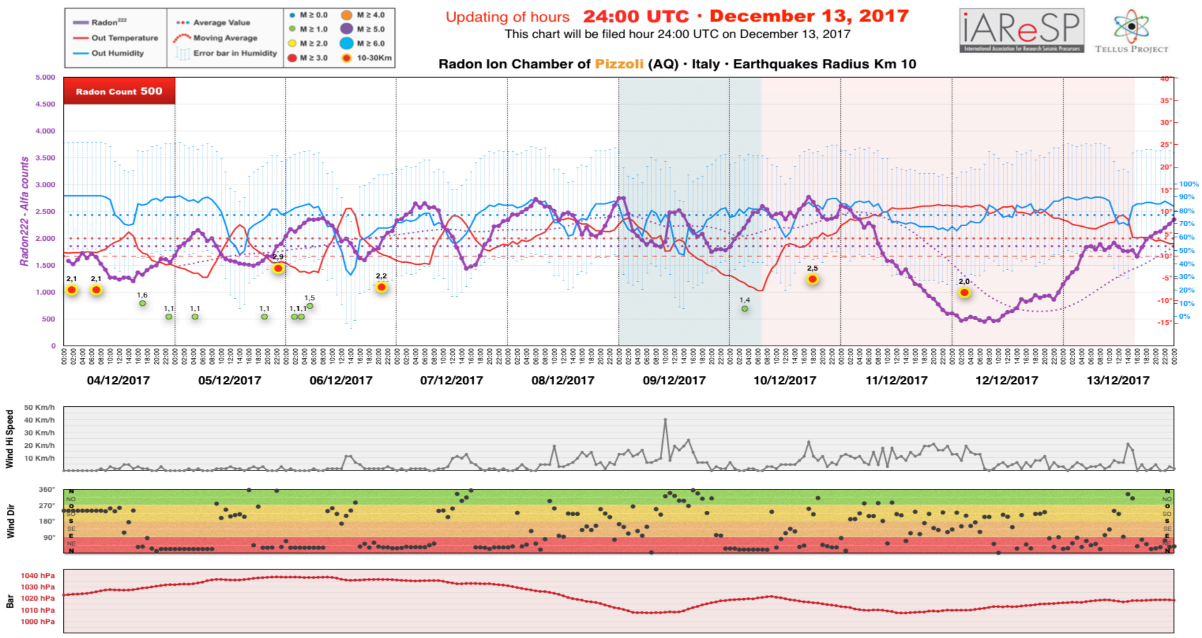

FIGURE 8
Results of December 13th, 2017.

CONCLUSION

The multi-parameter station of Pizzoli, as it has been designed and built, has shown a perfect continuity and reliability in the detection task. The collected data turned out to be very useful for the purposes of our study. The expected behaviour of emissions has been determined throughout the period (over two years) identifying a daily harmonica that follows with extreme precision the daily trend of the external temperature/humidity. On several other occasions, not described in this work, the daily harmonic has allowed us to identify anomalous trends caused exclusively by environmental factors. In a few occasions, we could identify anomalous trends, in addition to those caused by environmental factors, with subsequent earthquakes of various relevance, located near the station itself.

Also the Cagnano Amiterno (AQ) station has shown complete reliability and on several occasions it has been possible to correlate the detected anomalies with those of the Pizzoli station: the two measurement complexes are at a distance of about 9 Km each other.

The Cagnano Amiterno station results have not been described in this work because the beginning of its activity dates to less than one year ago.

The Capitignano station too, which is planned to start operations in early 2018, will have the same instrumental characteristics of the previous two ones, and it will be located further north forming a perfect triangle with sides of about 9/11 Km.

The results we obtained demonstrate the great potential of this monitoring technique, if carried out in real time. In the future, it could provide a new interpretation key for the identification of anomalies of seismogenic nature, in order to anticipate an earthquake occurrence. In particular, the technique seems mature to determine if a sharp anomaly in the radon emissions can be followed or not by an earthquake, roughly within the Dobrovolsky radius. The correlation between radon anomalies and earthquake energy has to be determined yet with an acceptable accuracy.

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