Response to Reviewer 1:

I am most grateful for your comments on the manuscript. Thank you for your suggestions. All your recommendations are highly valuable. They provide significant guidance for our paper and research work. We have revised the manuscript in accordance with your suggestions (marked in red in the revised version). Our responses to each point of revision are as follows:

Specific Comments：

Comment 1:

A general comment that I have is that the text and the processing focus on the pre-seismic period and ignores completely the post seismic period. Of course, it is well explained by the authors, that the manuscript examines the possible anomalies on the preparatory stage of a strong earthquake, but since the earthquake occurred in 2013, and a long time passed since this event, it would be interesting to see if the area, and the geomagnetic and strain data from the same stations, shows any similar behavior as during the pre-seismic period. In other words, as a validation of this processing it could be interesting to examine the years after the earthquake if there was another period that these magnetic and strain stations show anomalous days without the occurrence of an earthquake, BUT still this may be the subject for another publication.

Response 1:

Thank you for your suggestions.

We agree that further examination of geomagnetic and borehole strain data from the same region and the same observation stations over the years following the earthquake—particularly an analysis of whether there were anomalous days not accompanied by strong earthquakes—is of significant value for assessing the stability, false-alarm rates and long-term applicability of the proposed method. The research objectives of this paper are primarily focused on the extraction of anomalies and the analysis of multi-parameter coupling characteristics during the pre-seismic phase of the 2013 Lushan Ms7.0 earthquake; consequently, the current work concentrates on the identification, cumulative evolution and temporal correlation of pre-seismic geomagnetic disturbances and borehole strain anomalies, whilst systematic verification of anomaly recurrence and false alarm rates over a multi-year post-seismic timescale has not yet been undertaken. Future work will further extend the time window to investigate whether the same geomagnetic and borehole strain stations exhibit anomaly patterns similar to those observed in the pre-earthquake phase but not accompanied by seismic events in the years following the earthquake, thereby more comprehensively verifying the effectiveness and reliability of this method in long-term monitoring scenarios.

Comment 2:

The authors used geomagnetic data only few months before the earthquake (since January 2013). In lines 299-301 :'‘…were selected to characterise the short- to medium-term background variations…'‘ the authors clearly describe that they focus on ‘‘short- to medium-term'‘ on geomagnetic data, but the strain data cover longer period … >1 year "….to characterise the strain evolution over a longer time scale'‘. I think that they just have to add a more well justified explanation for this discrepancy concerning the time span of the two data sets.

Response 2:

Thank you for your suggestions.

We agree that the original text did not adequately explain the discrepancy in the time spans of the geomagnetic and borehole strain data; we have therefore added further clarification in the revised manuscript. From a physical mechanism perspective, it is understandable that there is a difference in timescale between borehole strain anomalies and geomagnetic anomalies. Localised stress accumulation and deformation of the fault medium may first be recorded by borehole strain observations; subsequently, microfracture activity and changes in pore pressure drive fluid migration within the porous fault medium, generating flow currents through relative motion at the solid–liquid interface, thereby inducing electromagnetic anomalies (Fenoglio et al., 1995; Ren et al., 2016). Furthermore, stress changes may also influence the local geomagnetic field via stress–magnetic coupling (Gao et al., 2025). Consequently, this paper does not treat geomagnetic data and borehole strain data as directly equivalent sequences with the same background timescale; rather, it utilises longer time windows to characterise the slow accumulation of the strain field, and short- to medium-term windows to characterise the subsequent geomagnetic response processes that may occur.

This paper applies different time windows to the two types of data, primarily based on their differing physical response time scales and research objectives. Borehole strain primarily reflects local tectonic stress accumulation, deformation of fault media, and tectonic loading processes on a longer timescale; therefore, this paper selects borehole strain data from May 2012 to April 2013 to characterise the strain evolution and non-linear accumulation processes on a longer timescale prior to the earthquake. Consequently, geomagnetic data from January to April 2013 were selected for this paper, primarily to analyse the evolution of geomagnetic disturbances in the months preceding the earthquake, rather than to establish a multi-year geomagnetic background model. We have added this clarification in the revised manuscript to prevent readers from interpreting the difference in the time windows of the two types of data as an inconsistent definition of the background. On page 13, line 301 of the original manuscript (now lines 303–309 on page 13 of the revised manuscript), the text is amended to read:

“This time-window setting is primarily based on the differences in the response time scales of two types of observations: borehole strain more directly reflects the long-term loading of tectonic stresses and the deformation processes of fault media, whilst geomagnetic anomalies are typically associated with electromagnetic responses induced by micro-fracture propagation, pore pressure changes, fluid migration and stress–magnetic coupling during the short- to medium-term stages prior to an earthquake; therefore, this paper employs a longer time window to characterise the strain accumulation process and a window spanning several months prior to the earthquake to analyse the evolution of geomagnetic disturbances.(Fenoglio et al., 1995; Ren et al., 2016; Gao et al., 2025)”

Comment 3:

Lines 139-141 “The YRY-4 four-component borehole strainmeter, developed in China, is characterised by high sensitivity, wide-band response, and long-term operational stability.” A reference or a URL about the instrument may be useful to the reader.

Response 3:

Thank you for your suggestions.

Qiu et al.(2013) indicates that the YRY-4 four-component borehole strainmeter is installed at a depth of approximately 40–60 m, with a data acquisition sampling rate of once per minute. The unique design of the YRY-4 four-component borehole strainmeter allows for a quantitative assessment of data reliability through consistency testing, without the need for geotidal or any other specialised signals. Furthermore, the study proposed a relative correction method for specification sensitivity and demonstrated its effectiveness in enhancing data reliability. Consequently, this confirms that the YRY-4 four-component borehole strainmeter is capable of continuously monitoring changes in crustal stress and strain, thereby providing reliable data support for earthquake prediction and the study of tectonic movements. We amend lines 139–141 on page 5 of the original manuscript, and lines 139–141 on page 5 of the current manuscript, as follows:

“ The YRY-4 four-component borehole strainmeter, developed in China, is characterised by high sensitivity, wide-band response, and long-term operational stability(Qiu et al., 2013). ”

Comment 4:

Lines 169-170 “According to the empirical formula for the pre-earthquake influence radius proposed by Dobrovolsky, ….” Something is missing in these lines…it is a syntax issue please rephrase!

Response 4:

Thank you for your suggestions.

We have reviewed the grammar of the original text and found that the sentence in question does indeed contain an incomplete formula and lacks grammatical clarity. To avoid ambiguity, we have amended lines 169–170 on page 6 of the original text, and lines 169–170 on page 6 of the current draft, as follows:

“ The pre-earthquake influence radius was estimated using the empirical formula proposed by Dobrovolsky et al., $D = 10^{0.43M}$ km, where M denotes the earthquake magnitude. ”

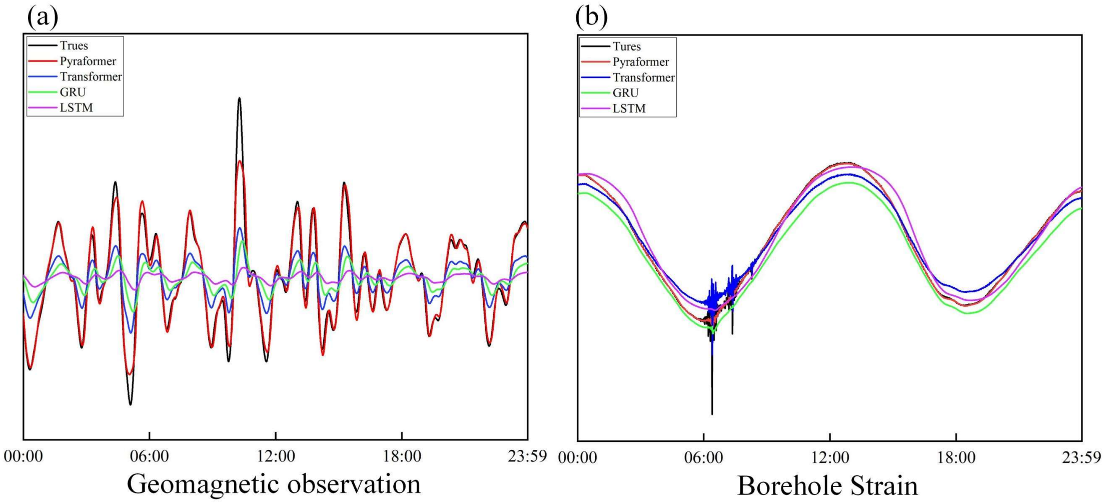
Comment 5:

Line 270- Figure 6. On the legend the black line is defined as “Trues” on (a) and “Ture” on (b). I am not sure what these means. True/observed data? Please clarify. Similarly in other figures (Figure 9, 10). Also concerning Figure 6 a scale of X axis (horizontal) would be helpful.

Response 5:

Thank you for your suggestions.

We have reviewed Figure 6. In the original figure, the terms “Trues” and “Ture” were not entirely accurate and there were inconsistencies in spelling. To avoid ambiguity, we have changed “Ture” to “Tures” to bring it into line with the other figures in the paper, and have added time scale labels for the representative anomalous days, enabling readers to better understand the temporal correspondence between the model’s predictions and the observed data on those example days. The figure has been amended as follows:



Comment 6:

Line 340 – Figure 9. On the inset figure a horizontal scale may be useful. Also, in the figure caption the authors have to describe better what the figure demonstrates (for example the ‘‘grey” area is the inset figure)… as well as, see my previous comment about the ‘‘Tures”. Also, this figure maybe has to be enlarged … it is a bit difficult to see it clearly.

Response 6:

Thank you for your suggestions.

We have reviewed Figure 9; the terms “Trues” and “Ture” in the original figure were not entirely accurate and there were inconsistencies in spelling. To avoid ambiguity, we have changed “Ture” to “Tures” to ensure consistency with the other figures in the paper, and have added more detailed information to the figure caption to enable readers to better understand the comparison between the model’s predictions and the observed data at outliers. The text on line 341 of page 16 in the original manuscript, and lines 348–349 on page 17 in the revised manuscript, has been amended as follows:

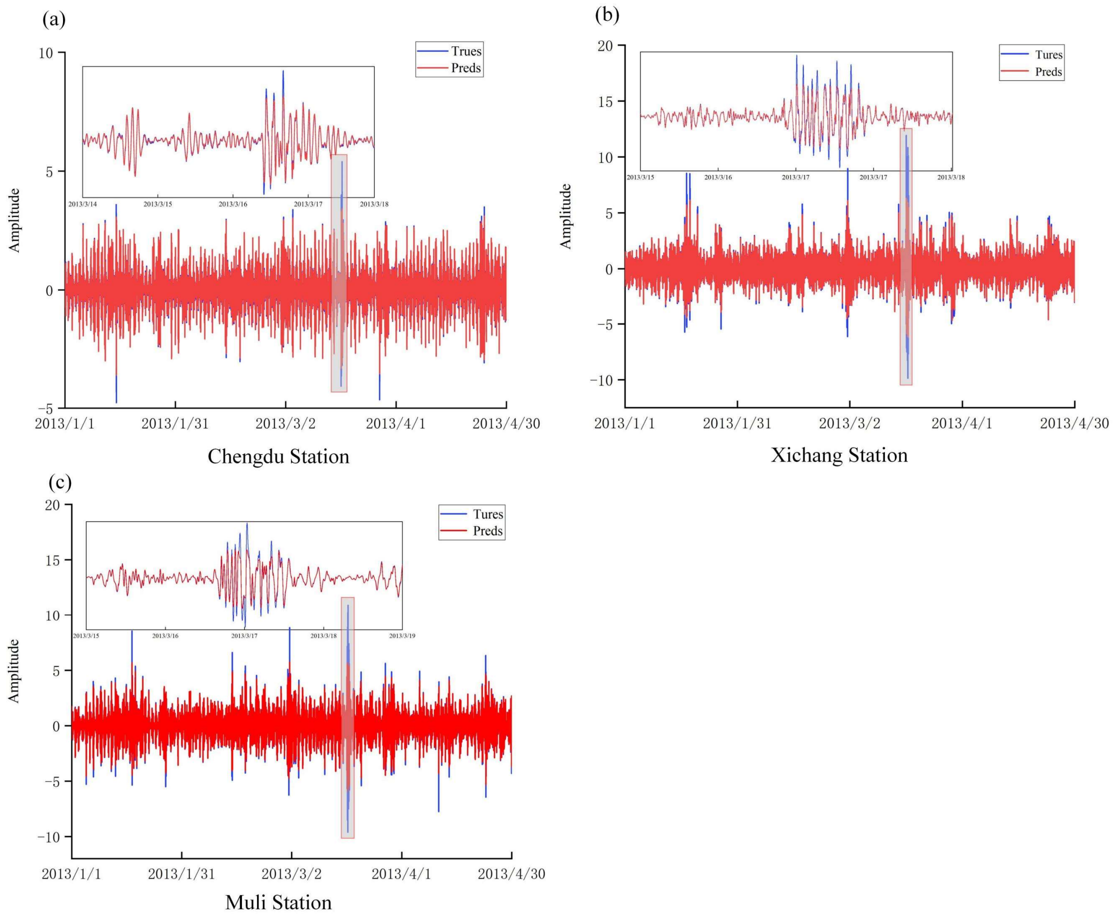


Figure 9: Detailed information on the results of geomagnetic data modelling for Chengdu, Xichang and Muli. The grey areas indicate geomagnetic anomalies.

Comment 7:

Line 354 – Figure 10. I have the same comments as for the figure 9. But in this figure, I think that it is even more important to have the time scale in the inset figure since it appears that the width of anomaly is very narrow especially for Xiaomiao station.

Response 7:

Thank you for your suggestions.

We have reviewed Figure 10. In the original figure, the terms "Trues" and "Ture" were not entirely accurate and there were inconsistencies in spelling. To avoid ambiguity, we have changed "Ture" to "Tures" to bring it into line with the other figures in the paper, and have added more detailed information to the figure caption. The text on line 354 of page 17 in the original manuscript, now lines 363–364 on page 17 of the revised manuscript, has been amended as follows:

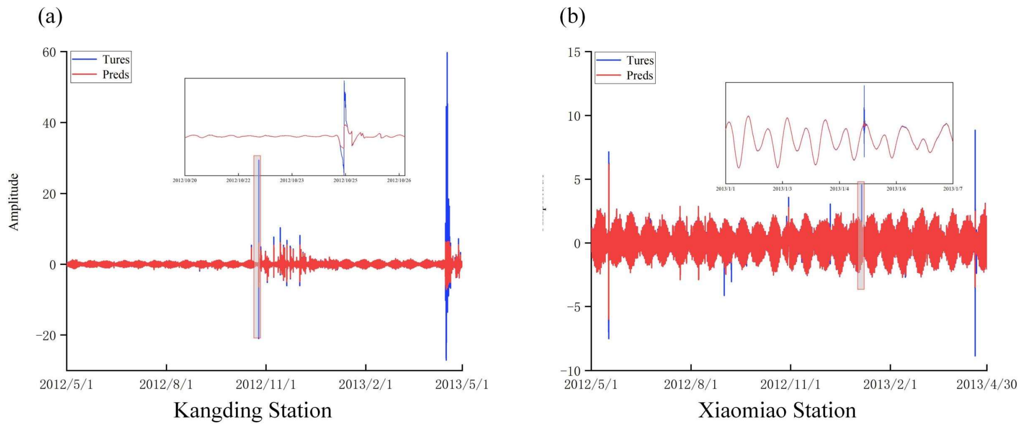


Figure 10: Detailed results of the model predictions for the strain data from the Kangding and Xiaomiao boreholes. The grey areas indicate geomagnetic anomalies.

Comment 8:

Line 375. Just for completeness define what et

Response 8:

Thank you for your suggestions.

We have identified that the formula in this sentence is indeed incomplete. We have revised and redefined the content of the formula, amending lines 376–379 on page 18 of the original manuscript (now lines 386–389 on page 18 of the revised manuscript) as follows:

“where, e_t represents the absolute deviation between the observed value and the model prediction at time step t, y_t denotes the observed value from geomagnetic or borehole strain observations, $\hat{y}_t$ represents the corresponding model prediction. This residual sequence reflects the component of the observed signal that is not captured by the model’s fitted background component and serves as the key basis for subsequent anomaly identification.”

Comment 9:

Line 401. The figure caption does not describes what information is in the tables … expand!

Response 9:

Thank you for your suggestions.

We have identified that the figure caption does indeed contain incomplete information. We have revised the caption to include more detailed descriptions of the data in the table shown in the figure. The changes, which were originally on page 19, line 401 of the draft manuscript and are now on pages 20, lines 417–423 of the revised manuscript, are as follows:

“Figure 11: Cumulative results for the number of days with geomagnetic anomalies in Chengdu, Xichang and Muli. The Boltzmann–Sigmoid fitting function is used, where parameter A1 represents the initial asymptotic level of the cumulative anomaly curve in the early stage, A2 represents the final asymptotic level when the accumulation process stabilises in the later stages, X0 denotes the inflection point of the curve—that is, the critical time at which the rate of anomaly accumulation reaches its maximum or transitions from slow to rapid growth—and dx represents the parameters controlling the transition width and growth rate of the curve. The reduced Chi-Sqr value, Coefficient Of Determination (COD), and Adjusted R-squared are used to evaluate the goodness of fit."

Comment 10:

Lines 408-409 "The first stage began in early January, approximately 100 days before the earthquake, during which anomalous signals appeared sporadically and then temporarily stabilised by the end of the month'' So this first period is considered as the ''background'' ? or it is an early preparatory stage? Maybe the authors could (somehow) be more specific of how they treat this period, especially since their ''background'' data are not covering a longer period.

Response 10:

Thank you for your suggestions. We have found that the article does indeed contain some gaps in its presentation of the content.

Ma et al.(2014) point out that the genesis and occurrence of crustal earthquakes are typically accompanied by sudden displacement processes along faults, involving the formation, expansion and interaction of multiple strain release zones. This process can be summarised in three stages: first, small-scale strain release zones form locally along the fault; subsequently, as regional stress continues to accumulate, these release zones gradually expand spatially; when strain energy reaches a critical state, the various strain release zones interact and ultimately trigger rupture.

This study does not regard the period from early January to late January as a completely stable 'background phase', but rather interprets it as the early emergence stage of pre-earthquake anomalous evolution, or the initial stage of the transition from background fluctuations to the process of anomalous accumulation. The rationale for this is that, whilst some residuals during this phase had already exceeded the statistical threshold and been identified as anomalous days, the frequency of anomalies was low and their persistence weak; the slope of the cumulative anomaly curve was gentle, and the characteristics of sustained intensification from February onwards and rapid accumulation immediately prior to the earthquake had not yet manifested. Therefore, this phase is more appropriately described as an 'early sporadic anomaly phase' rather than a purely background phase.

To avoid drawing excessive conclusions, we have revised the relevant wording in the revised manuscript to emphasise that this stage is a relatively early anomalous phase identified on the basis of residual thresholds and cumulative anomaly curves within the study period covered by this paper. This interpretation is also consistent with Ma et al.'s phased understanding of the seismic incubation process, in which strain release zones form locally, expand gradually, and ultimately undergo coupled rupture; that is, the early stage may manifest as low-intensity, intermittent local anomalies rather than a continuously intensifying strong anomalous response. Amend lines 399 on page 18 to line 418 on page 20 of the original manuscript, and lines 411 on page 19 to line 440 on page 21 of the current draft, to read:

"Ma et al.(2014) point out that the genesis and occurrence of crustal earthquakes are typically accompanied by sudden displacement processes along faults, involving the formation, expansion and interaction of multiple strain release zones. This process can be summarised in three stages: first, small-scale strain release zones form locally along the fault; subsequently, as regional stress continues to accumulate, these release zones gradually expand spatially; when strain energy reaches a critical state, the various strain release zones interact and ultimately trigger rupture.

As shown in Figure 11, the cumulative statistical analysis of geomagnetic anomalies prior to the Lushan earthquake, combined with sigmoid-function fitting, indicates that the Chengdu, Xichang, and Muli stations all exhibited a common evolutionary pattern characterised by a transition from slow to rapid growth during the earthquake preparation stage. Inter-station differences in the onset time, growth rate, and cumulative amplitude of the anomalies reflect the spatial heterogeneity of regional tectonic stress loading and the response characteristics of the geological medium (Huang, 1994). From a chronological perspective, the pre-earthquake development process can be divided into three stages. The first stage began in early January, approximately 100 days before the earthquake, during which anomalous signals appeared sporadically and then temporarily stabilised by the end of the month. The second stage started in early February, when the cumulative growth rate of anomalies increased markedly and continued to intensify through the end of March, corresponding to approximately 70 to 20 days before the earthquake, indicating the persistence and expansion of anomalous activity. The third stage began in early April, during which the slope of the cumulative anomaly curve increased rapidly, anomaly points became highly concentrated, and this accelerated trend persisted until the earthquake occurred, showing a distinct pre-earthquake acceleration pattern. The latter two stages of this three-stage evolution model are broadly consistent with the results reported by Yu et al. (2024) regarding the evolution of pre-earthquake geomagnetic anomalies in terms of their characteristics and overall trends. This indicates that the anomaly identification method based on prediction residuals adopted in this study not only reliably reproduces the pre-earthquake characteristics reported in previous studies, but also further clarifies the continuity of early-stage anomaly evolution."

Comment 11:

Line 420. Figure caption 12, also provide info about the tables included in the figure.

Response 11:

Thank you for your suggestions.

We have identified that the figure caption does indeed contain incomplete information. We have revised the caption to include more detailed descriptions of the data in the table shown in the figure. The changes, which were originally on page 20, line 420 of the draft manuscript and are now on pages 21, lines 442–448 of the revised manuscript, are as follows:

"Figure 12: Cumulative results of the number of days with abnormal strain data from the Kangding and Xiaomiao boreholes. The Boltzmann–Sigmoid fitting function is used, where parameter A1 represents the initial asymptotic level of the cumulative anomaly curve in the early stage, A2 represents the final asymptotic level when the accumulation process stabilises in the later stages, X0 denotes the inflection point of the curve—that is, the critical time at which the rate of anomaly accumulation reaches its maximum or transitions from slow to rapid growth—and dx represents the parameters controlling the transition width and growth rate of the curve. The reduced Chi-Sqr value, Coefficient Of Determination (COD), and Adjusted R-squared are used to evaluate the goodness of fit."

Comment 12:
Figures 11 and 12 clearly show that after the April 20, 2013 event the Cumulative results of the number of days with abnormal geomagnetic and strain data continues to increase. But how this phenomenon evolves?Actually, this note is linked to me initial comment about the post seismic period. Personally, I would like to have a comment from the authors of when the data ‘‘return‘‘ to background levels.

Response 12:

Thank you for your suggestions. The research objectives of this paper focus primarily on the extraction of anomalies and the analysis of multi-parameter coupling characteristics during the pre-seismic phase of the 2013 Lushan Ms7.0 earthquake; consequently, the current work concentrates on the identification, cumulative evolution and temporal correlation of pre-seismic geomagnetic disturbances and borehole strain anomalies. A systematic investigation into when post-seismic data ‘return’ to background levels has not yet been undertaken. Future work will further extend the time window to investigate when post-earthquake data from the same geomagnetic and borehole strain stations ‘return’ to background levels, thereby enabling a more comprehensive discussion of the method’s effectiveness and reliability in long-term monitoring scenarios.

Comment 13:
Line 478 -Figure 13. Panels in (a) describe regional factors, but the panels in (b) and (c) refer to which area? Please provide more details in the figure caption.

Response 13:

Thank you for your suggestions.

We have added regional labels to the section explaining environmental factors so that readers can relate them to the boxed areas in Figure 2 and better understand the content of the article. Lines 479–481 on page 22 of the original manuscript (lines 507–509 on page 24 of the current draft) have been amended as follows:

“To ensure that the identification of pre-earthquake geomagnetic and borehole strain anomalies is not affected by external environmental disturbances, this paper presents a systematic analysis of space weather and meteorological factors within the observation period (101–105° E, 27.5–32.5° N). ”

Comment 14:
Line 517 – Figure 14. Be more specific and detailed on what is presenting this figure. The authors have include physical parameters (ie TEC) together with station info (ie Muli) provide a more detailed figure caption.

Response 14:

Thank you for your suggestions.

We have rewritten the caption for Figure 14, incorporating the information contained in the figure, so that both the legend and the caption demonstrate that the pre-earthquake anomalies in the borehole and geomagnetic data appeared earlier and overlapped with other anomalous periods. Line 516 on page 24 of the original manuscript, and lines 545–549 on page 26 of the revised manuscript, have been amended as follows:

“Figure 14: Comparison of pre-earthquake anomalies from multiple sources. The anomalies for Xiaomiao and Kangding were derived from borehole strain observations, whilst those for Chengdu, Muli and Nanshan were derived from geomagnetic observations. TEC, Latent Heat Flux, Temperature, Surface Temperature and Groundwater Radon refer respectively to anomalies in total electron content (TEC) in the ionosphere, latent heat flux, air temperature, surface temperature and groundwater radon, as reported in previous studies.”

Comment 15:

Finally, Lines 528-534 – “ Conclusion “ . I think that the authors have to rewrite this section.

Response 15:

Thank you for your suggestions.

We agree that the summary section was rather brief and failed to summarise the conclusions drawn from the study in sufficient detail. We have rewritten the Conclusion section to outline the methods, findings and results of this paper, so that readers may gain a clear understanding of the study’s findings. Lines 528–534 on page 24 of the original manuscript (lines 560–577 on page 26 of the revised manuscript) have been amended as follows:

“This study focuses on the 2013 M 7.0 Lushan earthquake in Sichuan. By comprehensively utilising vertical component data from geomagnetic stations in Chengdu, Xichang and Muli, as well as surface strain data from borehole strain stations in Kangding and Xiaomiao, the study proposes a framework for identifying pre-earthquake anomalies that integrates VMD and Pyraformer. This method utilises VMD decomposition and modal reconstruction to attenuate background disturbances such as long-term trends, diurnal variations and solid tides, and employs Pyraformer for predictive modelling. Furthermore, based on the prediction residuals, it identifies anomalous points and days and constructs cumulative anomaly curves. The results indicate that both geomagnetic anomalies and borehole strain anomalies prior to the Lushan earthquake exhibited distinct phased accumulation characteristics: geomagnetic anomalies generally followed a sigmoid-shaped evolution, transitioning from a slow increase to a rapid intensification, whilst borehole strain anomalies accumulated continuously and gradually intensified over the months preceding the earthquake. Comparisons across multiple stations and parameters reveal that borehole strain anomalies generally appeared earlier than geomagnetic anomalies, with a time lag of several days to several weeks between the rapid accumulation phases of the two. This suggests that borehole strain may record local stress accumulation and fault medium deformation processes at an earlier stage, whilst geomagnetic anomalies may reflect the subsequent electromagnetic response. Overall, the VMD–Pyraformer framework is capable of effectively separating background evolution from local anomalous disturbances, providing a quantifiable and interpretable method for the identification of pre-earthquake anomalies across multiple stations and parameters, as well as for the analysis of stress–strain–electromagnetic coupling; however, its general applicability still requires verification through further earthquake case studies.”

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Gao, Y., Zhao, J., Zhou, G., Chen, C. H., Sun, Y. y., Zhang, X., Li, Y., Yao, C., Meng, Z., and Bai, X.: Electromagnetic Fields Generated by an Earthquake Due to the Piezomagnetic Effect, Journal of Geophysical Research: Solid Earth, 130, e2025JB031181, 2025,https://doi.org/10.1029/2025JB031181

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Ren, H., Huang, Q., and Chen, X.: Numerical simulation of seismo-electromagnetic fields associated with a fault in a porous medium, Geophysical Journal International, 206, 205-220, 2016,https://doi.org/10.1093/gji/ggw144.https://doi.org/10.1093/gji/ggw144