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Nonlinear Event-Space Analysis of Radon and Meteorological Parameters for Seismic Anomaly Identification

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Abstract

Radon (^{222}Rn) dissolved in soil gas serves as a well-established geochemical tracer for crustal deformation and seismic precursory research. However, radon concentration time series recorded at near-surface monitoring stations are systematically contaminated by meteorological parameters, principally atmospheric temperature, humidity, barometric pressure, and precipitation and rigorous characterization of these influences is a prerequisite for reliable earthquake precursor signals. Conventional linear correlation analyses are fundamentally limited in their capacity to capture transient, event-driven, and nonstationary radon responses that are most likely to encode seismically significant precursory signals. This study presents a comprehensive **nonlinear event-space analytical framework** applied to 11,572 hourly soil-gas radon data recorded at the Jiaosi monitoring station in northeastern Taiwan spanning January 2021 to April 2022. The methodology integrates time-series first-order differencing to isolate event-based change signatures, classification of hike, drop, and normal meteorological change states, and Locally Weighted Scatterplot Smoothing (LOWESS) for nonparametric characterization of radon response curves in change space. In the linear amplitude domain, temperature ($r = 0.500$), atmospheric pressure ($r = -0.384$), and humidity ($r = 0.158$) emerge as the dominant meteorological correlates of radon variability. Critically, these correlations weaken markedly when evaluated in the nonlinear event domain, revealing that temperature, pressure, and humidity primarily modulate quasi-stationary and periodic background radon signals rather than transient excursions. In striking contrast, rainfall which exhibits negligible linear correlation with radon reveals a pronounced **U-shaped nonlinear response** in event space. The nonlinear rainfall response remained stable across all threshold configurations and accumulation windows, confirming the robustness of the event-space framework. in the event domain that is consistent across all precipitation accumulation windows (24-hour, 72-hour, and 240-hour), and is mechanistically attributable to the rainfall capping effect, piston effect, and soil drainage dynamics. This pattern constitutes the primary source of false positives in radon-based precursor identification. The event-space LOWESS framework substantially enhances the discriminability of meteorologically driven noise from potentially geophysically significant anomalies, providing a computationally accessible complement to Empirical Mode Decomposition–Hilbert-Huang Transform (EMD-HHT) approaches. The methodology has direct implications for operational earthquake precursor detection frameworks and multi-station radon monitoring networks.

Keywords: radon precursors; nonlinear analysis; LOWESS; event-space analysis; seismic anomaly; soil-gas geochemistry; Taiwan tectonics; rainfall capping effect; Jiaosi monitoring station; empirical mode decomposition; earthquake precursor detection.

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1. Introduction

Taiwan is located in a very seismically active convergent plate boundary region between the Eurasian Plate and the Philippine Sea Plate (Suppe, 1984; Hu et al., 1996). The seismotectonic setting generates frequent seismic activity, from minor tremors to major destructive earthquakes that makes the island an excellent natural laboratory for research into geochemical earthquake precursors. Soil-gas geochemical measurements are crucial for continuous monitoring of soil-gas along active fault systems as part of the activities of reliable short-term seismic hazard assessment.

Radon (^{222}Rn), a naturally occurring radioactive noble gas formed by alpha-decay from radium-226 in crustal rocks and soils, is one of the geochemical tracers used in seismic precursor studies which has been of continuous scientific interest for the past five decades (Cicerone et al., 2009; Petraki et al., 2015; Hartmann and Levy, 2005). Radon is transported to beneath the earth's surface by diffusing through the cracks in the earth's crust and porosities in the soil under the effect of pressure and temperature differences (Fleischer and Mogro-Campero, 1978; Planinič et al., 2004). It is hypothesized that pre-seismic stress accumulation causes changes in fault-zone permeability, stress changes to pore pressure distributions, and measurable perturbations to subsurface radon fluxes, which can result and become measurable in the form of concentration anomalies at surface radon from days to weeks before earthquake occurrence (Petraki et al., 2015; Thomas, 1988).

One important barrier to research on radon precursors is the ability to distinguish tectonic signals from ubiquitous meteorological noises. The ones which change periodically or episodically with the atmospheric temperature, barometric pressure, soil moisture and precipitation, can mask, mimic or obscure a potentially true seismically induced anomaly (Arora et al., 2017; Kumar et al., 2015; Barman et al., 2016). Arora et al. (2017) showed that of total radon variability, the two contributions from temperature and pressure only accounted for 10-14% and other meteorologically induced perturbations due to the capping effect and pore-pressure dynamics were actually the major source of false positive detections of precursors at the Hsinchu monitoring station in the north of Taiwan as determined by Singular Spectrum Analysis (SSA) along with partial correlation analysis. Chowdhury et al. (2025) used the same dataset of Jiaosi for applying EMD-HHT method, and 11 IMF components were finally identified from the dataset after removing diurnal and semi-diurnal components, which are related to the temperature and the pressure cycle, respectively. Background IMF components, in total, were estimated to 15, but the top five remaining components were up to the order of the four associated with 15 corresponding seismic events.

Existing studies have demonstrated the use of advanced signal decomposition methods, such as Singular Spectrum Analysis (SSA) (Arora et al., 2017) and Empirical Mode Decomposition–Hilbert–Huang Transform (EMD-HHT)(Chowdhury et al., 2025), to be useful for separating periodic

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meteorological components from radon time series and better identification of possible seismic anomalies. They are mainly amplitude or frequency domain methods that aim at decomposing signals instead of explicitly describing the response of radon to transient meteorological phenomena. Therefore, threshold dependent and event conditioned responses, especially over the periods of onset and cessation of rainfall, are still difficult to directly interpret. These techniques are effective in separating oscillatory parts, but they do not offer intuitive framework to understand the localized nonlinear relations between sudden changes in meteorological fields and radon fluctuations. This restriction is the reason for the present study, which proposes a framework based on event space analysis to address the first-order changes in the system, instead of the amplitude of the signal, and enables an explicit description of the transient nonlinear interactions between meteorological and radon parameters.

Although SSA and EMD-HHT have significantly improved the interpretation of radon time series by separating periodic and non-stationary components, both approaches primarily operate in the amplitude or frequency domain and are designed to decompose signals into intrinsic modes. Consequently, they do not explicitly characterize transient, threshold-dependent responses associated with individual meteorological events, particularly the onset and cessation of rainfall. This methodological limitation motivates the present study, which investigates radon variability in an event-space framework based on first-order changes rather than signal amplitudes. By combining event-space transformation with LOWESS smoothing, the proposed framework directly characterizes localized nonlinear meteorological responses while providing an interpretable complement to decomposition-based approaches.

To address the above research gap, this study applies a nonlinear event-space analytical framework to 11,572 hourly soil-gas radon observations collected at the Jiaosi monitoring station between January 2021 and April 2022. The objectives are: (1) to develop an event-space framework for characterizing nonlinear meteorological influences on soil-gas radon; (2) to determine whether transient rainfall events produce localized nonlinear responses that cannot be adequately identified using conventional linear correlation or decomposition-based methods; and (3) to evaluate the capability of the proposed framework to separate meteorologically induced radon variability from signals potentially associated with earthquake-related processes. This work is an attempt to fill the missing link by proposing and applying to the hourly soil gas radon data from Jiaosi monitoring station a framework that uses nonlinear event space analysis. Total 11,572 observations of soil-gas monitoring were obtained from January 2021 to April 2022 to explore the effects of meteorological factors on soil-gas radon. The first goal was to create an event-space analytical approach to describing the non-linear relationships

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between soil-gas radon and the key meteorological parameters. The study also explored if meteorological transients, specifically rainfall events, give rise to a non-linear response pattern that can not be captured by the typical linear correlation or decomposition technique. Lastly, the feasibility of the proposed event-space framework was examined as an alternative tool to identify meteorologically driven radon variations from the possible large seismic anomalies. Unlike the decomposition-based methods which are mostly frequency domain centered, the present framework enables explicit characterization of threshold dependent nonlinear responses in the event domain directly investigating transient meteorological-radon interactions.

2. Literature review

2.1 Radon as a seismic precursor

The first report of anomalies in radon activity in groundwater prior to the 1966 Tashkent earthquake was reported and the hypothesis was formally advanced that such anomalies could occur before earthquakes. Few decades later, extensive empirical literature emerged due to monitoring programs in Japan, China, India, Greece, Italy and Taiwan, (Cicerone et al., 2009; Petraki et al., 2015; Igarashi et al., 1995). The two main physical mechanisms suggested are: (1) the dilatancy diffusion model (Scholz et al., 1973) in which a volumetric expansion of crustal rock due to increased deviatoric stress results in the formation of new microcracks which increases the permeability of the rock, and thus promotes the migration of radon; and (2) the fracturing model that proposes rupture of void surfaces between mineral grains due to deviatoric stress and freeing of radon from the mineral grain surfaces, which results in an increased surface area on which radon may emanate (Fleischer and Mogro-Campero, 1978; Planinič et al., 2004). Many of the issues identified by the critical reviews, such as the lack of uniqueness of the anomalies patterns observed from radon measurements, and the inability to distinguish between seismograms and meteorological artifacts, still exist (King, 1980; Woith, 2015). However, Woith (2015) identified a seemingly negative relationship between the number of reported anomalies and the strictness with which the meteorological correction is done and seem to have found that many of the reported precursors are instead due to poorly corrected meteorology rather than true geophysical precursors. This highlights the need for the present study to be analytical.

In Taiwan, Walia et al. (2009) set-up continuous soil-gas monitoring along the Hsincheng and the Hsinhua fault systems and presented new operability rules for soil-gas characterization which include requirements related to the magnitude of the possible earthquake (≥ 5 ML), epicentral distance, (< 150 km), focal-depth, (< 40 km) and to the time window prior to the event (precursory time window, within 3 weeks) (Arora et al.,

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2017; Walia et al., 2009; Walia et al., 2023). Pre-seismic radon anomalies before the M 6.6 earthquake occurred in the Meinong region were recorded in 2016, as reported by Fu et al. (2017). From the other side, precursor analysis was continued at San-Jie station by Walia et al. (2024) who found pre-seismic anomalies in the IMFs 6–8, based on EMD.

2.2 Meteorological influences on soil-gas radon

Periodic and quasi-periodic structures have been reported in the time series of soil radon received by meteorological parameters collected from soil, atmosphere, tides and precipitation (Chowdhury et al., 2025; Barman et al., 2016; Shapiro et al., 1985). The regular oscillatory parts due to diurnal and semi-diurnal variations in temperature and pressure have to be filtered out and otherwise the precursor analysis may become systematically incorrect, either by mis-identification of precursors or by failing to identify them (Chowdhury et al., 2025; Fu et al., 2017; Fujiyoshi et al., 2006; Baykut et al., 2010). The barometric pressure effect in the atmosphere causes advective upward drift of soil gas under low pressure, which temporarily increases the volume of radon in soil gas, and down drift under high pressure. The pumping effect of the atmosphere due to the barometric (BMP) effect is an advective upward gradient of soil gas under decreasing positive pressure in the atmosphere, which temporarily increases the volume of soil gas containing radon while decreasing soil gas under increasing positive pressure in the atmosphere. Arora et al. (2017) demonstrated in Hsinchu that pressure and temperature are only able to account for 10-14% of the overall variability of radon; the apparent pressure-radon correlation is actually a pseudo-effect from the strong anti-phase dependence between pressure and temperature, which has been quantified as $\approx r = -0.61$. Temperatures are the most predominant meteorological factors with a partial correlation of about 11–14% of the total variability.

The effects of precipitation on radon are significantly more intricate and synoptic, and are intrinsically nonlinear. Arora et al. (2017) described three types of sequential rainfall-radon response relations at Hsinchu: (1) The capping effect, which is induced by increase in moisture content in the surface soil which forms a weak cap on radon off-gas, and results in a peak of radon concentration that appears with delay of 12-15 hours after rainfall; (2) double exponential decay (DED) of radon concentration after cessation of rainfall, which expresses natural radioactive decay and gradual weakening of the cap; and (3) double exponential decay (DED) during rainfall recession with modulation of long-term radon migration by groundwater head changes caused by the rainfall recession. Importantly, radon anomalies induced by tidal effects often exhibit waveform patterns similar to pre-seismic precursor signals (Arora et al., 2017), making them a major source of false alarms in earthquake precursor studies. The difference in soil porosity and moisture levels before the rainfall was observed by Chowdhury et al. (2025) which had a faster response at Jiaosi (6-10 hours after receiving >20 mm rainfall).

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2.3 Nonlinear analytical frameworks

Interest in alternative methods to linear regression for geophysical nonstationary time series has been stimulated by the limitations of linear regression. Chowdhury et al. (2025) applied EMD-HHT to the Jiaosi radon series and extracted 13 IMFs with the aid of diurnal cycle of IMDs (IMFs 3 and 4 corresponding to 12-hour and 24-hour periods) being attributed to diurnal changes in temperature and pressure. Then, using HHT, the 11 pre-seismic anomalies of the 15 qualifying seismic events were detected after subtracting the aforementioned IMFs and applying the IE analysis simultaneously.Pre-seismic anomalies were then identified after removing the above-mentioned IMFs and simultaneously applying the IE analysis to 15 qualifying seismic events by using the HHT.

Arora et al. (2017) applied the SSA in the area of Hsinchu and found that the variance consist of less than 2% periodic signals and ~68% aperiodic signals, including transients (transients induced by rainfall and ones which might be caused by seismicity). BAYTAP-G Bayesian tidal analysis quantified temperature and pressure induced responses, and a tank model with double-exponential decay terms simulated rainfall responses. Nonlinear decomposition has been used successfully in Analogous EMD-based frameworks in India (Sahoo et al., 2020) and in Sichuan (EMD-LSTM) (Feng et al., 2022) and cave EMD-based frameworks (Central Europe) (Ambrosino et al., 2019; Ambrosino et al., 2021), indicating the consistent good performance of nonlinear decomposition over linear correction. For removal of diurnal and semi-diurnal components, Kumar et al. (2015) used the data set from the monitoring station in Hsinhua.

Flexible nonparametric, local regression models like LOWESS (Cleveland, 1979) do not assume any underlying functional form for the global model, but serve to characterize local trends and nonlinearities that are not seen in a parametric model. In the context of the present study, the application to "event space" scatter distributions offers a more computational-friendly and interpretable alternative to frequency-decomposition methods. However, although major progress has been made in recent years, the characterization of this coupling between the meteorology and the radon concentration in the event space, especially for rainfall-induced nonlinear behavior, is still largely under-researched.

3. Study area and data

3.1 Tectonic setting

Tectonic configuration of northeastern Taiwan and schematic depiction of the Jiaosi soil-gas radon monitoring system is depicted in figure1. The figure depicts the regional geological framework linked to the Okinawa Trough

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extensional regime, the position of the Jiaosi monitoring station, the RAD7 soil-gas sampling configuration, and the conceptual impact of geological deformation and meteorological factors on radon variability. The graphic compares linear stationary responses to nonlinear transient event-space behaviour, which is the basis of the analytical paradigm used in this work. Taiwan is located at a convergent margin where the Philippine Sea Plate is subducted to the southwest under the Eurasian Plate in the Manila Trench and the Luzon arc is colliding with the Eurasian continental shelf to the northeast (Suppe, 1984; Hu et al., 1996). The northern part of Taiwan is the west extrapolation of the Okinawa Trough, an extensional back-arc basin with high geothermal activities and active extensional tectonics (Chowdhury et al., 2025; Lee et al., 2022). Taiwan has 39 known active faults, and several magnitude ≥ 5 earthquakes are continually expected to occur in the country each year, both onshore and offshore along the eastern coast from the inter-plate convergence and on the fault-zone seismicity (Wu et al., 1999).

The monitoring site, Jiaosi, is located in the northernmost part of the Ilan plain in north-east Taiwan, which is located in a tectonically active area related to the Okinawa Trough extensional system (Chowdhury et al., 2025; Lee et al., 2022). The area is crossed by multiple active faults of the Hsuehshan Range fault system, making it vulnerable to medium to high magnitude earthquakes. The high subsurface heat flow and fluid circulation found in this geothermal environment are important in the understanding of the observed positive correlation between temperature and radon at Jiaosi, compared to other Taiwan stations.

3.2 Jiaosi monitoring station and instrumentation

The soil-gas monitoring station Jiaosi (24.83°N, 121.77°E) is set with a radon detector type of RAD7 (Durridge Company), which can measure the radon concentration in the range of 4–750,000 Bq/m³ (Chowdhury et al., 2025). A sealed PVC pipe is used to collect soil radon samples at a depth of 2 m and surface atmospheric contamination is minimised. Built-in RAD7 sensors simultaneously measure soil temperature and soil humidity. The Central Weather Administration (CWA) of Taiwan, (www.cwa.gov.tw) (Chowdhury et al., 2025) provided data for atmospheric pressure, precipitation, and seismological information. The station setup is similar to the one proposed by NCREE-NTU as described in Walia et al. (2009).

3.3 Dataset Description and Summary Statistics

The analysis is carried out for hourly soil-gas radon concentration data from January 2021 to April 2022, the same time period used by Chowdhury et al. (2025) for the analysis by the EMD-HHT method, which allows for direct comparison of the methods. After systematic data preprocessing, the final analytical dataset consists of 11,572 valid hourly observations. Summary statistics for all variables are presented in Table 1.

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The soil radon time series is characterized by a considerable variability (CV ≈ 14%) which is consistent with multi-driver influence of radon coming from a meteorological and a possible seismogenic source. The soil moisture condition was generally consistent from August 2021 onwards, with the highest change in moisture being observed during the early monitoring period. The peak rainfall was observed during typhoon months (September–October) of 2021.

4. Methodology

This study uses an analytical approach similar to a sequential, seven step pipeline, moving from traditional linear baseline characterization to nonlinear event space analysis. The complete workflow is shown in Table 3, and in a schematic form, the processing pipeline from the raw data acquisition to comparative synthesis is shown in a methodology flowchart.

4.1 Data preprocessing and temporal synchronization

The raw data were rigorously quality controlled prior to analysis. Rainfall measurements (instrument offset artifacts) and also atmospheric pressure measurements with zero value or below, and also radon concentrations lower than the detection limit of the RAD7 instrument (4 Bq/m3), were identified and removed. To maintain a sense of chronological integrity, gaps were filled between observations, and this was done to ensure that the differencing aspect of event-based analysis would be maintained. The followed criteria here is the same as of Arora et al. (2017), Chowdhury et al. (2025) and Walia et al. (2009). Figure 3 below demonstrates the detailed preprocessing and event-space transformation workflow for the Jiaosi radon data set to pre-process the data, perform temporal synchronization, first-order differencing, event classification, LOWESS smoothing of the data set, and extract radon data without meteorological influence.

Table 1. Summary statistics of the Jiaosi monitoring station dataset (January 2021–April 2022, n = 11,572).

Parameter	Min	Max	Mean ± SD	Units
Radon (^{222}Rn)	50,943	120,562	78,611 ± 11,126	Bq/m³
Soil Temperature	11.1	35.1	22.3 ± 5.8	°C
Atmospheric Pressure	986.8	1030.7	1011.4 ± 8.3	mbar
Soil Humidity	15.5	21.3	19.6 ± 1.2	%
Rainfall	0.0	~120 (peak)	Variable	mm/hr
Valid observations (n)	—	—	11,572	hourly

Table 2. Component description of the Jiaosi monitoring station dataset (January 2021–April 2022, n = 11,572)

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Component	Description
Radon Dataset	Continuous Radon-222 concentration measurements
Sampling Interval	1 hour (curated hourly data)
Observation Period	Jan 2021 – May 2022
Total Samples	~11,000+ hourly records
Sensor Location	Fixed Monitoring Station
Auxiliary Variables	Temperature, Pressure, Humidity, Rainfall
Earthquake Catalog	Regional seismic events ($M \geq 5.0$)

4.2 Linear correlation analysis (baseline)

The results of Linear Correlation Analysis (Baseline) is depicted in Figure 4. Linear-domain statistical analysis of the relationship between soil-gas radon concentration and meteorological variables as background. The left panel is the normalized Pearson correlation matrix of the environmental parameters, and the right panel is the linear regression relationship between rainfall and radon. Although there is apparent dispersion and there are extreme events which fall outside the general trend, there is essentially no linear global correlation of rainfall with radon, and this is the motivation for the nonlinear analysis of rainfall events developed in the next sections. The Pearson correlation coefficient (r) was calculated for the overall data set (n = 11,572) between the radon concentration and each meteorological parameter (rainfall, humidity, temperature, and atmospheric pressure). All correlations were checked for statistical significance (two-tailed p-values). These results provide the baseline linear characterization to compare with the nonlinear event-space analysis, and can be directly compared with previous linear analysis at other monitoring stations (Arora et al., 2017; Kumar et al., 2015). The known limitation of Pearson correlation described in geophysical settings: the failure to recognize the nonlinear, threshold dependent, and event conditioned responses motivates the analytical extension described in Sections 4.3 and 4.4.

4.3 Event-space transformation via first-order differencing

An important methodological development of this research is the shift in the domain of measurement from amplitude to event. For each meteorological variable X and radon concentration Y, first-order finite differences were computed as:

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$$\Delta X(t) = X(t) - X(t-1) \quad \text{and} \quad \Delta Y(t) = Y(t) - Y(t-1)$$

Event Classification Equation is described as follows:

$$E(t) = \begin{cases} \textit{Hike}, \Delta X \geq +2.0 \\ \textit{Drop}, \Delta X \leq -2.0 \\ \textit{Normal}, |\Delta X| < 2.0 \end{cases}$$

These differenced series separate the fast responding event-driven responses from the slower responding background state, which is controlled by diurnal and seasonal meteorological cycles. The differencing operation is similar to instantaneous fluctuation in energy which is used in the HHT approach of Chowdhury et al. (2025) and the aperiodic variance component identified by SSA in Arora et al. (2017). The events were categorized as a Hike event (ΔX ≥ +2.0 units/hr), Drop event (ΔX ≤ −2.0 units/hr), and Normal state (|ΔX| < 2.0 units/hr). Threshold values were chosen to provide meteorologically relevant change events in the dataset, while keeping the instrumental noise out, and the results were compared to three different thresholds (+/- 1.0, 2.0, and 3.0 units/hr), and the conclusions were found to be consistent between the different thresholds. Table 3 reports the statistics of event classification.

Table 3. Event classification summary: hike/drop event counts and mean radon change response magnitude by meteorological variable.

Parameter	Hike Threshold	Drop Threshold	Event Count (Hike/Drop)	Mean |ΔRn| Response
Temperature (°C/hr)	≥ +2.0	≤ −2.0	320 / 290	Moderate
Pressure (mbar/hr)	≥ +2.0	≤ −2.0	180 / 175	High (antisymmetric)
Humidity (%/hr)	≥ +2.0	≤ −2.0	95 / 88	Low
Rainfall (mm/hr)	≥ +2.0	≤ −2.0	215 / 198	High (U-shaped)

4.4 LOWESS nonlinear smoothing

A nonlinear relationship between meteorological change events (ΔX) and the radon change responses (ΔRn) in event space was characterized using locally weighted scatterplot smoothing (LOWESS) (Cleveland, 1979). Without any a prior assumption of a global functional form, LOWESS fits smooth curves through a weighted local polynomial regression, giving weight to each data point in inverse proportion to its distance from each local neighborhood. The bandwidth parameter (frac = 0.2) was

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chosen using leave-one-out cross-validation that is, by minimizing mean-squared prediction error. It is a nonparametric method which allows to detect local nonlinear trends, such as asymmetries between hike and drop responses, or saturation in extreme ΔX values, which are not possible to identify with linear regression. Scatter visualizations were used to distinguish between event-conditioned response patterns by color coding event classes (Hike/Drop/Normal).

LOWESS estimator is computed as:

$$\hat{y}(x) = \sum_{i=1}^{n} w_{i(x)y_i}$$

LOWESS was selected because it preserves localized nonlinear structures without imposing a predefined global functional relationship, making it particularly suitable for transient geophysical response analysis. Figure 5 represents the non-linear event-space analytical framework for radon-metrological coupling (relationship). First-order differenced meteorological and radon variables were transformed into event space, followed by threshold-based event classification, LOWESS nonlinear smoothing, extraction of localized nonlinear response structures, and isolation of meteorological noise components from observed radon variability. The framework enables identification of intrinsic nonlinear radon responses that are not observable using conventional linear regression methods.

4.5 Multi-window rainfall accumulation analysis

Since rainfall is the most important nonlinear parameter, a specific analysis was performed for the 24-hour, 72-hour (3-day), and 240-hour (10-day) accumulated rainfall windows (Fig.6). The multi-window design is inspired by the work of Arora et al. (2017) who showed that short-term capping effects are governed by short-term rainfall events (hours) and longer-term radon variations are controlled by ground water head variations due to 10–15-day accumulated rainfall. To describe the temporal structure of the rainfall-radon co-variability on several time scales, LOWESS regression curves were fitted, separately for each accumulation window and for subsets of the accumulation windows corresponding to the Hike/Drop events.

Accumulated rainfall was computed using a moving window formulation:

$$R_w(t) = \sum_{i=0}^{w-1} r(t-i)$$

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where $R_w(t)$ represents accumulated rainfall over window length w, $r(t)$ denotes hourly rainfall, and w corresponds to 24-h, 72-h, and 240-h accumulation intervals. It should be noted that negative values of ΔRainfall do not represent negative rainfall amounts. Rather, they indicate a decrease in rainfall intensity or the recession phase following a rainfall event (i.e., the first-order difference of accumulated rainfall becomes negative as accumulated rainfall declines). Throughout this study, positive ΔRainfall denotes increasing rainfall intensity, whereas negative ΔRainfall represents rainfall recession during post-rainfall drainage. First-order differencing was subsequently applied to the accumulated rainfall series prior to event-space transformation. LOWESS smoothing was independently fitted for each accumulation window to evaluate scale-dependent nonlinear response structures and temporal hydrological memory effects. The figure 6 highlights the conceptual framework of multi-window rainfall accumulation analysis. The hourly rainfall observations were converted to moving accumulated rainfall series with different moving windows (24 hours, 72 hours, 240 hours). First-order differenced rainfall and radon observations were used to build (B) event-space representations of the data for each accumulation scale. Each rainfall accumulation window was independently smoothed using (C) LOWESS to define scale dependent nonlinear response structure. Conceptual interpretation of hydrological response mechanisms related to short-term forcing from the atmosphere and delayed subsurface infiltration and the long memory hydrological coupling. The longer accumulation windows are extended, the more integrated rainfall–radon interactions and delayed nonlinear responses are observed.

5. Results

5.1 Linear domain analysis

Pearson correlation analysis across the full dataset (n = 11,572) yields the following results: temperature ($r = +0.500$, $p < 0.001$), atmospheric pressure ($r = -0.384$, $p < 0.001$), soil humidity ($r = +0.158$, $p < 0.001$), and rainfall ($r \approx 0.000$, ns). The results are summarized in Table 4 with the reference values from Arora et al. (2017) for Hsinchu for the comparison.

Table 4. Pearson correlation coefficients (r) between radon and meteorological variables at Jiaosi (this study, n = 11,572) and at Hsinchu (Arora et al., 2017) for comparison.

Parameter	r (Jiaosi)	p-value	r (Hsinchu)	r^2 (%)	Interpretation
Temperature	0.500	< 0.001	−0.45 (partial)	25%	Strong positive
Atmospheric Pressure	−0.384	< 0.001	~ −0.30	14.7%	Moderate negative

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Soil Humidity	+0.158	< 0.001	---	2.5 %	Weak Positive
Rainfall	~0.000 (ns)	> 0.05	~0.00	~0%	Non-linear driver

The positive partial correlation between the temperature and radon at Jiaosi ($r = +0.500$) is different from Arora et al. (2017) where negative partial correlation at Hsinchu ($r \approx -0.45$) was reported. This change indicates that the results are of site-specific and the difference is due to the geothermal environment of Jiaosi related to the Okinawa Trough hydrothermal system (Chowdhury et al., 2025; Lee et al., 2022). In geothermically active areas, with increasing temperature, the emanation rate of radon will also increase due to the increase in the temperature of the fracture matrices, and also due to the increase in advective transport of radon through increased thermally pressurized fracture networks, resulting in a positive temperature-radon relationship. The negative correlation at Hsinchu, a non-geothermal station, is caused by the increase in soil temperature using the more traditional method, which also led to a decrease in soil moisture, and entrapment of surface-layer radon. The correlation between the atmospheric pressure is $r = -0.384$, which is in line with what can be explained by the mechanism of barometric pumping (Arora et al., 2017; Clements and Wilkening, 1974). The scatter plots for the four main meteorological viz. temperature, atmospheric pressure, humidity, and rainfall correlates are displayed Figure 7. The fitted regression lines indicate weak-to-moderate global linear trends, with positive associations observed for temperature, humidity, and rainfall, and a negative relationship for atmospheric pressure. . Even in the presence of these trends, there is a large dispersion in the sample and the scatter plot is heterogeneous, making it difficult to draw simple linear correlation relationships.

5.2 Event-space analysis: temperature and pressure

The changes in radon concentrations (ΔRn) are a non-linear function of the changes in temperature (ΔT) as shown in Figure 8. The relationship between them is not obvious in the conventional linear correlation analysis. The LOWESS trend is nearly flat over most of the temperature range, suggesting that direct temperature effects had a limited influence on the concentrations of radon. The radon response is not markedly affected by temperature changes over the normal temperature range ($|\Delta T| <$ 2°C/hr). At larger temperature changes, however, there are small differences between temperature hike and drop events. The response of the temperature–radon system is slightly asymmetrical as the positive ΔRn seems to be slightly higher when the temperature goes down as compared to when the temperature goes up. This can be attributed to soil moisture differences due to the varying heating and cooling mechanisms of the soil, with consequent differences in gas transport and in diffusivity of

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radon. The overall LOWESS curve is flat, suggesting that the temperature is not a significant control on the short-term radon variability at this site. However, to assess the meteorological influences in the context of earthquake precursor studies, nonlinear temperature effect needs to be taken into account as indicated by the observed asymmetry at larger temperature changes.

The results are presented as a plot of ΔRn (changes in radon concentration) versus ΔP (changes in atmospheric pressure) and are presented in Figure 9. Pressure variations are most numerous at the lower end of the range and the LOWESS trend is almost flat, suggesting that moderate pressure changes have very limited effect on radon concentrations. Overall, however, there is a trend that radon levels rise during a decrease in pressure and fall during an increase in pressure, as was reported in other studies (Arora et al., 2017, Clements & Wilkening 1974) and as is expected under the barometric pumping mechanism. At larger changes in pressure, there is also a nonlinear behavior, as shown by the LOWESS curve. Beyond the normal range, as the magnitude of pressure change is increased, the radon response decreases, and eventually becomes constant, or saturated. This implies that the changes in radon concentration do not occur in the same ratios if extreme variations in pressure occur.

The results have significance for studies of earthquakes precursors. The response to radon might not be directly proportional in periods of rapid pressure changes, as would occur during a storm or powerful weather system. So linear regression correction methods are not necessarily adequate to eliminate meteorological influence from radon measurement records, and this could influence the detection of true seismic effects. The combination of Figures 8 and 9 indicates that temperature and pressure have a primary role as background modulations which are slow and quasi-stationary, but not as modulators of the sharp, transient excursions that are relevant to precursor detection.

5.3 Nonlinear rainfall response: the U-shaped event pattern

The results of the event-space analysis show that the most important nonlinear controls on the variations of radon concentrations on a short time scale are the rainfall. The LOWESS response curve (Fig. 10) suggests that there is a relatively strong nonlinear relationship between the rainfall and the radon, and a weak linear correlation. Radon has been found to fluctuate with large changes in precipitation, and is lowest for small changes in precipitation. This results in a unique "U"-shaped pattern in the event space. The above positive radar response to a rise in rainfall could be linked to the sporadic rise in radon in the near surface environment that can be caused by a fast soil sealing/capping effect. Conversely, if there is limited precipitation, soil moisture decreases and gas permeability increases that facilitates radon movement towards the surface. The high rainfall can occur with either increased or decreased rainfall, for two physical reasons. The U shape behavior

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appears in all the accumulation windows (24, 72, 240 hours) indicating the strong relationship and not one dependent on the window size of the rainfall accumulation. The largest response to rainfall is observed for the 24-hour prior to the rainfall window, reflecting that the response to short-term changes in rainfall is the most sensitive to the response of emissions from radon. The longer the accumulation window the broader and smoother the response is probably due to slower hydrological processes (soil moisture, groundwater changes). This implies that the Pearson correlation coefficient between rainfall and radon concentration is not very high as they are not linear, so the correlation value is not very high. The effects of both increases and decreases in rainfall are positive, resulting in cancelling effects in linear correlation analysis. Rainfall, however, is one of the most important sources of meteorological variability and false alarms in traditional statistical analyses of earthquake precursors, but can be unaccounted for in those analyses.

5.4 Short- and long-period rainfall response characteristics

Figure 11 shows that the concentration of radon is nonlinear and varies with the amount of rainfall accumulated over a short term (6 hours) or a long term (24 hours). The response pattern for the two accumulation periods is different, suggesting that there are different hydrological processes that drive the effects of rainfall on radon at different time scales. The LOWESS curve indicates that the concentrations of radon rise quickly with rainfall for the 6-hour rainfall accumulation, and then increase more slowly at the higher rainfall. This pattern indicates that short duration of high rainfall intensity is directly impacting on the radon emissions. The quick response may be due to temporary soil saturation and sealing (capping) which limits gas diffusion to the air and thus causes temporary increases in radon concentration in the shallow subsurface. By contrast, the real-time 24-hour rainfall totals show a more gradual and continuous rise in the amount of radon. This delayed response suggests that there is a time lag in the effects of extended rainfall on water infiltration, soil moisture variation, and groundwater movement, which therefore has an impact on radon transport over a longer time. This behaviour is an expression of the hydrological memory of the subsurface, which is the legacy of rainfall events after rainfall. The comparison illustrates that the relationship between rainfall and radionuclides is very time-scale dependent. The short-duration rainfall mainly influences near surface processes and causes a quick response of radon, while the long-duration rainfall influences the subsurface infiltration and groundwater transport, generating a delayed but sustained rise in radon level. These results indicate that the variability of radon during rainfall cannot be well represented by a linear model and should be analyzed as a nonlinear and time-dependent phenomenon when looking for possible earthquake-related radon anomalies.

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5.5 Ablation and component contribution analysis

To evaluate the contribution of each processing step in the proposed nonlinear event-space framework, an ablation analysis was performed by progressively adding the main analytical components: first-order differencing, LOWESS smoothing, and event-based classification. The objective was to determine whether the observed rainfall–radon relationship could be identified using conventional linear analysis or whether the complete nonlinear framework was required. The results are summarized in Figure 12.

The results of the event-space analysis show that the most important nonlinear controls on the variations of radon concentrations on a short time scale are the rainfall. The LOWESS response curve (Fig. 10) suggests that there is a relatively strong nonlinear relationship between the rainfall and the radon, and a weak linear correlation. Radon has been found to fluctuate with large changes in precipitation, and is lowest for small changes in precipitation. This results in a unique "U"-shaped pattern in the event space. The above positive radar response to a rise in rainfall could be linked to the sporadic rise in radon in the near surface environment that can be caused by a fast soil sealing/capping effect. Conversely, if there is limited precipitation, soil moisture decreases and gas permeability increases that facilitates radon movement towards the surface. The high rainfall can occur with either increased or decreased rainfall, for two physical reasons. The U shape behavior appears in all the accumulation windows (24, 72, 240 hours) indicating the strong relationship and not one dependent on the window size of the rainfall accumulation. The largest response to rainfall is observed for the 24-hour prior to the rainfall window, reflecting that the response to short-term changes in rainfall is the most sensitive to the response of emissions from radon. The longer the accumulation window the broader and smoother the response is probably due to slower hydrological processes (soil moisture, groundwater changes). This implies that the Pearson correlation coefficient between rainfall and radon concentration is not very high as they are not linear, so the correlation value is not very high. The effects of both increases and decreases in rainfall are positive, resulting in cancelling effects in linear correlation analysis. Rainfall, however, is one of the most important sources of meteorological variability and false alarms in traditional statistical analyses of earthquake precursors, but can be unaccounted for in those analyses. Overall, the ablation analysis demonstrates that the nonlinear rainfall–radon relationship does not emerge from any single processing step. Instead, it results from the combined effects of first-order differencing, nonlinear LOWESS smoothing, and event-based classification. These findings validate the proposed event-space framework as an effective approach for separating meteorological influences from soil-gas radon time series and improving the identification of potential earthquake-related radon anomalies.

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6. Discussion

6.1 Physical interpretation of linear correlations

At Jiaosi, the positive linear temperature-radon correlation (r = +0.500) indicates that the changes are caused by more than one physical pathway. Increased temperature decreases the solubility of radon in pore water (due to decreased Henry's law partitioning), increases the diffusion of radon in the gas phase and, at the geothermally active site of Jiaosi, may increase advective transport through thermally pressurized fracture networks in the Okinawa Trough hydrothermal system (Chowdhury et al., 2025; Lee et al., 2022). The sign difference relative to Hsinchu is therefore best understood not as an anomaly (Arora et al., 2017) but rather a site-specific geothermal context that needs to be included in any meteorological correction scheme that is designed for a network.

The negative pressure correlation (r = −0.384) is understood well from a physical mechanism perspective, which is barometric pumping, and is consistent at all stations in Taiwan that monitor the condition, thereby providing confidence in the robustness of this physical mechanism. The weak humidity correlation (r = +0.158) agrees with the small contribution of soil moisture in affecting gas-phase diffusivity at Jiaosi, due to the confined range of stable soil moisture (15.5–21.3%) for which the humidity correlation can be used.

6.2 Diminished meteorological influence in the event domain

The event space analysis shows that the diurnal and seasonal cycles are primarily shaped by the three parameters temperature, humidity and pressure, and that the influence of these parameters on the swift and transient radon excursions is much lower. This is in complete agreement with the EMD decomposition of Chowdhury et al. (2025) which showed that the diurnal temperature and pressure cycles are captured in IMFs 3 and 4 (12-hour and 24-hour) and these cycles have significant residual variability after their removal. The conclusion reached by Arora et al. (2017) on the SSA decomposition was the same: less than 2% of the total variance in radon is due to periodic signals from temperature and pressure, and the remaining variance (about 68%) is due to aperiodic transient signals. The event-space differencing approach used here also arrives at the same result along an independent analysis pathway: working in the event domain instead of the amplitude domain allows the method to directly separate the variance in the events that are not controlled by the quasi-stationary meteorological forcing. The result of this cross-validation with three independent analytical techniques—linear correlation, EMD-HHT, SSA and recently LOWESS event-space analysis— strengthens the conclusion made by any one method alone by a great deal.

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6.3 Physical mechanism of the U-shaped rainfall response

There is a nonlinear U-shaped response of radon to the rainfall changing events which is interpreted as a multi-stage physical framework as described by Arora et al. (2017) at Hsinchu:

1. When the rain starts, the capping effect that will start to occur when more water is in the surface soil will seal off the pores in the soil and will cause radon to accumulate under the moist cap, giving rise to a positive ΔRn pulse on the start of the rainfall. Chowdhury et al. (2025) noted the response within 6-10 hours after rainfall events >20 mm in the geothermal setting at Jiaosi, as compared to 12-15 hours in the geothermal setting at Hsinchu (Arora et al., 2017) and the response was due to the higher porosity and permeability of the volcanic soils. The negative branch of the U-shaped event-space response corresponds to rainfall recession rather than negative rainfall itself. Progressive soil drainage after the precipitation event decreases the water saturation and progressively restores the gas-filled pore connectivity. This allows the soil gas permeability to be restored and renewed radon migration towards the surface, which causes positive ΔRn responses during a rainfall recession. This is why there is a symmetric U-shaped response in the event space analysis, as the onset of rainfall as well as the drainage phase cause increased radon emissions, albeit by different physical mechanisms.
2. During drainage, a second positive ΔRn pulse can be generated when soil pores open up again, a gas-phase continuity is restored, and when the rain is falling, the soil gas in the deeper soil horizons corresponding to the downfall limb of the U-shaped curve is brought up to the surface by advective transport.
3. The wider, lower amplitude U-shape seen in the long-period accumulation analysis is due to the modulation of radon propagation by the overlying soil column from the change in groundwater head induced by extended rainfall periods over longer accumulation windows (240-hour).

This multi-stage physical model explains why the U-shape is symmetric, both the onset and the cessation can create positive ΔRn, and why it is totally invisible to linear correlation, because the mean effect of rainfall over the whole signal can almost be null. The capping-effect radon pulse is similar to that seen as a precursory anomaly associated with a seismic event (Arora et al., 2017) with direct operational implications: any precursor detection algorithm that does not explicitly model and remove this nonlinear rainfall response is subject to systematic false-positive responses during and directly following rainfall events.

6.4 Methodological comparison

Table 5 provides a structured comparison of the analytical properties of the present LOWESS event-

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space approach against linear correlation, EMD-HHT (Chowdhury et al., 2025), and SSA (Arora et al., 2017; Kumar et al., 2015). Critically, the rainfall radon response documented by Arora et al. (2017) and Chowdhury et al. (2025) is a paradigmatic example of a completely nonlinear and event driven phenomenon invisible to the linear analysis and is one of the biggest sources of spurious precursor signals. The studies were of great importance in terms of the scientific understanding of meteorological influences on radon measurements, and led to the development of a nonlinear decomposition procedure which was found to be an effective tool for alternative linear correction methods.

Table 5. Comparative properties of analytical methods for radon-meteorological characterization.

Criterion	Linear Correlation	EMD-HHT (Chowdhury et al., 2025)	SSA (Arora et al., 2017; Kumar et al., 2015)	This study (LOWESS Event-Space)
Captures nonlinearity	No	Partial	Partial	Yes —full event-space characterization
Stationarity assumption	Required	Not required	Not required	Not required
Event-triggered detection	No	Partial (IE plots)	No	Yes — differencing directly isolates events
Rainfall U-Shape detection	No	No	No	Yes — explicit in event domain
Computational complexity	Low	High	Moderate	Low–Moderate
Interpretability	High	Moderate	Moderate	High

The event space framework, as described by LOWESS, has unique complementary strengths: It explicitly describes transient, event-conditioned nonlinearities (including the U-shaped rainfall response) in a scatter-plot space that is accessible to computation, without relying on spectral decomposition. The main drawback of it compared to EMD-HHT is that it does not afford frequency resolved decomposition of the whole signal and is less desirable for identifying specific IMFs that

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correspond to diurnal or tidal cycles. The approaches are therefore non-competing, but rather complementary.

6.5 Implications for earthquake precursor detection

The present results show that most of the temperature and pressure change-induced variations are correlated with the slowly varying background environmental variability or with the predictable atmospheric forcing, while rainfall gives rise to nonlinear transient responses that are able to mimic earthquake-induced radon anomalies. This distinction is relevant to the issue of operational precursor screening, as transients from rainfall are one of the major sources of false-positive detections in a continuous radon monitor. The proposed framework explicitly describes these nonlinear rainfall signatures in event space, adding another layer of meteorological correction to the traditional linear correction methods, and making it easier to identify anomalous radon signals. The framework is not meant to replace existing decomposition-based methods (like the EMD-HHT method developed by Chowdhury et al., 2025, which focus on capturing the frequency domain information of the decomposition, but instead to add to such methods by capturing the transient information of the process-response relationship that may not be captured by the frequency domain information alone. Table 6 summarizes the complementary power of the traditional linear correction method, EMD-HHT and the proposed event space-approach. Event-space analysis combined with EMD-HHT may thus offer a multi-layer analysis strategy that can allow for the progressive separation of periodic background variability, meteorological transient events appearing as non-linear processes, and possible tectonic variability.

In the current tecto-physical approach suggested by Walia et al. 2009; 2023, whereby the earthquake's magnitude, epicentral distance, focal depth and precursor time window are used to determine its potential as a precursor candidate, the proposed nonlinear event space might constitute an extra preprocessing before anomaly screening. The approach can help to enhance the robustness of precursor identification and minimize false precursor detections due to meteorologically induced transient responses, especially in response to rainfall. But it is necessary to validate improvements in precursor detection performance through independent seismic datasets in the future to evaluate them quantitatively. The proposed event-space framework is quite general to describe threshold dependent nonlinear process–response relationships between radon and environmental forcing variables when threshold dependent transient responses arise, though it was most strongly nonlinear in the present data set. These environmental observables vary in their physical source, and they have the common problem of having a weak geophysical signal that is masked by the transient meteorological or

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environmental forcing. The same pre-processing methods may be applied to other multi-parameter Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) approaches, which integrate the radon data with ionospheric TEC, VLF/ULF electromagnetic signals, and outgoing longwave radiation (OLR) (Pulinets & Ouzounov, 2011; Nikolopoulos et al., 2024; Fu et al., 2020) and which may provide further potential for systematic study. The comparison of linear domain and nonlinear/event-space observation is described as follows in Table 6.

Table 6. Summary comparison between linear and nonlinear response domains

Parameter	Linear-Domain Observation	Event-Space / Nonlinear Observation
Temperature	Moderate positive linear association	Reduced influence during transient response events
Humidity	Weak linear correlation	Minimal event-conditioned contribution
Pressure	Moderate negative correlation	Localized influence during extreme drop events
Rainfall	Weak global linear association	Dominant nonlinear U-shaped response structure

7. Conclusions

The nonlinear event-space analytical framework, introduced and applied in this study, could characterize the relationship between soil-gas radon and meteorological parameters at the Jiaosi monitoring station in the seismically active northeastern Taiwan based on 11,572 hourly observations from January 2021 to April 2022. Five main conclusions are established:

1. **Linear domain correlations establish a robust baseline:** The main linear correlates of the radon variability are temperature ($r = +0.500$), atmospheric pressure ($r = -0.384$) and soil humidity ($r = +0.158$). The positive correlation between temperature and radon is different from the negative partial correlation at Hsinchu (Arora et al., 2017) due to different geothermal environment of Okinawa Trough geothermal system, which shows that site-specific calibration is needed in multi-station monitoring system.
2. **The quasi-periodic background variability is dominated mainly by meteorological parameters: When the radon background is shifted into the nonlinear event domain by first-order differencing, it is found that the main meteorological parameters that control slowly varying radon signals are temperature, pressure and humidity, with considerably less influence on the transient change events. This has also been independently validated**

using the EMD-HHT decomposition developed by Chowdhury et al. (2025) and the SSA analysis developed by Arora et al. (2017).

3. **Rainfall is the most prominent nonlinear driver of transient radon variations** although there is low linear correlation, rainfall shows a U-shaped LOWESS response in event space, and this response changes little with accumulation windows (24h, 72h, 240h). This pattern is due to the mechanistically known as the capping effect and pore drainage dynamics (Arora et al., 2017) and is completely hidden from the perspective of Pearson correlation analysis, although it is a major cause of false positive in linear regression based precursor detection.
4. **LOWESS event-space analysis as a complement to EMD-HHT:** A method that explicitly represents local nonlinearities, threshold-dependent responses, and event asymmetries in an easily interpretable and applicable scatter-plot framework that is readily accessible from a computational perspective. When combined with the EMD-HHT pipeline of Chowdhury et al. (2025) forms a multi-tier correction architecture that has a better false-positive rejection capability.
5. **General methodological implications:** The change from amplitude-domain to event-domain analysis together with nonparametric smoothing is a general rule that can be used for geochemical time-series analysis in earthquake precursor research. The framework can be extended to multi-station network analysis and multi-parameter precursor system that includes ionospheric, electromagnetic, and thermal anomaly monitoring (Pulinets & Ouzounov, 2011; Nikolopoulos et al., 2024).

The framework needs to be validated at more stations in the NCREE-IES monitoring network, and future works will include the inclusion of event-space features within the machine-learning models for the probabilistic detection of anomalies as well as the inclusion of multi-parameter Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) monitoring systems that integrate meteorologically corrected radon indices. Further studies with partial correlation, Granger causality, Mutual Information, and Wavelet Coherence can further elucidate the relationship between meteorology and radon and enhancement of operational precursor detection performance.

Data availability

The soil-gas radon and meteorological time series analysed during this study, together with the analysis code implementing the event-space and LOWESS framework, are available from the corresponding author upon reasonable request.

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Author contributions

RB and PK developed the nonlinear event-space methodology, implemented the data-processing and LOWESS analysis code, and prepared the original draft. VW conceived and supervised the study, secured the monitoring data, and revised the manuscript. CCF, HFL and SJL contributed to data curation, station operation and maintenance, and reviewed and edited the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Figure Captions:

Figure 1. Tectonic setting of northeastern Taiwan and schematic representation of the Jiaosi soil-gas radon monitoring system

Figure 2. Overview of the Jiaosi (JS) soil-gas monitoring dataset: (a) observed radon time series with LOWESS trend; (b) atmospheric temperature; (c) atmospheric pressure; (d) rainfall and regional earthquakes ($M \geq 5.0$), January 2021–April 2022

Figure 3. Detailed pre-processing for non-linear event-space analysis

Figure 4. Baseline linear-domain analysis between soil-gas radon concentration and meteorological variables. The left panel presents the Pearson correlation matrix for normalized environmental parameters, while the right panel shows the rainfall radon linear regression relationship

Figure 5. Schematic representation of the nonlinear event-space analytical framework used for radon–meteorological coupling analysis

Figure 6. Multi-window RA concept for investigating the relationship between rainfall and radon at a variety of hydrological timescales

Figure 7. Linear correlation analysis between soil-gas radon concentration and major meteorological parameters

Figure 8. Non Linear relationship between temperature and radon concentration changes.

Figure 9. Non-Linear relationship between atmospheric pressure and radon concentration changes.

Figure 10. LOWESS-smoothed nonlinear event-space response of radon concentration change (ΔRn) to rainfall change events (ΔRainfall)

Figure 11. The comparison of nonlinear responses of radon under short timescale rainfall during heavy rain

Figure 12. Ablation analysis of the proposed nonlinear event-space framework for rainfall–radon interaction analysis.

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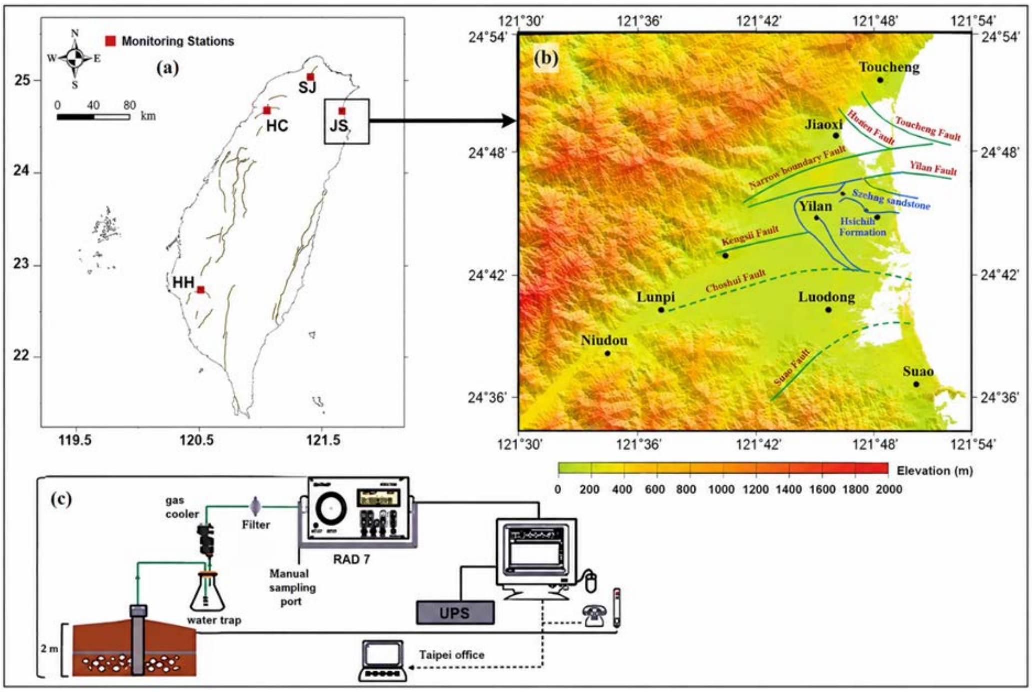

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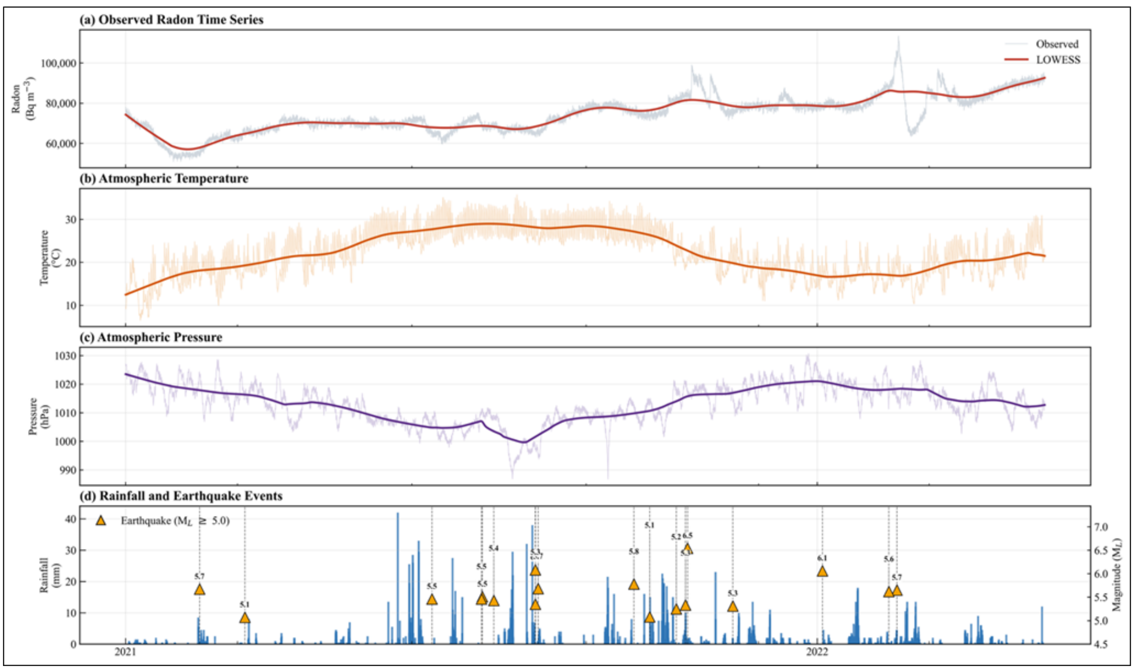

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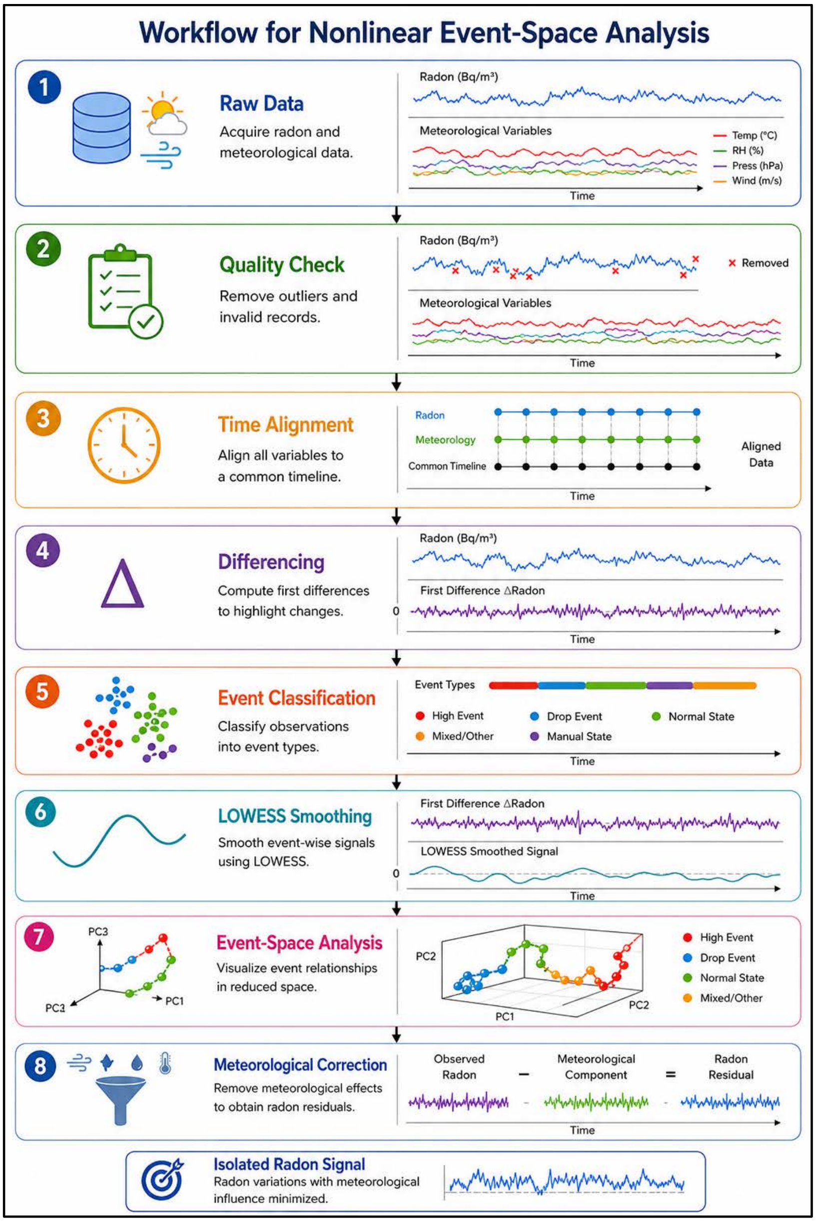

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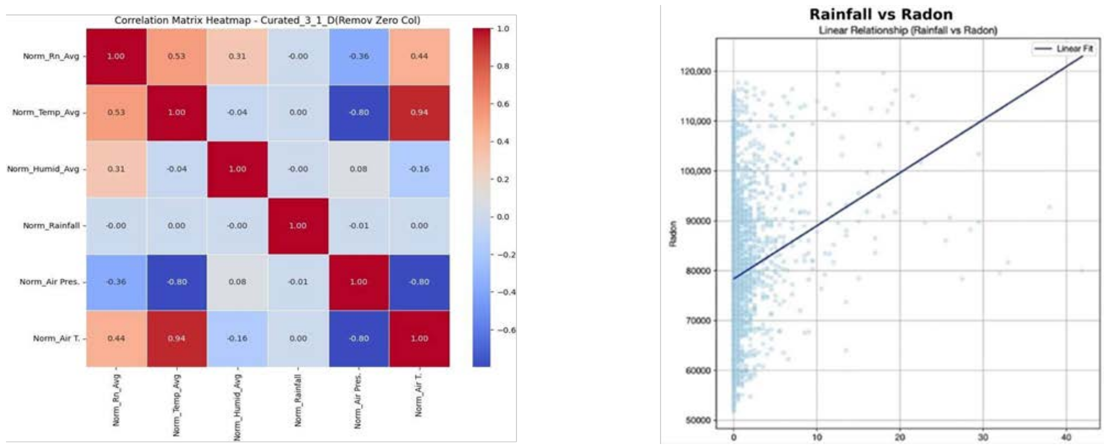

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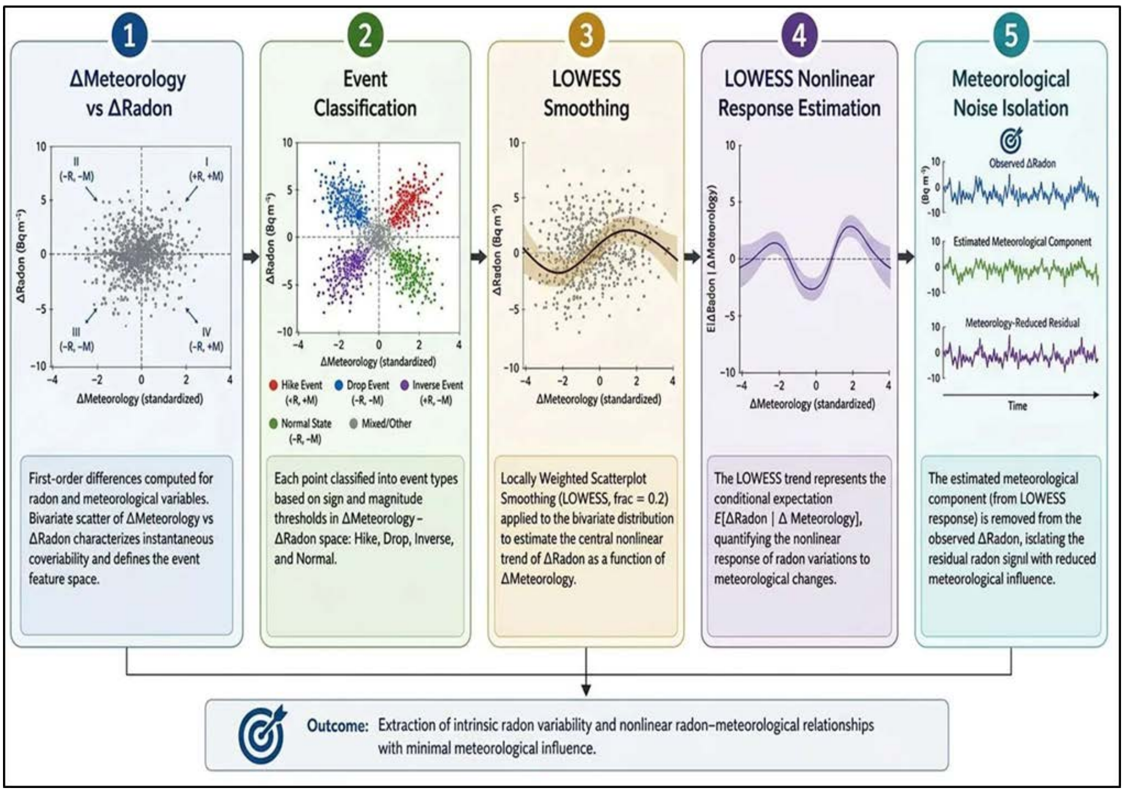

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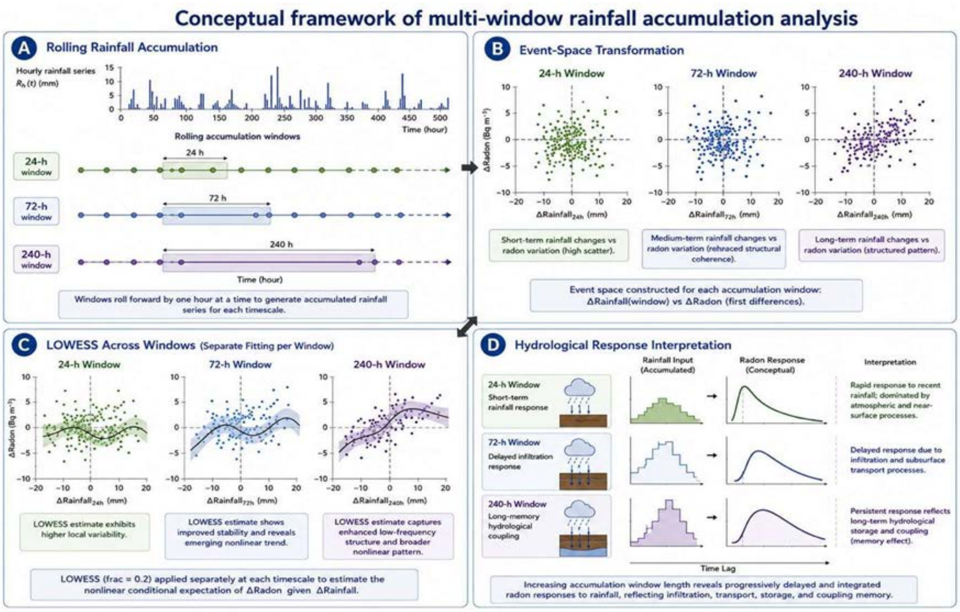

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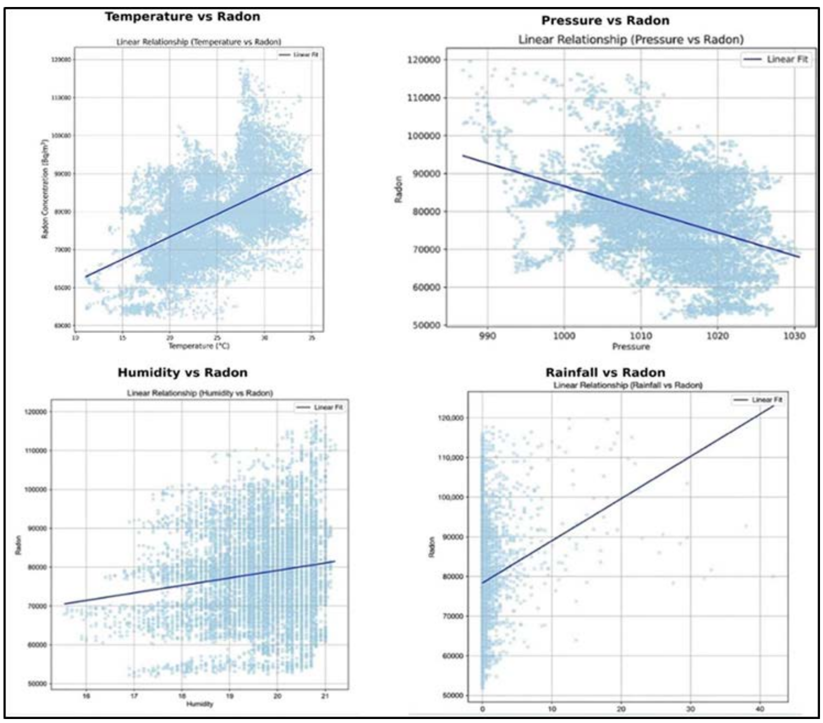

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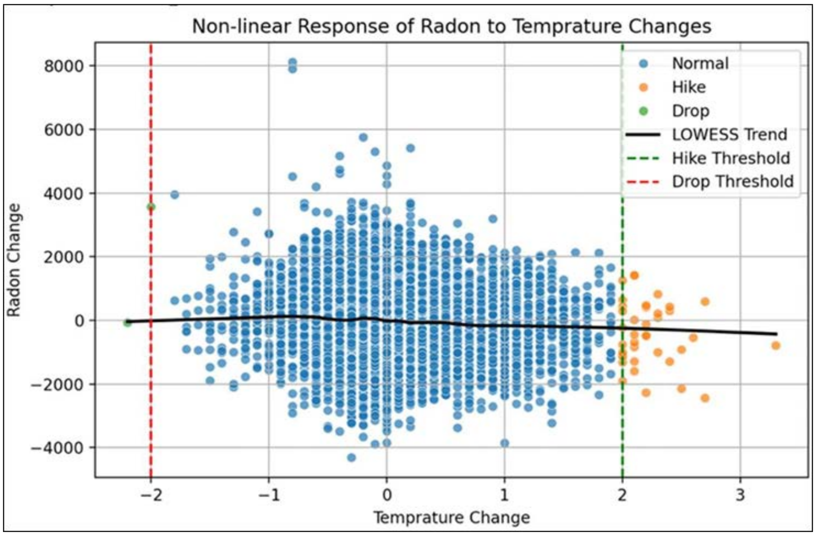

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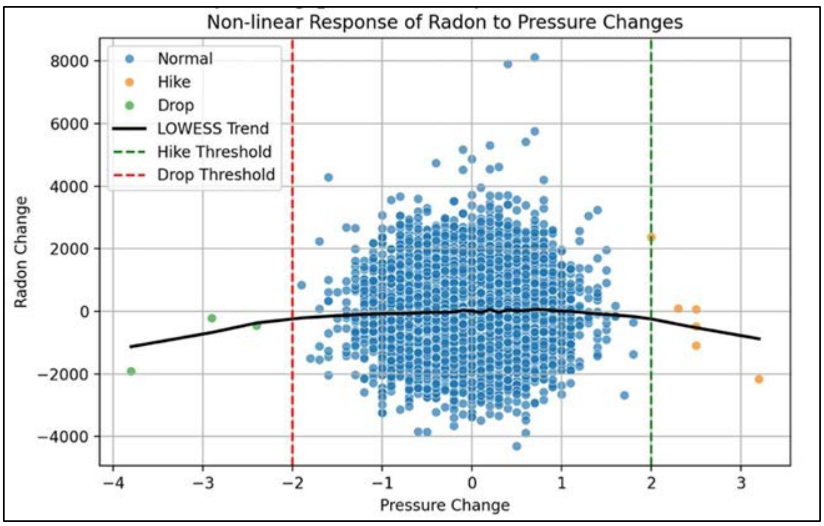

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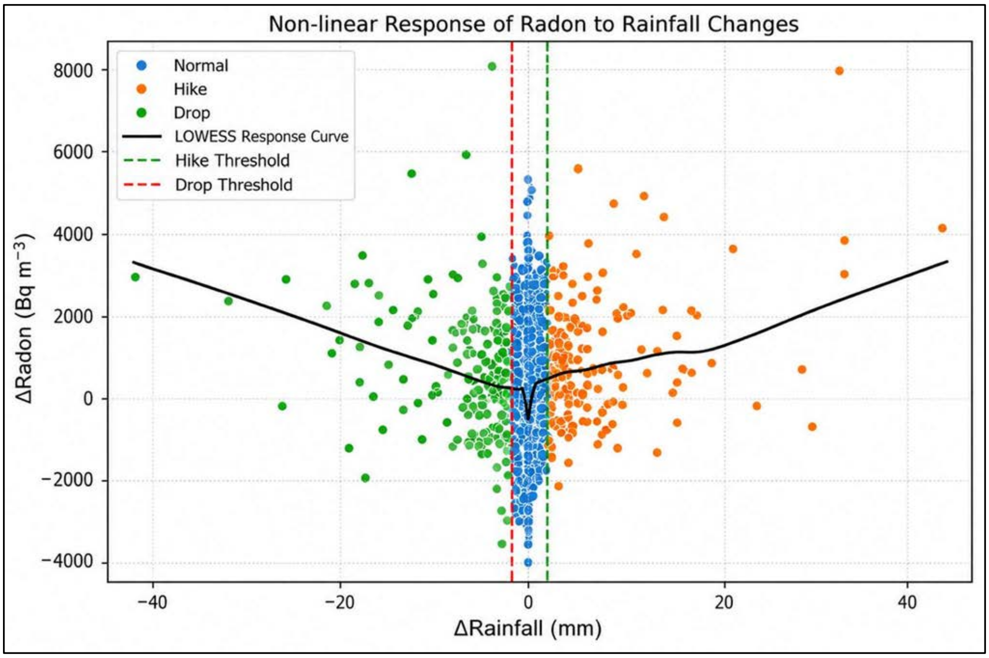

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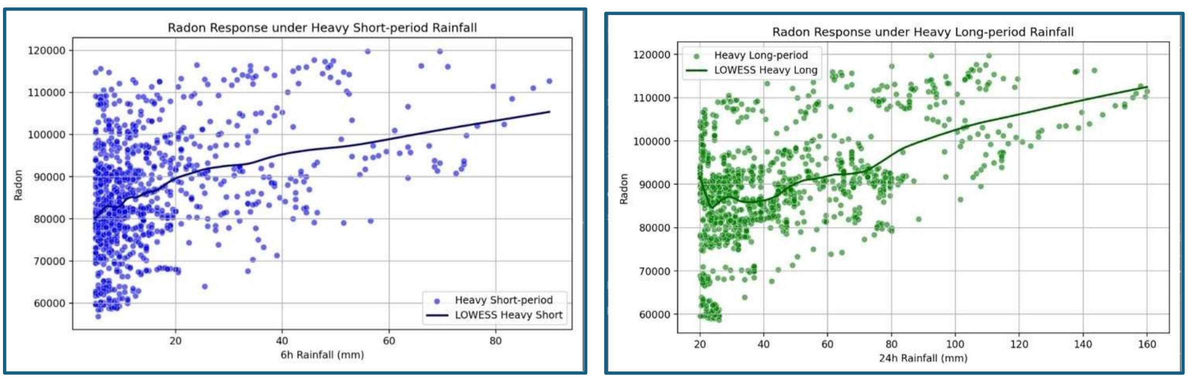

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Figure: 11

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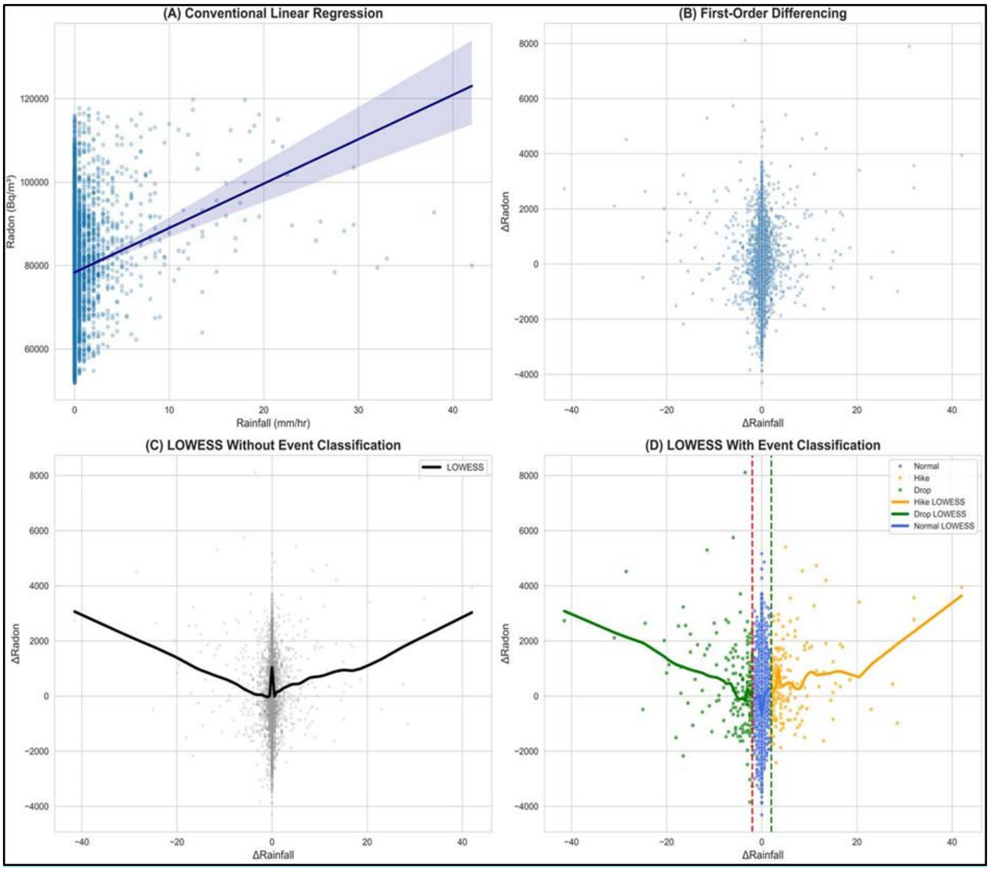

Figure: 12