SOIL RADON EMANATION AND ITS DEPENDENCE ON METEOROLOGICAL PARAMETERS IN KACHCHH REGION, GUJARAT, INDIA

SUSHANTA KU SAHOO,
Institute of Seismological Research, Gandhinagar, Gujarat, India-382009

MADHUSUDHANARAO KATLAMUDI,
Institute of Seismological Research, Gandhinagar, Gujarat, India-382009

G. UDAYA LAKSHMI
Department of Geophysics, Osmania University, Hyderabad, Telangana, India

Abstract: It is now established that soil radon (Rn^{222}) emission is influenced by meteorological parameters. However, the influence depends upon many local factors such as geology, structural fabric, porosity, composition of formations and climate variations in various seasons. In this paper, we studied the influence of different soil parameters (pressure, temperature and humidity) and atmospheric parameters (wind speed and rainfall) on soil radon emission at Badargadh in Kachchh region, Gujarat, India during 1st January to 31st December, 2017. We determined the descriptive statistics of all the parameters in order to see the back ground values. Soil radon and other parameters are found persistent nature. By linear regression and cross correlation techniques, we found that soil radon is negatively correlated with pressure & temperature and positively correlated with other parameters (humidity, rainfall and wind speed). Linear regression between radon and thoron shows that source of most of radon emission is deeper in Kachchh. Interestingly, most of the local earthquakes also occur at lower crust. We speculate that most of the radon emanation is caused by tectonic movements in Kachchh.

Key words: Soil radon (Rn^{222}), thoron (Rn^{220}), pressure, temperature, humidity, wind speed, rainfall, correlation.

I. INTRODUCTION

Radon is a radioactive gas formed by the decay of Uranium. There are 39 isotopes formed from the decay ranging from Rn^{193} to Rn^{231}. Among them, Rn^{222} is the most stable isotope and having half life of 3.82 days. After Rn^{222}, thoron (Rn^{220}) is the second most stable isotope with half life of 54.5 seconds. Due to its short life span, thoron is traced in smaller quantities compared to radon (Rn^{222}). Although soil is the primary source of radon, but radon is also available in building materials, fragmented rocks, underground and surface water etc. In water, the radon gets diluted, but in the porous medium and fragmented rocks, some percentage of radon is emanated and migrated though the pore fluid. The transportation of radon in the soil is mostly stimulated by two mechanisms, i.e. diffusive transport and convective transport [1]. In the diffusion process, radon moves through the soil pores (gases/liquids) by concentration gradient, but, in the case of convection, the pore fluid moves through the soil pores by the action of an external force such as pressure gradient [2]. If the medium is having soils of lower permeability, the diffusion process dominates, whereas, if the medium is having soils of more permeable, the transport process is dominated by convection mechanism [3]. A large amount of data on soil radon concentrations obtained from different locations has been used to understand the factors that affect radon emissions and exhalation from soil [4]. The radon concentration in the soil gas largely depends on the soil type and concentration of radium-226, but the complete dynamics of soil radon i.e. from emanation into pore spaces up to exhalation into atmosphere is also affected by both tectonic activity and meteorological parameters such as temperature, pressure, wind velocity, rainfall, and humidity [5]. The seasonal changes also influence the radon emission [6]. The radon emissions also dependent on soil permeability, soil porosity and site conditions [7]. The influence of these parameters on radon emission dynamics ranges with hours to several days [8]. In order to identify the influence of these parameters on the radon signal, several authors applied regression or correction methods on radon signal and meteorological parameters [9, 10]. Several papers reported impact of meteorological parameters on soil radon gas emanation at various environs [6, 10, 11, 12, 13].

In this study, we correlated the radon time series with meteorological parameters recorded at Badargadh in Kachchh region, Gujarat, India during 1st January to 31st December, 2017 in order to understand the influence of meteorological parameters on radon emissions.

II. GEOLOGY OF THE KACHCHH REGION

Kachchh basin is formed by the deposition of phanerozoic sedimentary formations of different ages in western part of Indian sub-continent [14]. The origin of Kachchh started in the Mesozoic tectonic events that took place during the break up of Gandwana land and northward migration of Indian plate. As a consequence of this break up, the Kachchh rift gets evolved and was controlled by number of faults [15]. The rift zone is surrounded by Nagar Parkar Fault (NPF) in the north, whereas the southern part of the basin is covered by North Kathiawar Fault (NKF). Both the faults are E-W oriented in the region. Again, the Radhanpur-Barmer arc is situated in the eastern side and the western side is covered by Arabian Sea. Other major E-W faults in the Kachchh region include the Kachchh Mainland Fault (KMF), Island Belt Fault (IBF), South Wagad Fault (SWF), Gedi Fault (GF), Banni Fault (BF), Katrol Hill Fault (KHF) etc. [16]. The succession of the broadly E-W trending faults that segmented the Kachchh basin is conventionally described as the reactivated precambrian signature, assuming that the Delhi Aravali orogenic trend that run in the NE-SW direction has changed its direction to the west after entering the Gujarat plains [14]. Because of disposition of various faults and lineaments, the Kachchh region is placed as Zone-V in the seismic zonation map of India. The Kachchh region is seismically the most active region in India after the Himalayas. Major earthquakes that occurred in Kachchh are the 1668 Indus delta (MM X), 1819 Kachchh (Mw 7.9), 1845 Lakhpat (MM VIII), 1956 Anjar (Mw 6.0) and the 2001 Bhuj (Mw 7.6) earthquakes.

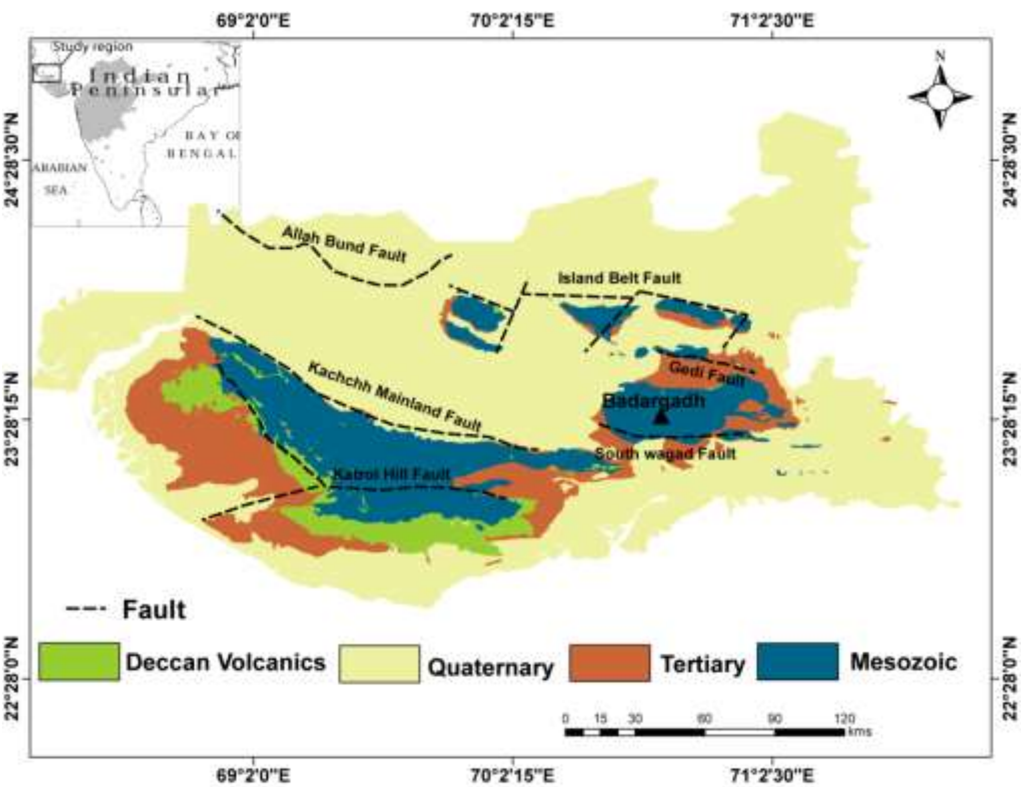

Figure 1: Location of radon monitoring station (black triangle) on Geological map of Kachchh. The inset shows the peninsular India map with study area (square).

III. MATERIALS AND METHOD

3.1 EXPERIMENTAL SETUP

For continuous monitoring of soil radon, Institute of Seismological Research (ISR) established an observatory at Badargadh (23°.47 N, 70°.62 E) in Kachchh region, Gujarat, India (Figure 1). The station is situated along the South Wagad Fault, an E-W trending and seismically active fault. For the measurement of soil radon (Rn^{222}) in the current study, the soil radon monitor (RTM 1688-2) manufactured by Sarad Instruments, Germany has been utilized. During the course of measurement, the instrument also measured other parameters such as pressure, temperature, humidity and soil thoron (Rn^{22o}) along with the soil radon. A sampling period of 10 minutes has been maintained for all the measured parameters. The soil gas that is released during the measurement is sent to an alpha spectroscopy via an internal pump after passing through the water trap and gas cooler. All the data is recorded and stored in the data logger. With the support of Radon vision software which is developed by the manufacturer, we can view the waveform data and export to text files. Figure 2 depicts the detailed picture of instrumentation and the procedure of the data acquisition. The radon probe is suspended by a cable inside a hole in the subsurface of earth at a depth of 3 ft as shown in the figure and the cable is connected to a data logger. The bottom of the hole is filled with gravels to prevent the contamination of water. Both the cable and radon probe in the hole is wrapped with a PVC pipe below the surface of earth. The data logger is connected with a computer or laptop for the real time visualization and downloading of the raw data and with a DC battery for power supply.

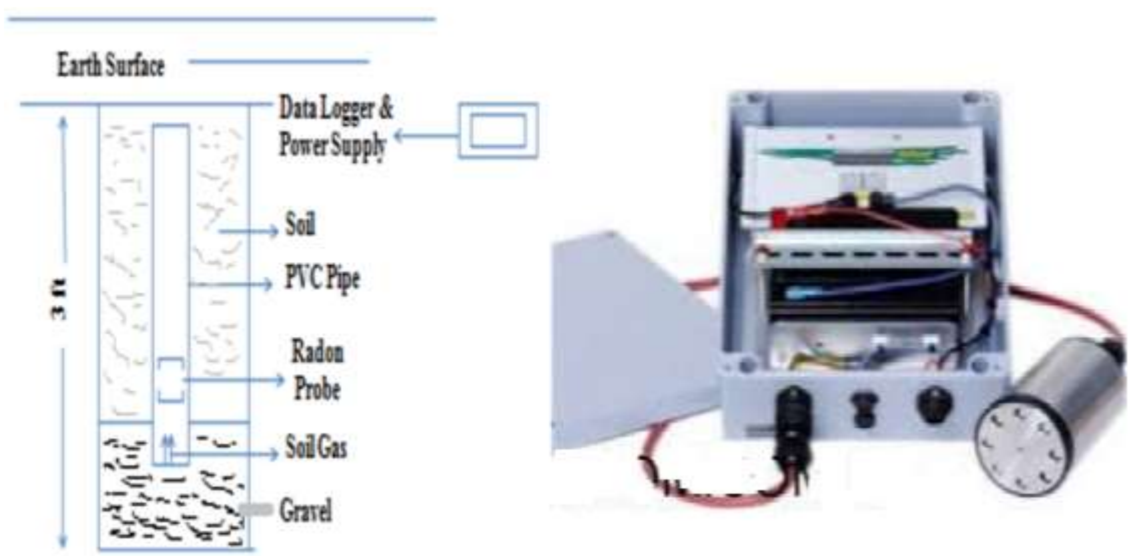

Figure 2: Experimental setup of radon monitoring station and radon instrument

3.2 METHODS

In order to understand the back ground values of radon, thoron, temperature, relative humidity and pressure in our study region, we first carried out the descriptive analysis such as minimum, maximum, average and standard deviation of these parameters. Then, we correlated the radon time series with other meteorological parameters using two different methods namely linear regression analysis and cross correlograms. To determine the long memory characters, the rescaled range analysis (R/S) of soil radon and other parameters is conducted. In the R/S analysis, there is a parameter known as the Hurst exponent (H) or the index of dependence is derived. The value of H is confined between 0 to 1. Based on the range of its value, the Hurst exponent divides the input time series into three categories, i.e. anti-persistent ($0<H<0.5$), random ($H=0.5$) and persistent ($0.5<H<1$) [17, 18]. In case of the random walk, the time series does not possess any long memory effect. In the anti-persistent category, the trend reversion is more probable than the trend continuation. For the persistent type, i.e. when the H value is confined between 0.5 and 1, the time series exhibit the long range correlation. The mathematical operation of the R/S method is described below:

Let us take a time series of N no. of observations, where $N \in \{N_1,N_2,N_3,\ldots\ldots\ldots,N_n\}$ is again divided into d non-overlapping intervals of N, ($N_{(k-1)(s+1)}$, $N_{(k-2)(s+2)},\ldots\ldots\ldots N_{k.s}$), where k= 1,2,3,….d with individual length s=n/d. The calculation of Hurst exponent, H is based on the following relation, i.e.

$$\left(\frac{R}{S}\right) = \frac{1}{d}\sum_{k=1}^{d}\left(\frac{R_{ks}}{S_{ks}}\right) \quad (1)$$

In the above equation (1), $R_{k.s}$ is calculated as,

$$R_{k\,s} = \max_{1<i<s}\{(Y_{k,s})i\} - \min_{1<i<s}\{(Y_{k,s})i\} \quad (2)$$

Here $(Y_{k.s})_i$ is the deviation of an individual observations of sub groups (i) and their mean $(X_{k.s})$ and calculated as ,

$$(Y_{k.s}) = \sum_{j=1}^{i}(X_{(k-1)s+i} - X_{k,s}) \quad (3)$$

The mean of the subgroups can be computed as

$$\overline{X} = \frac{1}{s}\sum_{i=1}^{s}(X_{(k-1)s+i}) \quad (4)$$

The parameter $S_{k,s}$ given in the equation (1) is defined as,

$$S_{k,s} = \sqrt{\sum_{i=1}^{s}(X_{(k-1)s+i} - \overline{X}_{k,s})^2 / s} \quad (5)$$

In the final step, the rescaled range (R/S) is linearly regressed with the sizes according to the following relation, i.e.

$$Log_{10}(\frac{R}{S}) = const + H_{obs}Log_{10}(s) \quad (6)$$

Where H_{obs} is the observed Hurst exponent (H)

IV. RESULTS AND DISCUSSION

4.1 DESCRIPTIVE STATISTICS OF RADON, THORON AND METEOROLOGICAL PARAMETERS

Figure 3 depicts the time series of soil radon, thoron, pressure, humidity, temperature which are recorded at Badargadh observatory and wind speed & rainfall data which are recorded at Khirai (23.4739°N, 70.6454°E) by Directorate of Agriculture, Government of Gujarat during January-December, 2017. The general statistics of radon, thoron and other parameters (temperature, relative humidity and pressure) have been analyzed for the study period (1st January to 31st December, 2017) and depicted in Table 1. In order to characterize the seasonal variation of radon, the detailed statistical analysis of radon has also been conducted during various seasons such as summer, winter and rainy seasons separately (Table 2).

Table 1: Descriptive Statistics of Soil radon and other parameters during the monitoring period

Parameters	Minimum	Maximum	Average	Standard Deviation
Radon (Bq/m3)	6	1134	344	89
Thoron (Bq/m3)	14	2993	1172	59
Pressure (mBar)	973	1002	989	6
Temperature (ºC)	11	45	28	6
Humidity (%)	33	97	56	15
Wind speed (km/hr)	0.69	7.6	2.11	0.89

From the analysis, it has been obtained that radon is showing an average value of 344 Bq/m3 for the total period of one year, while it is showing the average values of 247 Bq/m3, 550 Bq/m3 and 319 Bq/m3 during summer, winter and rainy seasons respectively (Table 2). From the seasonal statistics, it has been observed that radon shows maximum concentration during the rainy season with highest average and standard deviation values in comparison to the other two seasons. As soon as the rainy season is over, the radon values are coming down which is indicating that the radon emanation and transportation in the subsurface is influenced by the rainfall. Moreover, the wind speed is also higher (6-9 km/hour) during this season. The increase of radon with increase of rainfall was reported in earlier studies [19, 20, 21]. The conceivable explanation for increase of radon is that as soon as the rain water percolates into the soil, it enhances the permeability of the soil pores and hence the transportation of soil gas radon gets stimulated and there is an increase in its concentration. After a certain time duration, as the soil pores are completely saturated with water, there will be a moisture cover which is formed like a cap (capping effect) and it inhibits the exhalation of soil radon and hence, its concentration decreases.

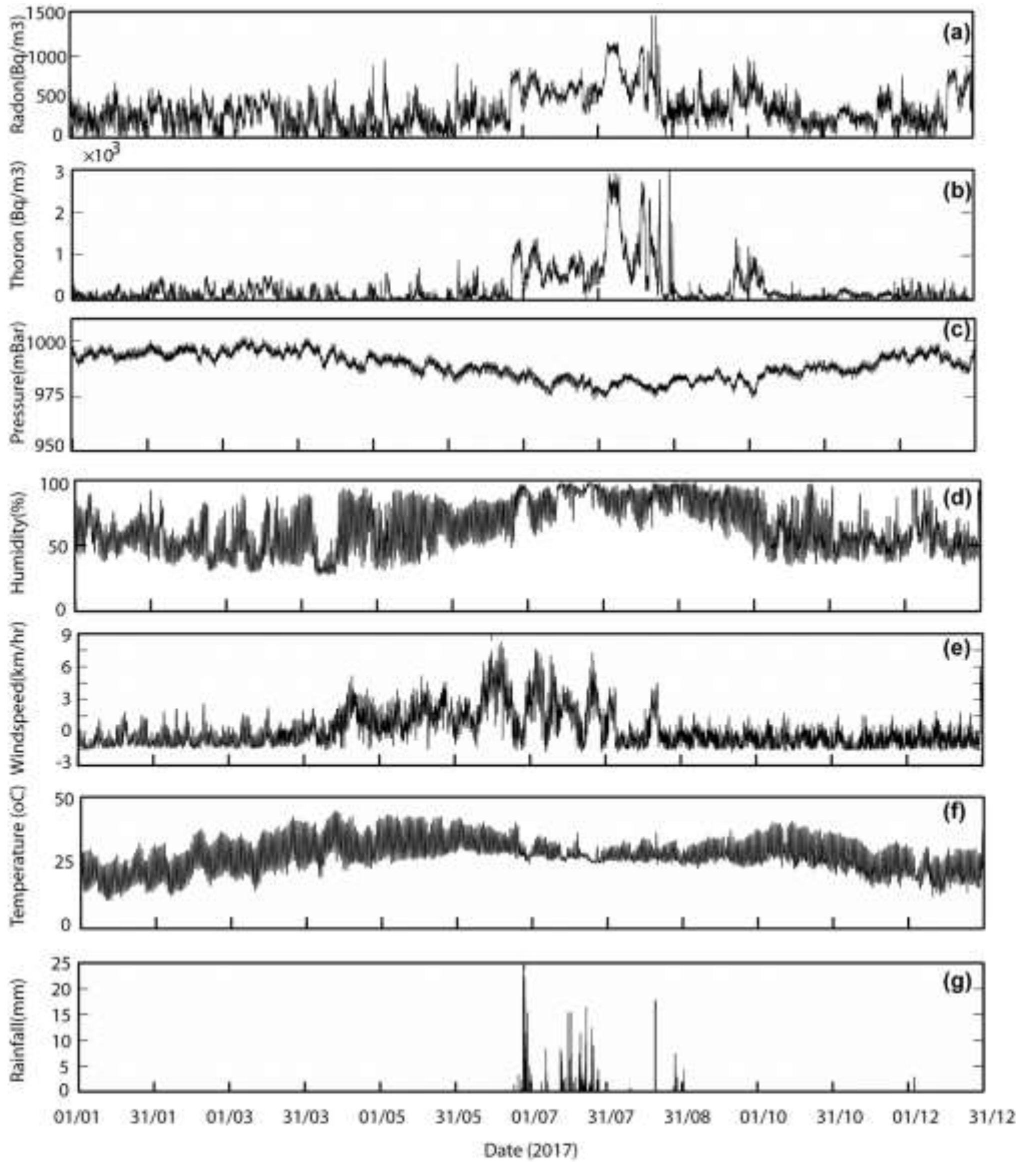

Figure 3: Soil Radon, Thoron, Pressure, Humidity, Wind speed, Temperature and Rainfall data recorded during January-December, 2017

In the Table 2, it has been observed that the concentration of soil radon is low during summer as compared to the other two seasons. The plausible explanation for decrease of radon is that the temperature inversion occurs during the rainy and winter months which are responsible for higher value of radon during these two seasons. Moreover, during summer season, the vertical mixing of air and its dispersal to higher altitudes reduces the concentration of radon near ground surface. Apart from these two reasons, the change in soil temperature and humidity also responsible for the seasonal variation of soil radon [22, 23, 24].

Table 2: Descriptive Statistics of Soil radon during all the three seasons

Radon (Bq/m3)	Minimum	Maximum	Average	Std.dev
Summer	6	964	247	70
Rainy	353	1500	550	136
Winter	116	1051	319	90

In order to find out whether recorded soil radon data is following normal distribution or not, we plotted the quantile (q-q) plot (Figure 4). During the monitoring period, we observed a good correlation between the quantiles of observed and expected values. This high correlation indicates that the soil radon is following normal distribution. As per Ahrens [25], soil radon generally follows fundamental laws of geochemistry with normal distribution.

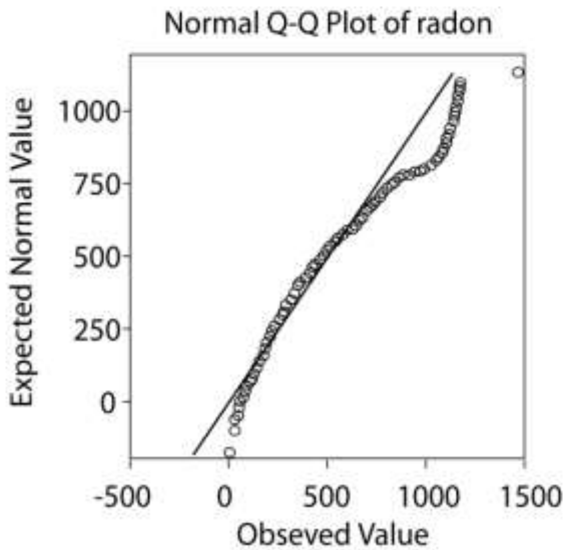

Figure 4: Quantile (q-q) plot of Radon time series at Badargadh

4.2 DETERMINISTIC ANALYSIS

A deterministic analysis of the soil radon along with all the other meteorological parameters has been carried out to understand the long range memory present in the corresponding datasets. This analysis will aid in understanding the dependency of one parameter over one or more parameters [18, 26]. The emission of soil radon is regarded as a non-linear and complex process due to its dependency on different chaotic variables such as pressure, temperature, humidity etc. [26, 27, 28]. The chaotic nature of radon time series was explored by computation of various parameters such as Hurst exponent (H), the Lyapunov exponent (λ) and attractor dimension. The Hurst exponent (H) can be computed through rescaled range (R/S) analysis on radon time series and other parameters. The H value generally varies between 0 to 1. Tatli [17] reported that high value of H in the region as an indication of the occurrence of drought due to possible association with large scale atmospheric circulations. Gkarlaouni et al. [18] revealed the hidden characteristics of long memory dependence and clustering between earthquakes by R/S technique. In the present study, we applied the R/S method on soil radon and other meteorological parameters during the monitoring period to determine the Hurst exponent of each and every parameter. From this analysis, it has been observed that the H value is 0.861 for radon, 0.845 for thoron, 0.725 for pressure, 0.763 for temperature, 0.626 for wind speed and 0.771 for humidity (Figure 5). As all the values of the Hurst exponent (H) are greater than 0.5, it can be concluded that all the parameters are persistent in nature and having the long memory characteristics. Barkat et al. [29] reported that the H value is in the range of 0.5 to 1 for soil radon and other meteorological parameters with persistent nature in northern Pakistan. Whereas Planinic et al. [27] found anti persistent nature of radon and persistent nature of meteorological parameters. In our study also we obtained H value greater than 0.5 for radon and other meteorological parameters which indicate that no chaotic behavior in the observed radon time series.

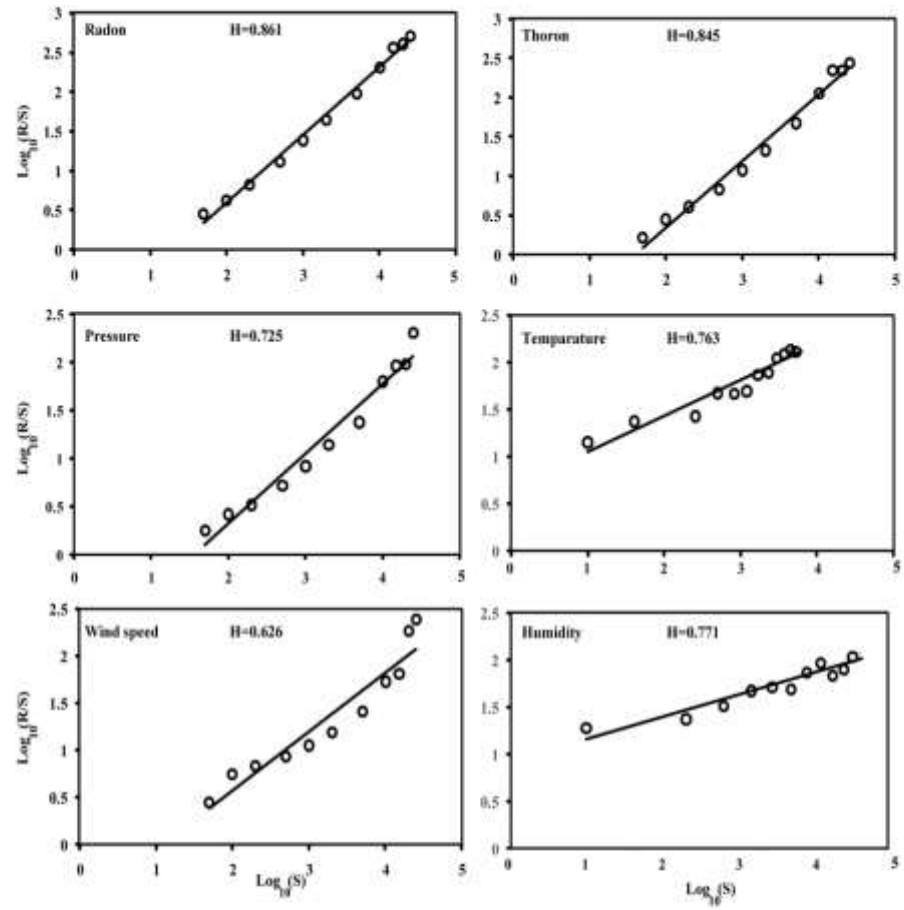

Figure 5: Calculation of Hurst exponent (H) for all parameters by R/S method

4.3 SOURCES OF RADON GAS EMISSION

Radon and Thoron are released by the decay of Uranium and Thorium inside the earth's crust. Its emanation and movement mainly depend on the physical conditions inside the earth rather than chemical processes [31]. The atmospheric influences also control the radon and thoron emanation along with geological conditions. The enhancement of radon flux is mainly dependent on cracks and fissures [30]. Generally the high concentration of radon is found in soils which are overlain by fractured rocks i.e. earthquake prone areas and volcanic areas [31]. During the earthquake preparation period, new fractures and fissures are created inside the earth. Subsequently, the radon gets more spaces to travel and the radon emission is more. There are two possibilities of radon emanation based on its source of emanation; either it can be deeper source or shallower source. For the deeper source, crustal stress/strain is main attributers for the movement of radon gas along with other carrier gases. For the shallower source, micro fractures before moderate earthquakes are the main attributers for the enhancement of these gases. So, the source of radioactive emission is an important component for understanding the earthquake process.

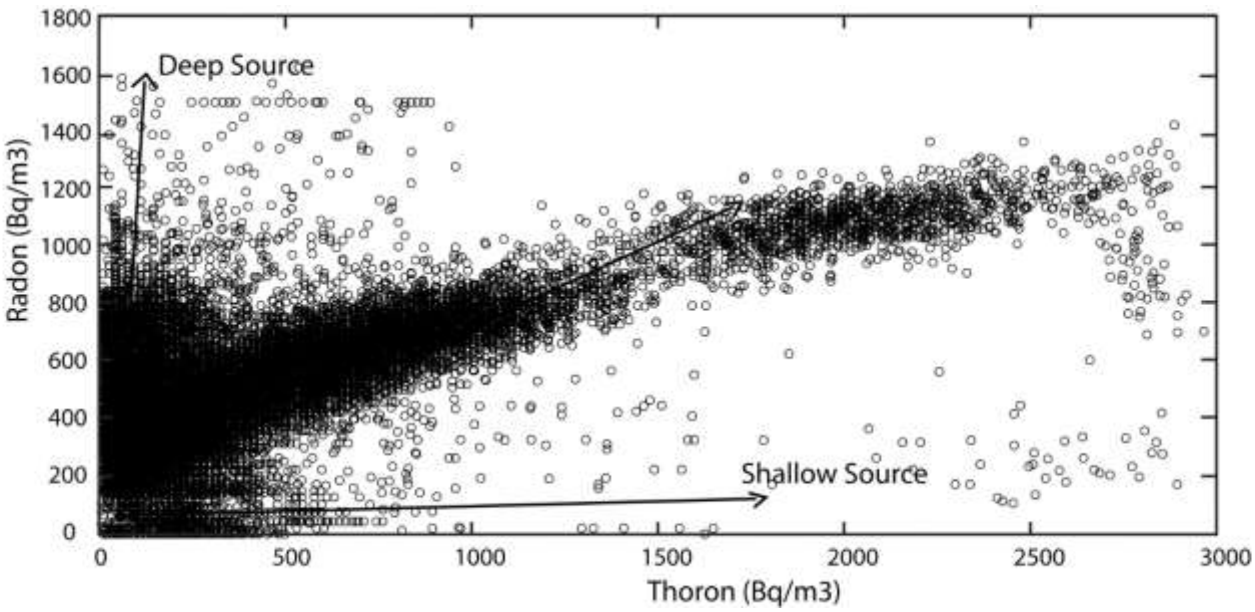

Figure 6: Correlation between Soil radon (Rn^{222}) and Thoron (Rn^{220}) and source of emission

The source of radioactive emission can be determined from the correlation between radon and thoron [32]. In case of high radon level and low thoron concentration, the source of radon is deep and in the case of low radon level and high thoron level, the source of radon is shallow. The high ratio of radon to thoron indicates that the radon gas has been transported from deep sources due to stress/strain alterations. Whereas, the low radon and high thoron indicates that the radon is generated at shallow level due to micro-fracturing during earthquake preparation process before occurrence of earthquakes [32]. Figure 6 depicts the radon versus thoron plot which shows both high and low values of radon to thoron ratio. We may conclude that both shallow and deep sources are present in the radon emission [33]. The radon and thoron show a good correlation which may indicate that the majority of radon and thoron has been carried from the deep source in the crust due to the release of stress. As per earthquake catalog of ISR Annual report, 2017-18 [34], it is clear that most of the earthquakes in Kachchh are having the focal depths in the range of 13-27 Km. This may suggest that majority of radon emission is from deep source. As shown in above section 2.0 and Figure 1, the Kachchh basin contains several major E-W–trending faults. It is observed that the radon gas emission is more near faults and fractures in any area which serve as good conduits for radon gas transport. Such areas generally have more permeability and porosity as compared to solid hard rock areas that enable radon gas to buoyantly migrate to surface of earth and subsequently, increase of radon gas takes place [35]. However, we can clearly see some peaks in thoron concentrations without increase of radon concentration, we cannot explain this phenomenon with solely of deeper source, and we have to incorporate the shallow source of radon gas generation. This shallow source can contribute towards the propagation of low radon gas compared to the thoron due to the micro-fracturing in the rocks prior to the moderate earthquakes. This impact of shallow source can be clearly seen in thoron level due to its half-life differences between thoron and radon and it is imperative that the thoron is more sensitive to the shallow focus earthquakes as compared to radon level [32]. However, it is difficult to exactly pinpoint about the source of radon emission whether it is from deeper source or shallower source as it is complex phenomenon which may require long duration radon data with many occurrences of earthquakes of both shallow and deep focus.

4.4 CORRELATION OF RADON CONCENTRATION WITH METEOROLOGICAL PARAMETERS

The meteorological parameters have a great contribution towards the dynamics of the soil radon, i.e. starting from its generation to migration and emission [36]. Among all the meteorological parameters, the soil radon is influenced primarily by precipitation [37], but also by barometric pressure, temperature and wind speed [38, 39, 40]. The emanation level of radon depends upon the amount of soil moisture present in the soil grains [41]. Broadly, the transportation of soil radon can be occurred by the process of diffusion, convection or the combination of both [1]. Diffusion is defined as the process when radon propagates through the pore fluid (liquid or gases) due to the action of a concentration gradient, and in case of convection, the transmission of pore fluid takes place in the soil pores along with the radon atoms due to the impact of some external forces.

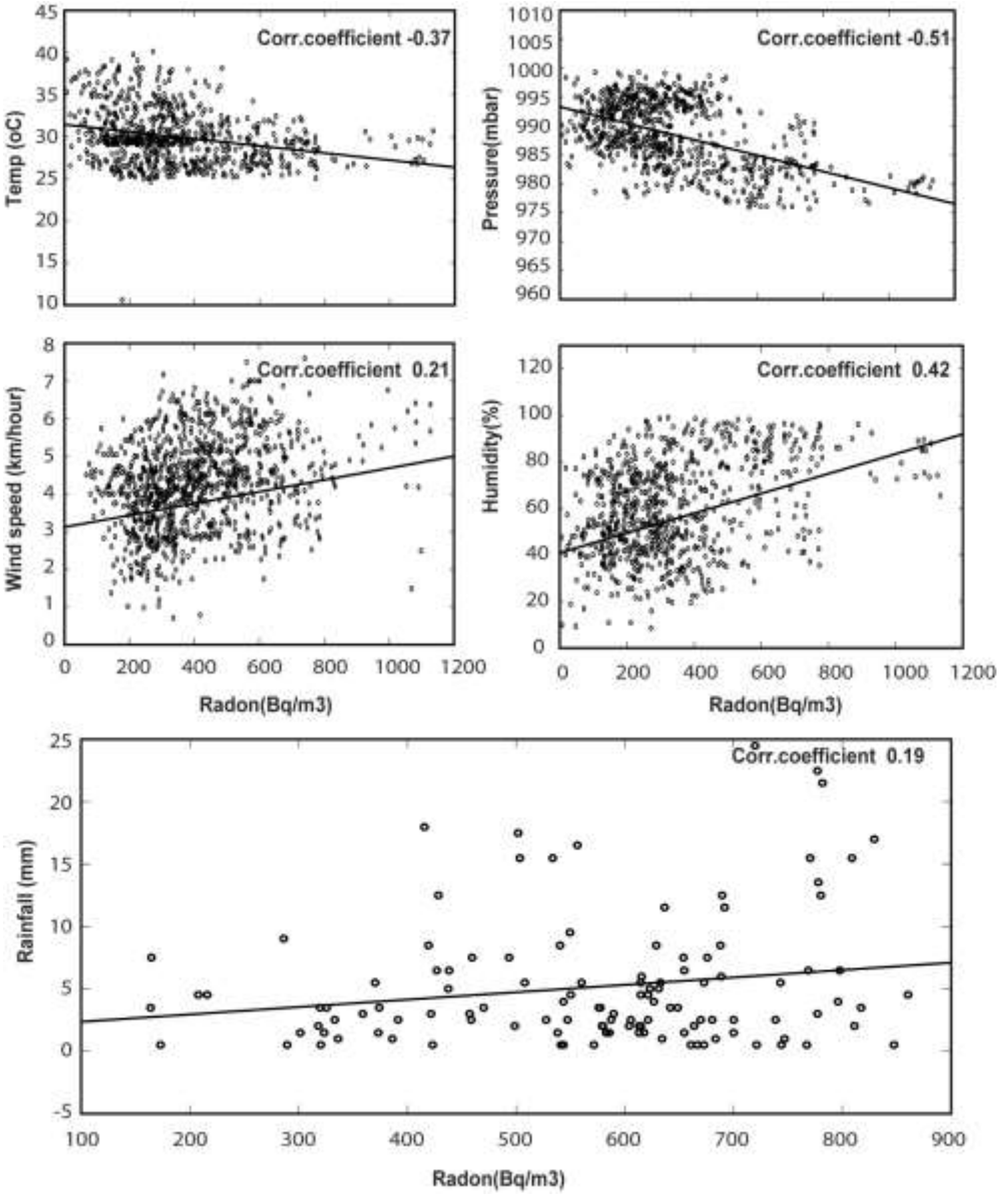

Figure 7: Linear regression between radon with pressure, temperature and humidity

The diffusion process became dominant in case of the high permeable soil, whereas, the low permeability of soil is suitable for the convective transport. The dry soil has more potential of the radon migration compared to the soil saturated with water. In this study, linear regression has been applied between radon and meteorological parameters to understand the influence of meteorological parameters on the soil radon emanation during the study period. From the linear correlation between radon with meteorological parameters (pressure, temperature and humidity), it has been obtained that pressure and temperature show a negative correlation with radon, while the humidity varies positively with radon (Figure 7). The correlation coefficients were computed for each variable with radon (Table 3). From the above table, it can be observed that the temperature showed a moderate negative correlation (-0.37) with radon during the study period, i.e., the concentration of soil radon decreases with the increase in temperature. The reduced temperature has allowed the convective transport of soil radon.

Table 3: Correlation coefficient of Soil radon and other meteorological parameters

Parameters	Correlation Coefficient
Radon and Pressure	-0.51
Radon and Temperature	-0.37
Radon and Humidity	0.42
Radon and Wind speed	0.22
Radon and Rainfall	0.19

Jaishi et al. [12] reported a moderate negative correlation between radon and temperature along the Mat Fault, Mizoram, India and suggested that the upward movement of radon by convection process gets stimulated in lower air temperature compared to the soil temperature and vice-versa. Sahoo et al. [13] have also found a similar negative correlation between the temperature and radon. Whereas, Walia et al. [11] observed the existence of positive correlation of radon with temperature, humidity and rainfall, but found a negative correlation of radon with wind speed at the MBT of N-W Himalayas, India. Again, the barometric pressure shows a moderate negative correlation (-0.51) with soil radon which means the increasing pressure forces atmospheric air into the soil, diluting the near-surface soil gas and driving radon deeper into soil [2].

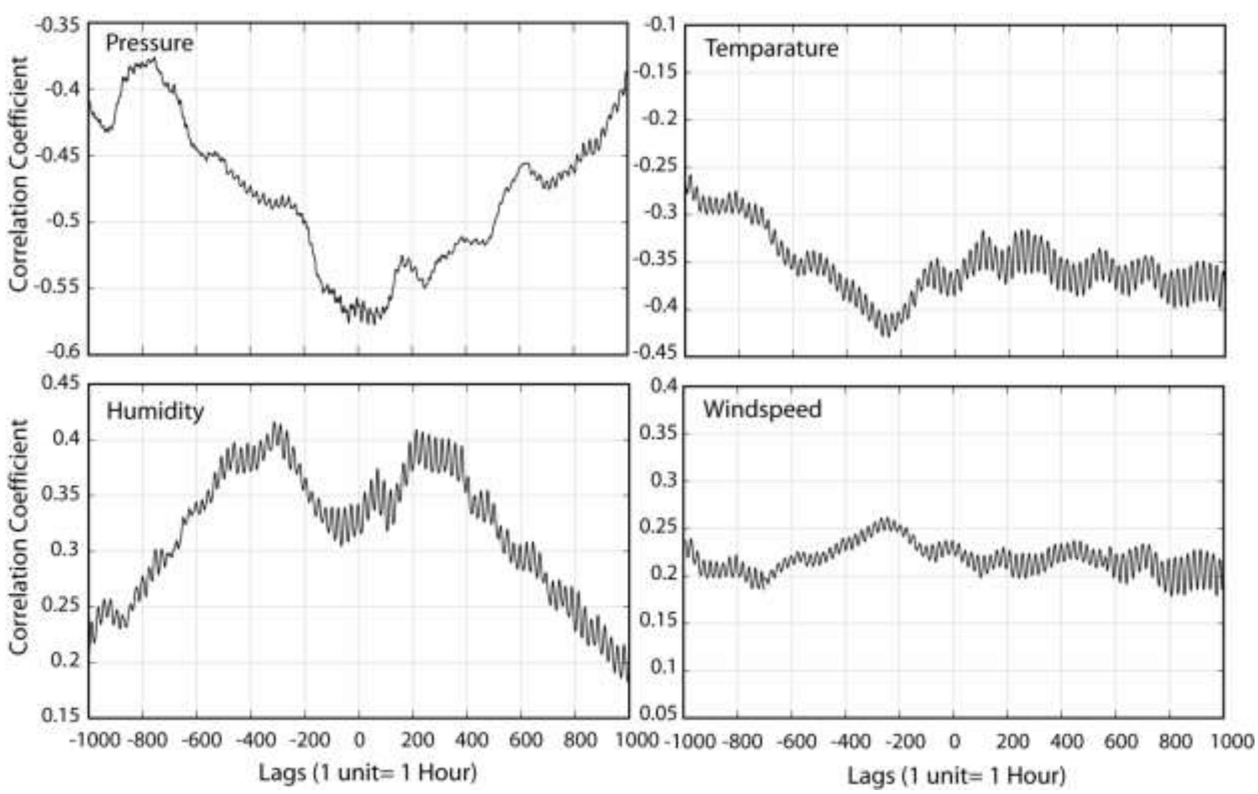

Figure 8: Cross Correlograms between radon and other meteorological parameters

The atmospheric moisture content (Humidity) showed a moderate positive correlation (0.42) with the soil radon emission. The enhancement of the humidity formed a cap in the atmosphere that reduces the upward migration of soil radon and hence increasing its concentration. At Aizawl, Mizoram, India, similar positive correlation with humidity was reported by the authors in (42). The relation between rainfall and radon was found to be positive. This indicates that whenever the rainfall increases the radon emission increases. During high rainfall, all the ground become wet and because of capping affect which stops the radon flow in to the atmosphere which ultimately increases the soil radon level [43]. Figure 8 depicts the cross correlograms between radon and other meteorological parameters. The extent of similarity between radon and other meteorological parameters with respect to time has been determined by analyzing through time-lagged cross correlation.

The cross correlation between radon and temperature oscillates above and below the zero point indicating that there is a good correlation exists between the pair of variables. The time lags are showing two directions, i.e. the positive lags and the negative lags. The positive lags indicate the time duration by which the temp has been shifted forward with respect to the radon, while the negative lags indicate the backward shifting. The cross correlation between radon and all other parameters (i.e. pressure, temperature and humidity), the time difference between two corresponding peaks or troughs in both positive and negative sides is maintained as 24 hours. This existence of such a specific lag of 24 hours indicates that all the parameters a diurnal variation with radon during the monitoring period. Similar observation is obtained by Kumar et al. [44] and Arora et al. [45]. Again, in case of the correlation with pressure, the trough has been found before the peak in the positive lag direction indicating that on gradual shifting of humidity in forward direction, there is an opposite alignment between radon and humidity occurred prior to the constructive alignment. However, whatsoever the lagging time between the parameters, the correlation value between radon and other meteorological parameters are found to similar to what we got in linear regression.

V. CONCLUSION

Soil radon (Rn^{222}) and other parameters (pressure, temperature and humidity) are measured continuously at Badargarh of Kachchh region of Gujarat, India for the whole year 2017 with a sampling period of 10 minutes. As per the descriptive statistics of all the parameters, the soil radon varies between 6 Bq/m3 to 1134 Bq/m3 with an average value of 344 Bq/m3. Similarly, the thoron varies between 14 Bq/m3 to 2993 Bq/m3 with an average of 1172 Bq/m3. The temperature has minimum of 11ºC and maximum of 45ºC with an average of 28ºC; humidity varies between 33 to 97% with an average of 55%; pressure is 973 to 1002 mBar with an average of 988 mBar and wind speed varies between 0.69 km/hr to 8 km/hr with an average of 2.11 km/hr. The Hurst exponent (H) value is found to be greater than 0.5 for radon and other meteorological parameters which indicate that no chaotic behavior in the observed radon time series. Radon is found to be negatively correlated with two parameters (pressure and temperature) and positively correlated with other parameters (humidity, rainfall and wind speed). The increase in the air temperature compared to the soil temp had inhibited the convective transport of soil radon and hence its concentration decreased with temperature. The enhancement of barometric pressure has forced the soil radon to drive downward and hence decreased with increase in pressure. Similarly, the plausible explanation for positive correlation with humidity is that the enhancement of the humidity formed a cap in the atmosphere that reduces the upward migration of soil radon and hence increasing its concentration. The linear regression between soil radon (Rn^{222}) and thoron (Rn^{220}) has revealed the deeper source for most of radon emission in Kachchh. The deeper source of radon emission can be linked to tectonic movements in Kachchh as most of the local earthquakes occur at lower crust.

Acknowledgement: The authors are thankful to the Director General, ISR for his encouragement, scientific support and permitting us to publish this work. The authors would like to thank Department of Science and Technology, Government of Gujarat for funding to establish multi parametric geophysical observatory network in Kachchh, Gujarat for earthquake precursory research.

REFERENCES

1. Tanner, A.B., *Radon Migration in Groundwater, The Natural Radiation and Environment* III, Houston, Texas PP. 5-56, (1980).
2. Schumann RR, Owen DE. *Relationship between geology, equivalent uranium concentration, and radon in soil gas, Fairfax Country, Verginia*: USGS open file report 88–18, p 28, (1988).
3. Sexm, R.G., Moed, B.A., Nazaroff, W.W., Revzan, K.L., and Nero, A.V., *Investigations of soil as a source of indoor radon, in Hopke, P.K., ed., Radon and its decay products*: American Chemical Society Symposium Series 331, pp.10-29, (1987).

4. Shebell P, Miller KM, *Analysis of eighteen years of environmental radiation monitoring data*. Environ Int 22(Suppl 1):S75–S83 (structure of the material. Geochim. Cosmochim. Acta. 57, 1783–1797, (1996).
5. Fujiyoshi, R., Sakamoto, K., Imanishi, T., Sumiyoshi, T., Sawamura, S., Vaupotic, J., Kobal, I. *Meteorological parameters contributing to variability in 222Rn activity concentrations in soil gas at a site in Sapporo, Japan*. Sci. Total Environ. 370, 224–234, (2006).
6. Sundal AV, VidarValen, Oddmund Soldal, Terje Strand. *The influence of meteorological parameters on soil radon levels in permeable glacial sediments*, j.scitotenv, 418–428, (2008).
7. Inan, S., T. Akgul, C. Seyis, R. Saatcilar, S. Baykut, S. Ergintav and M. Bas, *Geochemical monitoring in the Marmara region (NW Turkey): A search for precursors of seismic activity*, J. Geophys. Res., 113 (B3), (2008).
8. Inan, S., A. Kop, H. Cetin, F. Kulak, Z. Pabuccu, C. Seyis, S. Ergintav, O. Tan, R. Saatcilar and M.N. Bodur. *Seasonal variations in soil radon emanation: long-term continuous monitoring in light of seismicity*, Nat. Hazards, 62 (2), 575-591, (2012).
9. Cigolini C, Poggi P, Ripepe M, Laiolo M, Ciamberlim C, Delle Donne D. *Radon surveys and real time monitoring at Stromboli volcano: influence of temperature, atmospheric pressure and tidal forces on 222Rn degassing*, J Volcanol Geotherm Res 184:381–388, (2009).
10. Singh, M., Ramola, R. C., Singh, S., & Virk, H. S. The influence of meteorological parameters on soil gas radon. Expl. Geophys, IX, 85–90, (1988).
11. Walia, V., Su, T. C., Fu, C. C., & Yang, T. F. Spatial variations of radon and helium concentrations in soil gas across Shan-Chaio fault, Northern Taiwan. Radiation Measurements, 40(2-6), 513–516, (2005).
12. Jaishi, H. P., Singh, S., Tiwari, R. P., & Tiwari, R. C. Correlation of radon anomalies with seismic events along Mat fault in Serchhip District, Mizoram, India. Applied Radiation and Isotopes, 86, 79–84, (2014).
13. Sahoo S.K., Rao K.M., Shaji J.P., Murali Krishna K.S., Udaya Lakshmi G., Influence of meteorological parameters on the soil radon (Rn^{222}) emanation in Kachchh, Gujarat, India, Environ Monit Assess, 190:111, (2018).
14. Roy A.B., Chatterjee A., Chauhan N.K., Geological evolution of Kachchh: An epitome of successive Phanerozoic events. Current Science, Vol. 112, No. 5, (2017).
15. Rajendran K., Rajendran C.P., Thakkar M., Tuttle M.P., The 2001 Kachchh (Bhuj) earthquake: coseismic surface features and their significance. Current Science, Vol. 80, No. 11, (2001).
16. Biswas, S. K. Regional framework, structure and evolution of the western marginal basins of India, Tectonophys, 135, 302–327, (1987).
17. Tatli, H., Detecting persistence of meteorological drought via the Hurst exponent, Meteorol. Appl. 22 (4), 763–769, (2015).
18. Gkarlaouni, C., Lasocki, S., Papadimitriou, E., George, T., Hurst analysis of seismicity in Corinth rift and Mygdonia graben (Greece). Chaos, Solit. Fractals 96, 30–42, (2017).
19. Fukui, M. 222Rn concentrations and variations in unconfined groundwater. J. Hydrol. 79, 83–94, (1985).
20. Hamada, H. Estimation of groundwater flow rate using the decay of 222Rn in a well. J. Environ. Radioact. 47, 1–13, (2000)
21. Monnin, M.M., Seidel, J.L. Radon concentration in karstic aquifers. Geofi´s. Int. 41, 265–271, (2001).
22. Grasty, R. L. Summer outdoor radon variations in Canada and their relation to soil moisture. Health Phys. 66, 185–193, (1994).
23. Mostafa AMA, Yamazawa H, Uosif MAM, Moriizumi J. Seasonal behavior of radon decay products in indoor air and resulting radiation dose to human respiratory tract. Journal of Radiation Research and Applied Sciences, 8(1), 142–7, (2015).
24. Arvela, O. Holmgren and P. Ha¨nninen, Effect of Soil Moisture on Seasonal variation in Indoor Radon Concentration: Modeling and Measurements in 326 Finnish Houses, Radiation Protection Dosimetry, Vol. 168, No. 2, pp. 277–290, (2016).
25. Ahrens, L.H. The lognormal distribution of the elements (a fundamental law of geochemistry and its subsidiary). Geochimica et Cosmochimica Acta 5: 49–73, (1954).
26. Barbosa, S.M., Steinitz, G., Piatibratova, O., Silva, M.E., Lago, P., Radon variability at the Elat granite, Israel: heteroscedasticity and nonlinearity. Geophys. Res. Lett. 34 (15), (2007).
27. Planinić, J., Vuković, B., Radolić, V., Radon time variations and deterministic chaos. J. Environ. Radioact. 75 (1), 35–45. (2004).
28. Külahcı, F., Şen, Z., On the correction of spatial and statistical uncertainties in systematic measurements of 222Rn for earthquake prediction. Surv. Geophys. 35 (2), 449–478, (2014).
29. Barkat, A., Ali, A., Rehman, K., Awais, M., Tariq, M.A., Ahmed, J., Iqbal, T., Multiprecursory analysis of phalla earthquake (July 2015; Mw 5.1) near Islamabad, Pakistan. Pure Appl. Geophys. 1–16, (2018).
30. Holford D J, Schery S D, Wilson J L and Phillips F M. Modeling radon transport in dry, cracked soil, J. Geophys. Res. 98(B1) 567–580, (1993).
31. Reddy D V, Sukhija B S, Nagabhushanam P, Reddy G K, Kumar D and Lachassagne P. Soil gas radon emanometry: A tool for delineation of fractures for ground water in granaitic terrains; J. Hydrol. 329, 186–195, (2006).
32. Yang, T. F., Walia, V., Chyi, L. L., Fu, C. C., Chen, C. H., Liu, T. K., Song, S. R., Lee, C. Y., & Lee, M. Variations of soil radon and thoron concentrations in a fault zone and prospective earthquakes in SW Taiwan. Radiation Measurements, 40(2), 496–502, (2005).
33. Padilla, G. D., Hernandez, P. A., Padron, E., Barrancos, J., Perez, N. M., Melian, G., Nolasco, D., Dionis, S., Rodriguez, F., Calvo, D., & Hernandez, I. Soil gas radon emission and volcanic activity at El Hierro (Canary Island): the 2011– 2012 submarine eruption. Geochemistry, Geophysics, Geosystems, 14(2), 432–447, (2013).

34. ISR (Institute of Seismological Research) annual report for the year 2017-18 https://isr.gujarat.gov.in/sites/default/files/Annual%20report_2017-18.pdf
35. Chen Z., Y. Li, Z. Liu, J. Wang, X. Zhou and J. Du, Sci. Rep. 8, 16772, (2018).
36. Klusman, Ronald & Webster, James. Preliminary analysis of meteorological and seasonal influences on crustal gas emission relevant to earthquake prediction. Bull. Seismol. Soc. Am. 71, (1981).
37. Kitto, M. Interrelationship of indoor radon concentrations, soil-gas flux, and meteorological parameters. J Radioanal Nucl Chem 264, 381–385, (2005)
38. Washington, John & Rose, Arthur. Temporal Variability of Radon Concentration in the Interstitial Gas of Soils in Pennsylvania. Journal of Geophysical Research. 97. 9145-9159, (1992).
39. Riley, W. J., A. L. Robinson, A. J. Gadgil, and W. W. Nazaroff, Effects of variable wind speed and direction on radon transport from soil into buildings: Model development and exploratory results, Atmos. Environ., 33(14), 2157–2168, (1999).
40. Robinson AL, Sextro RG, Riley WJ. Soil-gas entry into houses driven by atmospheric pressure fluctuations - The influence of soil properties. Atmospheric Environment, 31(10); 1487—1495, (1997).
41. Damkjaer, A., Korsbech, U., Measurement of the emanation of radon-222 transport from Danish soils. Sci. Total Environ. 45, 343–350, (1985).
42. Sanjay Singh., Jaishi, H. P., Tiwari, R. P., & Tiwari, R. C. A study of variation in soil gas concentration associated with earthquakes near Indo-Burma Subduction zone. Geo environmental Disasters, 3(1), 22. (2016).
43. Virk, H. S. and Walia, V., Radon/Helium monitoring in thermal springs and earthquake prediction. Publ. of the Centre of Advanced Study in Geol. 7, 106–107, (2000).
44. Kumar, A., Walia, V., Arora, B.R., Yang, T.F., Lin, S.-J., Fu, C.-C., Chen, C.-H., Wen, K.-L., Identifications and removal of diurnal and semi-diurnal variations in radon time-series data of Hsinhua monitoring station in SW Taiwan using singular spectrum analysis. Nat. Hazards 79 (1), 317–330, (2015).
45. Arora, Baldev., Kumar, Arvind., Walia, Vivek., Yang, Tsanyao., Fu, Ching-Chou., Liu, Tsung-Kwei., Wen, Kuo-Liang., Chen, Cheng-Hong. Assessment of the response of the meteorological/hydrological parameters on the soil gas radon emission at Hsinchu, northern Taiwan: A prerequisite to identify earthquake precursors. Journal of Asian Earth Sciences. 10.1016/j.jseaes.2017.06.033, (2017).